ISSN: 2755-8339

Journal of Business Research and Reports

SCIENTIFIC Research and Community

Research Article

Open Access

Beyond Model Accuracy: Comparing GTAP and GLOBIOM for Environmental Governance, Transparency, and Climate Justice in the Global South-A Critical Review

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ABSTRACT

Global land-use models increasingly shape assessments of biofuel sustainability, agricultural trade, deforestation and climate mitigation, yet the implications of their methodological choices for the Global South remain insufficiently examined. This qualitative literature review critically compares the Global Trade Analysis Project (GTAP) family, especially GTAP-BIO, with the Global Biosphere Management Model (GLOBIOM). Drawing on peer-reviewed research published from 2020 to 2026, the analysis integrates economic-model architecture, indirect land-use change, ecological accounting, uncertainty, reproducibility and environmental justice. Seven thematic findings emerge: structural non-equivalence; sensitivity of land-use and carbon estimates to assumptions; incompleteness of carbon-centric environmental indicators; spatial and social asymmetries in policy impacts; uneven representation of smallholders and Indigenous peoples; insufficiently standardised transparency; and opportunities for complementary rather than competitive model use. Evidence from Indonesia, Brazil and Africa suggests that model-based trade and climate rules can interact with pre-existing inequalities, although such effects are contingent rather than inherent to either model. The paper proposes a Transparent and Just Environmental Modelling Framework requiring scenario harmonisation, ecological triangulation, uncertainty disclosure, participatory appraisal, distributive safeguards and independent review. It concludes that modelling legitimacy depends on fitness for purpose, traceable evidence and accountable policy interpretation, not solely on numerical precision or model complexity.

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Received: October 16, 2026; **Accepted:** October 23, 2026; **Published:** October 31, 2026

Keywords: GTAP, GLOBIOM, Computable General Equilibrium, Land-Use Change, Environmental Justice, Global South, Indirect Land-Use Change, Deforestation, Model Transparency, Sustainable Trade

JEL Classification: Q56, Q57, F18, C68, O13

Introduction

Economic Models as Environmental Policy Infrastructure

The international debate on sustainable commodities is increasingly mediated by mathematical representations of how markets, land and ecosystems interact. Biofuel blending mandates, border-linked sustainability standards, forest conservation measures and agricultural trade reforms create effects that propagate beyond the jurisdiction where a rule originates. A demand shock in one market can change prices and consumption elsewhere, alter incentives to intensify production, displace agricultural output across borders, and put new pressure on forests or peatlands. Consequently, policymakers rely on simulation models to estimate indirect effects that cannot be observed simply by measuring emissions at the site of fuel production or commodity cultivation. The usefulness of these models is substantial, but their predictions depend on definitions, counterfactual scenarios, parameterisation and institutional judgments about what to include [1-3].

The Global Trade Analysis Project (GTAP) and the Global Biosphere Management Model (GLOBIOM) occupy prominent positions in this landscape. GTAP is simultaneously a widely used global input database, research community and family of general-equilibrium frameworks; GTAP-BIO extends the economic representation to biofuel-linked land allocation and indirect land-use change. GLOBIOM is a sectorally focused model of global agriculture, forestry and bioenergy that connects land competition, market clearing and spatial biophysical information over time. A headline numerical discrepancy between applications of these approaches may be interpreted as evidence that one is more credible. Yet such a conclusion is premature when the exercises define land conversion, the time horizon, environmental coverage and the simulated policy shock differently [4-6].

Environmental Significance and Research Gap

The stakes are particularly high in tropical countries where agricultural expansion overlaps with carbon-rich ecosystems, biodiversity hotspots, Indigenous territories and rural livelihoods. Remote-sensing and land-footprint studies demonstrate that land conversion and commodity consumption are geographically connected, while agricultural trade can embody emissions and biodiversity losses outside importing jurisdictions. The agricultural economy is therefore not environmentally neutral even when a

policy appears successful within the borders of the importing country. Studies of deforestation footprints, plantation expansion and carbon-rich forests make clear that environmental outcomes need more than nationally aggregated greenhouse-gas indicators [7-10].

A second problem concerns the politics of evidence. Model outputs may be incorporated into fuel carbon-intensity scores, due-diligence requirements, land-use restrictions and the reputational assessment of export commodities. Producers with limited access to geospatial data, certification services, legal documentation or modelling expertise may find compliance more expensive than established corporations. This is especially consequential when the environmental rules are formulated by powerful destination markets while adjustment costs are concentrated in lower-income producing regions. Evidence on Indonesian palm-oil certification, Brazilian deforestation-free supply chains and environmental trade regulation suggests that equitable implementation requires attention to livelihoods, financing and institutional capacity, not just formal compliance [11-14].

Recent evidence clarifies how unequal regulatory burdens can arise in practice. Participatory research with Indonesian oil-palm stakeholders identifies knowledge, organisational and financial barriers that prevent many independent growers from entering verified zero-deforestation chains; the authors emphasise that local inclusion must be accompanied by credible incentives and stronger land-governance arrangements [15]. Research on Peruvian cocoa and coffee supply chains similarly shows that due-diligence requirements interact with local institutions and rights, illustrating why procedural safeguards must be assessed in producer settings rather than inferred from a regulation's stated purpose [16].

A third gap is epistemological: most model comparisons prioritise sectoral coverage, numerical outputs or predictive plausibility rather than the distribution of authority to select assumptions and interpret results. Debate over GTAP-BIO illustrates the significance of disputed crop-yield responses, land definitions and emission factors. Malins, Plevin and Edwards questioned whether successive changes tended to produce overly favourable indirect land-use change estimates, while Taheripour, Mueller and Kwon defended the rationale and empirical support for key model improvements. Their disagreement is evidence of contestation, not proof that either assessment is universally correct [17,18]. The appropriate response is to make assumptions auditable, consider competing empirical interpretations and communicate sensitivity to policy users [19].

Purpose, Questions and Contributions

This article asks how differences in GTAP and GLOBIOM affect representations of trade, land-use change, carbon and biodiversity; which assumptions contribute most to uncertainty; how model-informed policies may affect Global South countries and stakeholders; and what governance procedures could enhance transparency and justice. The objectives are to compare model architectures, synthesise environmental evidence, evaluate social and distributional implications, and specify a practical framework for accountable model use. The manuscript offers a critical qualitative literature review, not a numerical head-to-head experiment, and accordingly does not claim that either model has a universally higher error rate. Its original contribution is to connect methodological comparability with distributive, procedural and recognition-based justice, while providing a sequenced design for policy assessments that are contestable and fit for purpose [20-22].

Literature Review

General-Equilibrium and Partial-Equilibrium Reasoning

A computable general-equilibrium model represents mutually dependent production and consumption decisions, markets for labour and capital, prices, trade flows and resource constraints within an accounting-consistent economy. Following a policy shock, a change in one sector may alter incomes, intermediate-input demand, wages, exchange-sensitive trade patterns and production elsewhere. The breadth of GTAP-type models is valuable when assessing cross-sectoral substitutions, tariff changes, biofuel demand or national welfare, although aggregation can conceal local ecological and household variation. GTAP variants are not identical: comparative-static implementations predominate in some applications, whereas dynamic, sectoral and geographically disaggregated adaptations have different capabilities [23,24].

A partial-equilibrium approach concentrates on a selected set of interacting markets while representing other economic conditions in simplified or exogenous ways. GLOBIOM uses this strategy to analyse production choices, land allocation and competition among agriculture, forestry and bioenergy, with spatial units carrying information on biophysical productivity and management options. Its recursive-dynamic structure supports the exploration of pathways and cumulative transitions, although broad non-land-sector feedbacks are not represented as fully as in an economy-wide equilibrium model. Because representation is modular and depends on the particular application, the assertion that GLOBIOM always delivers ecologically complete results would be as misleading as treating every GTAP implementation as spatially coarse [25,26].

The historical distinction is becoming less absolute. GTAP-SIMPLE-G connects global trade relationships with gridded crop and land-use decisions, allowing feedbacks between subnational agricultural adjustments and global markets. Likewise, GLOBIOM can be connected to other modelling systems to explore energy, climate and economic interactions. These innovations imply that scientific comparisons should specify the exact version, integrated modules, calibration year and experimental design. The theoretically relevant distinction is not simply 'economy-wide versus spatial' but whether the mechanisms that matter for the policy question are endogenous, empirically defensible and transparently implemented.

Table 1 distinguishes capabilities that are inherent in the general modelling traditions from those supplied by particular extensions and empirical applications. The comparison identifies complementary functions without assuming that either model can replace independent ecological observations or household-level evidence.

Table 1: Decision-Relevant Comparison of GTAP-Based and GLOBIOM-Based Assessments

Assessment feature	GTAP family / GTAP-BIO	GLOBIOM	Implication for comparison
Economic coverage	Economy-wide trade, prices and production interdependence	Sectoral equilibrium among agriculture, forestry and bioenergy	Use common policy shocks; do not conflate welfare with land-system outputs
Land representation	Economic land transformation; spatial detail depends on extension	Spatial land competition and biophysical production options	Document land classes, protections, management and geographical units
Temporal design	Often comparative static; dynamic variants also exist	Generally recursive dynamic	Align baseline year, adjustment horizon and carbon accounting period
Environmental metrics	Land/emissions modules vary by implementation	Land, agriculture and forestry impacts vary by implementation	Validate carbon, peat, habitat and biodiversity independently
Justice and social evidence	Aggregate welfare does not automatically identify smallholder outcomes	Detailed spatial outputs do not automatically capture customary rights	Add distributional appraisal, rights evidence and stakeholder review

The table demonstrates why valid comparison requires attention to model versions, rather than relying on labels such as "general equilibrium" or "spatially explicit". Its final row also establishes that environmental and distributional justice must be assessed through additional evidence even when the models are linked [27].

Indirect Land-Use Change and Causal Interpretation

Indirect land-use change (ILUC) refers to land conversion mediated through market responses when a policy changes demand for an agricultural or bioenergy commodity. Its estimation requires a credible counterfactual: the analyst must compare a scenario with the policy against an otherwise comparable trajectory without it. A model therefore predicts a difference between simulated worlds rather than measuring all hectares that have been causally converted by a policy. Studies of sustainable aviation fuel pathways illustrate how feedstock-specific induced conversion is assessed through scenario-based carbon accounting [28]. Prices, consumer demand, trade substitution, crop yields, multiple cropping, co-products and access to unmanaged land jointly shape the result. An apparently precise ILUC number can therefore conceal several layers of structural and empirical uncertainty.

In a GTAP-BIO application, land transformation is linked to economic incentives and elasticities, often within agroecological-zone aggregations, with emissions calculated from land transitions and associated emission factors. GLOBIOM more directly represents biophysical land competition and conversion choices over time but requires decisions about management systems, protected areas, spatial resolution and future productivity. Neither representation establishes a uniquely correct counterfactual; both require external evidence on agricultural responses and land-use histories. Different treatment of crop intensification and available forest frontiers can strongly change the balance between expanding cropland and producing more from existing land. Comparing emissions factors without aligning the underlying area changes and accounting periods is therefore insufficient [29].

Environmental Accounting Beyond Carbon

Greenhouse-gas emissions are important but incomplete measures of environmental integrity. Commodity-driven conversion may fragment habitat, reduce species populations, interrupt hydrological functions, expose peat to oxidation and modify local resilience even if an emissions accounting exercise suggests a modest global carbon effect. Global footprint analyses link consumption to tropical forest pressure, and biodiversity assessments show that the location and type of land conversion matter as much as aggregated area. This implies that an evaluation of biofuel or crop policy should include location-specific habitat and ecosystem-service indicators alongside land-carbon estimates [30].

The carbon dimension itself has contested measurement boundaries. Empirical comparisons of tropical forest loss highlight the importance of non-market governance and the timing of forest protection for social values [31]. Estimates of land-use carbon flux differ because methods define managed land, degradation, regrowth, peat emissions and counterfactual ecosystem dynamics differently. Peatland emissions in Indonesia illustrate why surface vegetation categories and default carbon factors may be inadequate substitutes for water-table conditions, oxidation, drainage history and management. Moreover, carbon stocks are not interchangeable with the annual flow of greenhouse gases, and a choice of amortisation period changes the apparent carbon intensity assigned to a litre of biofuel. Consequently, harmonised accounting and explicit uncertainty intervals are prerequisites for meaningful comparison [32,33].

Environmental Justice, Recognition and Legitimacy

Environmental justice has at least three connected dimensions. Distributive justice asks who receives climate and biodiversity benefits and who bears the monetary or opportunity costs. Procedural justice concerns whose views shape decisions, while recognition justice asks whether institutions respect Indigenous rights, customary tenure and culturally different relationships with land. These distinctions are particularly important when economically aggregated model results are used to justify geographically targeted obligations. An aggregate positive net benefit cannot demonstrate that a subsistence-oriented smallholder, landless worker or forest-dependent community is better off.

Integrating environmental objectives with rights protection also requires more than adding social indicators after model completion. Evidence from Brazil's soy supply chains indicates that instruments addressing deforestation have frequently treated land-tenure concerns inadequately, despite their close practical relationship; this supports incorporating tenure assumptions and grievance mechanisms at the point of scenario design. As a result, the proposed justice assessment must distinguish a model's quantified welfare outputs from the independent normative and legal obligations affecting land rights.

Evidence from tropical landscapes shows why social heterogeneity matters. Profit-maximising farm configurations can conflict with ecological multifunctionality, certification effects vary with prior livelihoods, and Indigenous stewardship can be associated with avoided deforestation under specific conditions. These are substantive mechanisms that cannot be inferred from national welfare changes or spatial carbon maps alone. They motivate distributionally disaggregated indicators, explicit land-tenure information and meaningful representation of affected groups in scenario design rather than the unexamined assumption that greater spatial resolution guarantees justice [34-36].

Reproducibility and Scientific Accountability

Model transparency extends beyond publishing a conceptual diagram or a source-code repository. A reproducible analysis requires versioned baseline databases, documented licences and restrictions, transparent transformations, parameter provenance, exact scenario files, solver settings, convergence checks, emissions accounting code and interpretable outputs. Scientific openness also requires a practical route through which an independent researcher can obtain the inputs necessary to reproduce key results or understand limitations imposed by proprietary datasets. FAIR data principles and reproducible computational-workflow initiatives provide useful operational precedents, although adopting a repository structure alone does not resolve disputed scientific assumptions [37].

As presented in Figure 1, the two model families provide complementary analytical inputs rather than an automatic hierarchy. The diagram clarifies why model harmonisation should precede ecological and equity assessment.

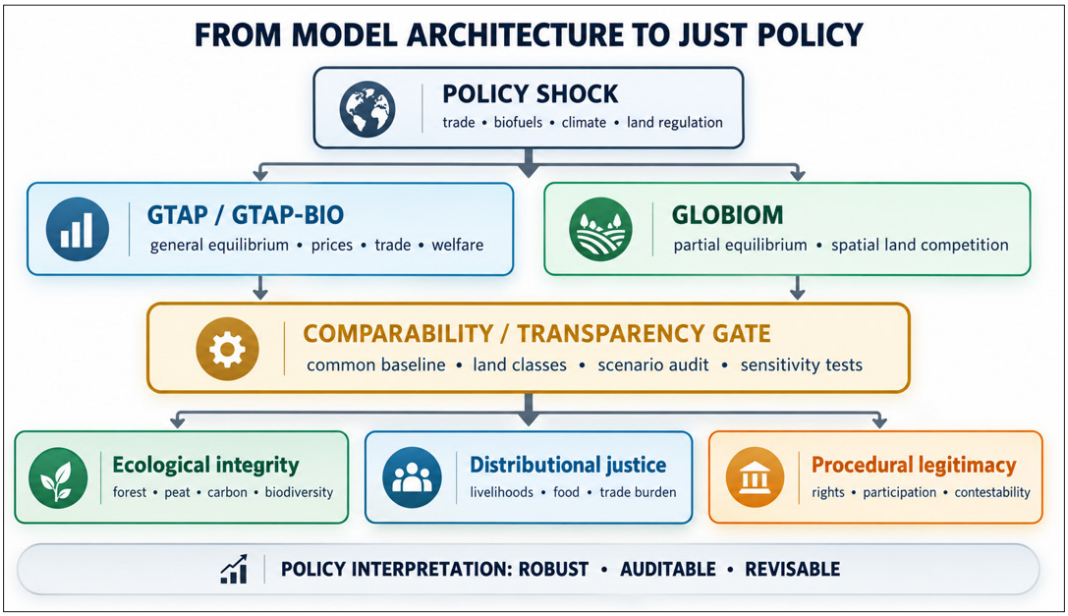


Figure 1: Conceptual Architecture of the GTAP–GLOBIOM Comparison and the Justice-Oriented Assessment Gates

Figure 1 outlines the analytical relation between model architecture, comparability requirements and environmental-justice appraisal. Its key message is that GTAP and GLOBIOM need not be treated as mutually exclusive competitors: they can contribute complementary information provided differences in their boundaries are communicated. The lower part of the diagram deliberately separates ecological integrity, distributive outcomes and procedural legitimacy so that one favourable result cannot silently substitute for another.

Methodology

Critical Qualitative Literature Review

This study adopts a critical qualitative literature review rather than a systematic literature review or meta-analysis. The method aims to develop an explanatory synthesis of modelling practices, empirical environmental evidence and justice-related policy implications, rather than to calculate pooled effects or count all studies meeting a protocol-defined set of eligibility criteria. The literature window is January 2020 to 14 October 2026. Sources are selected purposively for conceptual importance, empirical credibility, relevance to GTAP/GLOBIOM and coverage of contrasting disciplinary positions. The approach is appropriate because the research questions span incommensurate objects of inquiry: economic model structure, spatial forest dynamics, livelihood consequences and institutional legitimacy.

Source Identification and Appraisal

Search concepts include GTAP, GTAP-BIO, GLOBIOM, computable general equilibrium, agricultural partial equilibrium, ILUC, biofuel emissions, tropical deforestation, trade footprints, model uncertainty, reproducibility, smallholders, Indigenous territories, and environmental justice. The search strategy emphasises peer-reviewed work in economic modelling, land-system science, ecological economics, sustainability and development journals; citation following was used to connect methodological controversies to related empirical research. The material is organised into direct modelling studies, cross-model or methodological assessments, observational or causal environmental studies, and social or policy-governance research. This classification reduces the risk that model outputs are misrepresented as observations or that justice principles are presented as measured empirical results.

Quality appraisal attends to journal credibility, the transparency of data and methods, the match between claims and research design, treatment of counterfactuals and the disclosure of uncertainty. Studies advancing conflicting explanations are deliberately retained, particularly where the dispute concerns yield elasticities, managed versus unmanaged land, land conversion, or the proper interpretation of ILUC. No publication count is

interpreted as proof that a position is correct, and no invented harmonised GTAP–GLOBIOM numerical experiment is reported. The analytical outcome is a thematic synthesis, with the strength of inference explicitly distinguished from speculation and from policy preferences.

Thematic Coding and Comparative Procedure

A qualitative extraction matrix captures model family and version, sectoral and spatial scope, baseline and policy scenario, time structure, land-cover categories, treatment of productivity and trade, emissions accounting, distributional indicators, stated limitations and reproducibility provisions. First-cycle thematic coding identifies mechanisms that influence outcomes; second-cycle coding connects those mechanisms to environmental risks, policy effects and justice concerns. Indonesia and Malaysia, Brazil and selected African countries are used as illustrative contextual cases, not as a controlled three-country comparative sample. Inference remains conditional on the evidence available for each context and does not treat the Global South as homogeneous.

The conceptual Transparent and Just Environmental Modelling Framework (TJEMF) is derived through interpretive synthesis. It proposes six assessment gates: structural fitness; environmental integrity; transparency; distributional justice; procedural and recognition justice; and policy robustness. Its value is heuristic and institutional rather than empirically validated within this review. The paper thus avoids reporting a fictional model accuracy score or proposing an arbitrary composite index that would conceal competing values. Later validation would require application to harmonised, documented policy cases and deliberation with affected stakeholders.

Results: Thematic Findings

Theme One: Structural Non-Equivalence Rather than Model Hierarchy

The clearest finding is structural non-equivalence. GTAP-family models are strongest when commodity substitution, trade, price adjustment, sectoral reallocation and economy-wide welfare are central to the research question. GLOBIOM is particularly suitable for studying interdependent choices across agriculture, forestry and bioenergy and the geography of land allocation over time. A more detailed land map does not automatically generate a credible estimate of wages, exchange-sensitive exports or aggregate welfare; conversely, a sophisticated trade matrix does not identify exactly which forest parcel becomes more vulnerable. The appropriate assessment should therefore start with the causal mechanisms of the policy under examination rather than the prestige or age of a model family.

Studies applying different models to agricultural and land-sector transformation also indicate that climate policies can interact with production pathways, diets, management practices and trade. Model-based analysis of alternative proteins suggests potentially significant land and emissions consequences of dietary substitution, while agricultural carbon-sink studies show that producer incentives and financing conditions change the feasibility of mitigation. These findings demonstrate the comparative strength of land-focused scenario analysis but do not eliminate the need to measure wider economic spillovers. Integrated modelling is most informative when the division between endogenous predictions and externally imposed assumptions is explicit.

Theme Two: ILUC and the Centrality of Discretionary Assumptions

The controversy over GTAP-BIO reveals that modeled ILUC values are shaped by highly consequential parameter choices. Assumed crop-yield responsiveness influences whether additional demand is met by greater output per hectare or by converting new land; treatment of co-products affects the net feed demand; and rules defining potentially convertible lands influence where expansion can occur. In addition, the geographic distribution of conversion changes carbon estimates because forests, savannas, grasslands and peatlands contain different carbon stocks. Malins, Plevin and Edwards viewed several GTAP-BIO modifications as insufficiently established, whereas Taheripour, Mueller and Kwon defended improvements with alternative interpretations of historical data. The exchange does not establish a universal winner but provides a strong case for assumption-level stress testing.

Analyses of US biofuel policy and its links with Southeast Asian vegetable-oil markets show another important mechanism: substitutability. A shock to US corn or soybean biofuel demand can influence other oil markets, but the magnitude of land-use change in Indonesia and Malaysia depends on trade relationships, relative prices and production responses rather than on a direct physical transfer of land demand. Taheripour and Tyner found comparatively limited simulated land expansion in their specified GTAP-BIO scenarios, while other strands of the literature caution that modelling improvements have not fully resolved uncertainty over ILUC. This difference should motivate scrutiny of baseline assumptions, not the selective quotation of a single result to demonstrate that land-use concerns are either negligible or overwhelming

.

Theme Three: Environmental Leakage and the Limits of Carbon-Only Indicators

Trade-driven environmental displacement is a major theme. A restriction on forest-linked imports may lower the footprint of a regulated supply chain but shift producers toward other customers or induce expansion in alternative regions. Deforestation footprint studies reveal why an importing country can improve its domestic forest indicators while sustaining overseas pressure through consumption, and analyses of agricultural emissions embodied in trade point to similar displacement mechanisms. Yet leakage is not necessarily complete or inevitable: the Brazilian soy literature identifies partial domestic leakage with different cross-border effects under the particular scenarios examined. The size of leakage must be estimated rather than inferred automatically from the existence of international trade.

Observed land transitions complicate this account. Research on the global land rush links agricultural land deals to potential carbon releases and mitigation opportunities, underscoring the materiality of frontier governance [38]. Remote sensing identifies oil-palm expansion into carbon-rich forests in Indonesia and Malaysia, but attributing an observed change to one specific foreign biofuel rule requires a defensible counterfactual. Global deforestation footprinting can connect commodities and consumption to forest loss; it does not independently settle the economic mechanism by which a marginal policy shock produces that loss. Similarly, field-based research on Indonesian peat plantations adds process-rich emissions evidence without independently quantifying global trade feedbacks. A credible evaluation should use these evidence streams together, recognising that their strengths answer different questions.

Figure 2 maps the successive assumptions separating an initial policy shock from environmental and distributional conclusions. These stages should be documented individually because

uncertainty can arise at more than one point in the modelling chain.

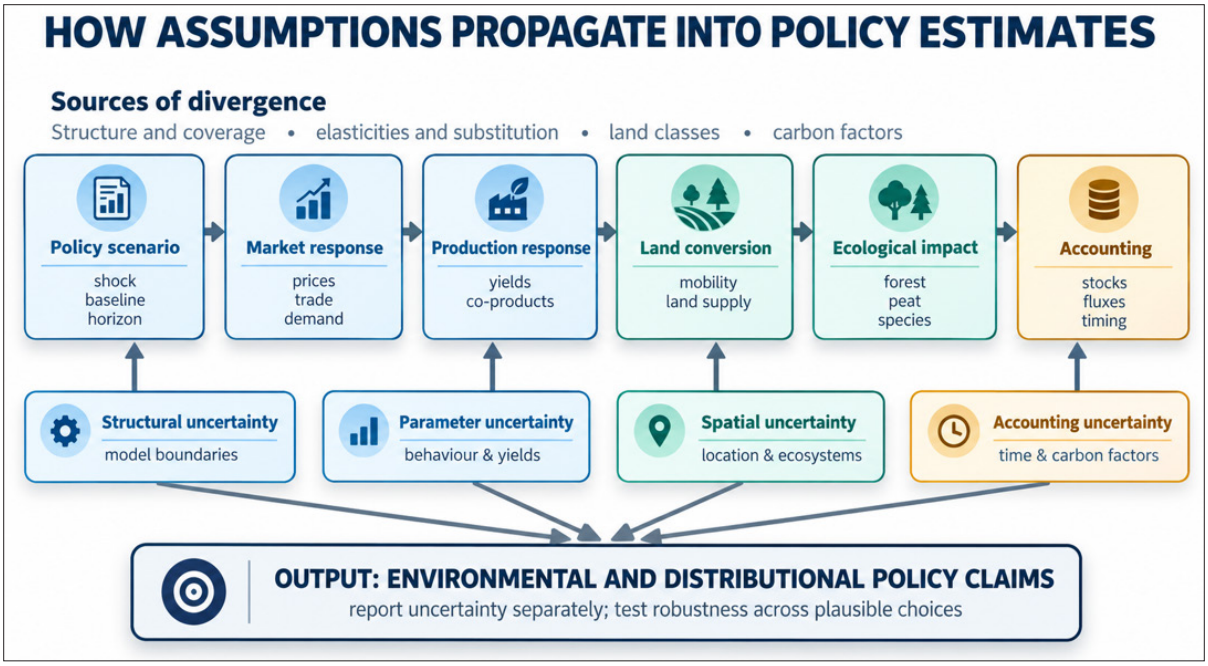


Figure 2: Causal Propagation of Assumptions into Environmental Estimates and Policy Interpretations

Figure 2 traces how a policy shock can produce a wide range of estimated environmental consequences even before uncertainties in ecological measurement are introduced. The diagram separates market responses, land-system responses, ecological conversion and emissions-accounting choices, because the same headline carbon intensity can arise from different causal pathways. It also shows why divergence between models should prompt targeted sensitivity analysis of underlying mechanisms rather than a debate restricted to final numbers.

Theme Four: Biodiversity, Peatlands and Spatial Ecological Heterogeneity

Land area alone is an incomplete ecological indicator. A hectare converted from previously degraded agricultural land differs profoundly from one converted from species-rich forest, peat swamp or a landscape supporting traditional livelihoods. Studies of the global biodiversity effects of agricultural trade and spatial land planning underscore the importance of location and conservation condition. GLOBIOM's spatial representation may provide a stronger starting point for locating land-system changes, while GTAP's economy-wide structure can identify trade and consumption pressures that spatial assessments need to take into account. Neither delivers comprehensive biodiversity or tenure outcomes unless appropriate indicators and linkages are added.

Peatlands illustrate the risk of inappropriate aggregation. Carbon release can continue long after conversion and depends on drainage, water management and subsidence dynamics, while short carbon-accounting horizons can shift perceived mitigation benefits. Furthermore, estimates of land-use carbon flux vary with treatment of managed land, regrowth, natural sinks and degradation. These differences are sufficiently consequential that harmonising land-cover categories without addressing ecological processes may create an appearance of comparability rather than actual comparability. The environmental assessment of palm-derived biofuels or plantation commodities must therefore test sensitivity to peat and forest categories, carbon-stock data, temporal accounting and post-conversion management.

Theme Five: Food Security, Economic Resilience and Distributive Effects

Environmental policy can affect food security through prices, land availability, employment and government revenues. Economy-wide models can estimate broad adjustment pressures, while land-system models can examine production location, agricultural intensification and the balance of food, feed and energy crops. Research using dynamic trade and climate models projects that heat and water stress may impair food supply, reinforcing the need for environmental assessments to account for background climate vulnerability. Other scenarios suggest that land-based mitigation can place highly unequal pressure on cropland across countries; these are conditional forecasts, not assured future outcomes [39,40].

The African case provides an instructive corrective to overly simplified trade-versus-environment narratives. Scenario analysis of continental trade integration and agricultural development suggests that lowering trade barriers alone will not resolve underlying farm-level supply constraints or undernourishment, whereas complementary productive investment can change the outlook. Other research finds that urbanisation-mediated dietary shifts may reshape African food demand and biodiversity pressures. Taken together, these findings imply that a model which measures only the export value of affected commodities can miss important nutritional and ecological consequences. Interpreting policy as just or unjust requires attention to food affordability, regional production capacity and public investment rather than reliance on national GDP changes.

Theme Six: Social Difference Within Producing Countries

Rural producers are not an internally uniform category. Studies of smallholder landscapes in Indonesia show trade-offs between financial profit and multifunctional ecological outcomes, while certification research finds that socioeconomic benefits depend in

part on villages' prior livelihood systems. Independent smallholders may face obstacles involving land legality, geolocation, record-keeping, financing and organised market access. When a model aggregates all oil-palm production into one representative activity, it may overlook these differences and provide an incomplete picture of compliance burdens or sustainable-transition opportunities.

The problems are particularly visible when verification depends on digital maps and documentary evidence. Eggen et al. find that independent oil-palm smallholders are underrepresented in compliant zero-deforestation supply chains and identify locally grounded measures for improving participation. In coffee value chains, Gallemore et al. demonstrate that errors in the classification of agroforestry systems may produce exclusionary market-access outcomes even where producers have not recently deforested land; classification accuracy and accessible avenues for correction are therefore part of environmental justice, not merely technical refinements.

Land rights and tenure further complicate the picture. Research on Indigenous territories in the Amazon and pan-tropical Indigenous Lands suggests that protection and stewardship can reduce deforestation or degradation under important contextual conditions. Studies of tropical dry forests warn that agricultural intensification does not necessarily spare land when the economic gains induce expansion, but Indigenous stewardship can alter that relationship. These results matter for modelling because land-conversion elasticities and administrative protected-area layers cannot fully substitute for institutional mechanisms governing property, enforcement and collective action. A socially credible model-informed policy must therefore differentiate smallholders, workers, plantations and customary-rights holders [41].

Theme Seven: Transparency, Contestability and Model Governance
The literature indicates that transparency is multidimensional. Descriptions of equations do not reveal whether the baseline inputs, calibration procedures, restricted datasets or emissions post-processing can be independently reproduced. Conversely, public code may be formally accessible but impractical to run without training, licences, computing capacity or clear documentation. The FAIR-oriented climate repository and ENCORE reproducibility framework provide examples of practices that strengthen provenance and computational scrutiny. In an environmentally consequential regulatory setting, an additional requirement is contestability: affected jurisdictions should be able to review assumptions, request alternatives and receive reasoned explanations when objections are rejected.

The importance of transparent reporting is heightened by model uncertainty. Climate-impact model ensembles identify substantial variation across model processes; food-system modelling reviews emphasise socio-political feedbacks, links between global and local levels and the need for participatory approaches. Uncertainty is not only a technical interval around a best estimate: uncertainty can arise because a model excludes labour informality, customary land institutions, shifting cultivation or important ecological states altogether. Better uncertainty analysis thus requires both quantitative sensitivity testing and qualitative examination of missing mechanisms. A policy decision can be scientifically defensible despite residual uncertainty, provided decision makers disclose and govern that uncertainty rather than hide it behind a single figure.

Illustrative Comparisons Across the Global South
Indonesia and Malaysia illustrate the intersection of palm oil, trade, peat-carbon dynamics and smallholder welfare. US biofuel demand can indirectly alter oilseed markets, but simulations of the effect depend on substitution, regional calibration and baseline production conditions. Satellite observations document environmentally damaging plantation expansion, while village research reveals variation in the livelihood consequences of certification. The combination makes a single carbon-intensity score inadequate for deciding whether all producer groups should face identical obligations. Policy evaluation should incorporate peat safeguards, traceability costs, smallholder inclusion and the possibility of development on existing agricultural land.

Brazil illustrates how trade incentives, territorial governance and leakage intersect. Commodity-price responses can make frontier expansion attractive under weak protection, while international due-diligence measures differ across cattle, soy, coffee and other export sectors in their feasibility and distributive effects. A Brazilian soy study shows that successful supply-chain restrictions can coexist with partial domestic leakage, undermining both blanket claims of complete displacement and optimistic assertions of perfect effectiveness. The regulatory challenge is therefore to improve traceability without merely excluding weaker suppliers and to coordinate importing-market rules with Brazilian institutions and landscape governance.

African cases bring a different set of development priorities. Increasing intra-regional agricultural trade can support resilience, but improving market integration without complementary investment leaves persistent production constraints. Urban growth, changing diets, biodiversity protection and the consequences of climate stress create multiple and sometimes conflicting objectives. The policy-relevant question is whether model comparisons permit decision makers to identify distributionally acceptable agricultural transformation pathways, rather than simply choosing the scenario with the lowest aggregate emissions. Local participation is essential when spatial modelling assumptions intersect with contested tenure, protected landscapes and livelihood options.

Figure 3 compares qualitative trade, ecological and justice pathways for Indonesia–Malaysia, Brazil and selected African contexts. The region-specific diagram is illustrative and avoids presenting non-comparable numerical impact estimates or attributing outcomes to a particular model without harmonised experiments.

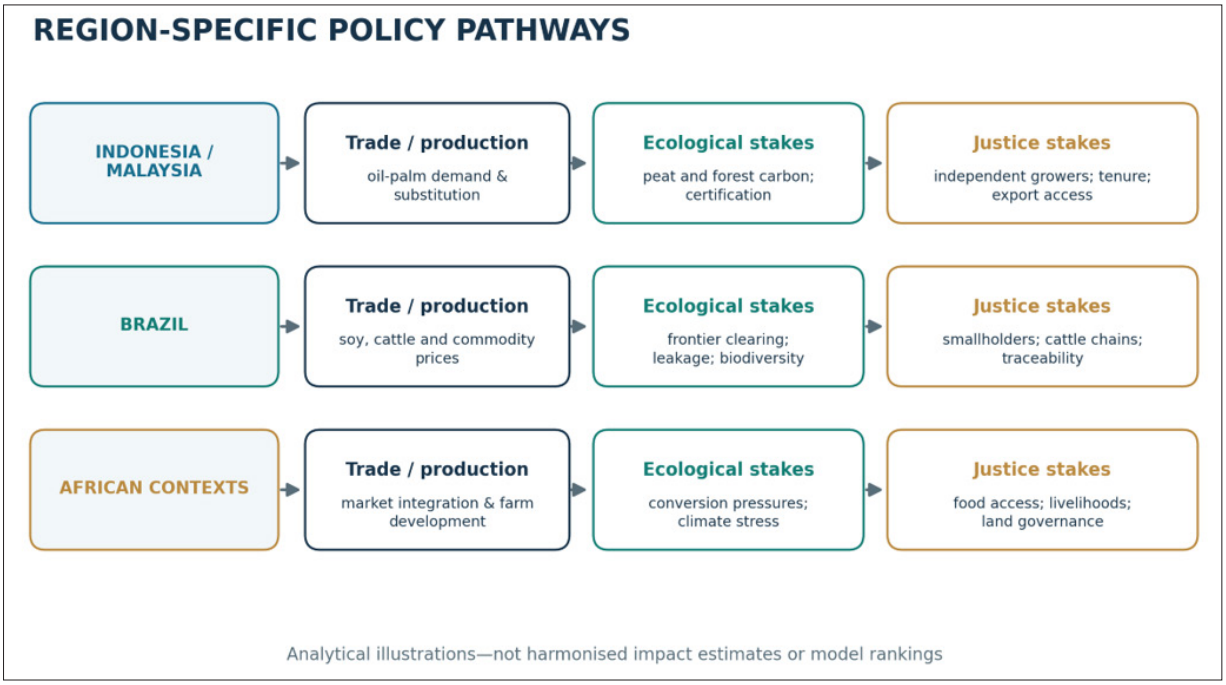


Figure 3: Illustrative Trade, Environmental and Justice Pathways Across Three Global South Contexts

Figure 3 summarises the three regional pathways without suggesting that they are identical or quantitatively comparable case studies. Palm-oil substitution and peat concerns dominate the Southeast Asian illustration, commodity frontier dynamics and supply-chain leakage are central in Brazil, and market integration and food security feature prominently in the African illustration. Each pathway leads to ecological, distributive and procedural questions that should be assessed simultaneously before a policy recommendation is made [42].

Discussion and Analysis

What Model Disagreement Actually Means

Disagreement between GTAP and GLOBIOM can reflect at least five different sources: divergent policy shocks, different baseline data, structural model closures, parameter and behavioural assumptions, and environmental accounting conventions. It can also arise because one model includes a category of emissions or land conversion that the other treats as exogenous or excludes. These distinctions are more important than the superficial observation that two studies report different numerical outcomes; global land-cover analysis also indicates that the estimated magnitude of land-use transitions depends on temporal and classification methods [43]. The soundest interpretation begins by reconstructing the causal pathway and asking where the studies cease to be equivalent, rather than averaging their outputs indiscriminately.

A more rigorous model-comparison protocol would progressively harmonise shocks and assumptions. First, policy boundaries, products, regions and the counterfactual baseline should be identical. Second, comparable land classes, conversion possibilities, agricultural productivity assumptions and environmental factors should be used where technically feasible. Third, differences that cannot be eliminated because of the architectures should be reported as structural variation rather than treated as statistical error. Finally, the analyst should document which estimates can reasonably be compared across frameworks and which have different scopes. Such an approach will not eliminate uncertainty, but it will reveal whether particular divergences are driven by science, modelling convenience or genuine scenario differences.

Why Single-Model Policy Thresholds Require Caution

Some environmental regulations convert model-derived outputs into eligibility categories, default emission values or rankings of commodity pathways. The attraction is administrative simplicity: a single indicator seems to permit consistent decisions across exporters and fuel technologies. The risk is that a model assumption is effectively transformed into a binding economic rule without adequate scrutiny of uncertainty or differential exposure. Research comparing fuel standards illustrates how divergent ILUC accounting conventions may produce different assessments of the same broad fuel pathway. The appropriate response is not necessarily to abandon model-based thresholds, but to accompany them with uncertainty ranges, periodic review and transparent routes for evidence-based challenge.

Where a regulatory indicator is highly sensitive to uncertain elasticities or carbon factors, an automatic prohibition or subsidy may be disproportionate to the strength of the underlying evidence. Decision makers should distinguish robustly adverse outcomes from outcomes that change sign across credible parameter settings. Precaution may still be justified for irreversible harm to primary forests or peatlands, but it should be articulated as a policy principle rather than disguised as a deterministic model fact. Similarly, uncertainty should not become a pretext for disregarding repeatedly observed environmental damage. A defensible decision rule combines scientific sensitivity, rights protection, the expected irreversibility of harm and proportionate support for compliance.

The Politics of Conservation and Development Trade-Offs

Models can illuminate trade-offs without resolving their normative legitimacy. A scenario may reduce global emissions at the cost of higher food prices or slower agricultural expansion in a poorer producing region. Another may raise national agricultural income while contributing to forest loss or unequal land concentration. The answer cannot be determined solely by summing monetary welfare or carbon emissions, because the moral and legal significance of livelihood security, food access and Indigenous rights cannot always be expressed in commensurable units. The correct institutional response is transparent multicriteria evaluation

that reveals trade-offs rather than hiding them within unexplained weights [44].

This consideration is especially relevant when emissions reductions are achieved through displacement of production or through land-use restrictions without compensatory development pathways. Research demonstrates that agricultural intensification may be associated with rebound effects, that certification benefits are socially heterogeneous and that the wealthy can influence tropical crop expansion through investment. These mechanisms expose a limitation of policy narratives that attribute all environmental outcomes to smallholder production decisions alone. Equity-oriented model use should therefore identify the roles of corporate investment, state institutions, consumer demand and differentiated access to land and capital. Otherwise, regulation risks imposing the burden of adjustment on actors with the weakest bargaining positions.

The EUDR as an Illustration of Model-Informed Governance

The European Union Deforestation Regulation (EUDR) is useful as an illustrative governance context, although its legal requirements are not reducible to GTAP or GLOBIOM outputs. Studies examining its design and foreseeable economic effects emphasise the potential for improved supply-chain accountability alongside unresolved concerns about smallholder compliance, market leakage and regulatory power. Assessment of Brazilian sectors suggests uneven readiness to comply, while research on agroforestry warns that simplified forest classifications can produce unintended exclusion of farmers whose production systems retain substantial tree cover. The broader lesson is that the sophistication of an environmental policy objective does not ensure that its operational categories are fair or ecologically comprehensive.

Model-informed assessments can help anticipate these effects if they incorporate destination-market substitution and heterogeneous producer constraints. Research on the forest-sector implications of the EUDR highlights potential changes in production, trade and employment, while economic analysis of Argentina suggests that aggregate macroeconomic effects under one particular policy simulation may be limited. Neither finding implies that local costs are negligible; a small national GDP effect can coexist with severe losses in specific supply chains or communities. Conversely, policies designed to remove deforestation from traded products may produce real environmental benefits under sufficiently broad coverage and credible enforcement. Interpretation should therefore attend to both leakage and distribution, as well as the jurisdictional limits of each modelling exercise.

These risks are not confined to tropical oil palm and soybeans. Evidence from Peruvian cocoa and coffee production shows that environmental and human-rights due diligence can become difficult to implement when compliance rules do not account for local capabilities and governance arrangements. Classification-related exclusion in coffee landscapes provides a second example: maps that do not reliably distinguish agroforestry from prohibited conversion may turn a technical error into a market-access barrier [45]. Thus, equity audits should include tests of classification error, administrative burden and accessible correction procedures alongside conventional simulations of trade displacement.

International cooperation matters because unilateral measures may redirect trade and create divergent incentives across importing markets. Research on possible EU-China policy convergence argues that diplomacy, market conditions and cooperative mechanisms are central to reducing imported deforestation beyond one jurisdiction. Studies of voluntary sustainability standards also indicate that certification alone may not satisfy all regulatory due-diligence requirements, potentially increasing burdens on small producers with limited administrative capacity. These findings suggest the importance of interoperability across assurance systems, recognition of credible domestic arrangements and transparent technical assistance. A model of trade displacement can inform this process, but participatory governance must determine how unavoidable transition costs are shared [46,47].

Six Components of the Proposed TJEMF

The first TJEMF component is structural fitness. Every study should present a model-purpose statement showing why the policy mechanism requires economy-wide feedbacks, spatial land dynamics or a coupled system. This statement should identify excluded sectors, the temporal interpretation of elasticities, the treatment of unmanaged land and the modelled socioeconomic groups. When a tool is unsuitable for a crucial mechanism, its limitation should be addressed through coupling, independent analysis or explicit caveats, rather than by multiplying spatial detail or reporting more decimals. Recent developments in gridded GTAP applications and food-system model integration offer plausible routes to bridge traditional gaps.

The second component is environmental integrity. Modelled land-use changes should be linked to transparent carbon-stock and flux assumptions, sensitive ecosystem categories, biodiversity pressures and relevant hydrological processes. Independent remote-sensing, field measurement and consumption-footprint data should be used to judge plausibility wherever these evidence streams address a compatible spatial or temporal question. Neither GTAP nor GLOBIOM alone should be presumed to assess every ecological dimension adequately. This component would reduce the likelihood that an emissions-focused policy is declared successful while peat degradation, species loss or displaced land conversion remains materially unexamined.

The third component is transparency and reproducibility. At minimum, analyses should publish a structured model card that records software version, baseline dataset, geographical and sectoral aggregation, policy shock, closure assumptions, elasticity sources, land-conversion rules, calibration methods, emissions factors, solver configuration, data licences and known limitations. Where legal or commercial restrictions prevent full disclosure, the missing elements and their implications for reproducibility should be recorded, and a secured independent auditing mechanism should be considered. Repositories should contain machine-readable scenario inputs and accessible explanatory materials for policymakers, not merely generic code. These steps draw on established open-science and provenance practices while adapting them to the demands of international environmental regulation.

The fourth component is distributional justice. National GDP, aggregate welfare, farm revenue and overall mitigation costs should be supplemented with indicators of affected household types, poverty, food access, land tenure, employment and compliance expenses. The selection of indicators must fit the affected value chains and social institutions: independent palm-oil growers, cattle ranchers, forest-based agroforesters, Indigenous territories and plantation workers face different risks. Modelled income changes should be triangulated with qualitative field evidence rather than assumed to capture household wellbeing. The aim is not to force every model to represent every group endogenously but to ensure that the policy decision does not conceal important unequal burdens.

The fifth component is procedural and recognition justice. Producer-country technical experts, affected communities, Indigenous and customary-rights representatives, civil society, industry and importing-country regulators should be engaged before critical assumptions become de facto regulatory defaults. Participation must permit scrutiny of scenario selection, geographical classifications, land rights, uncertainties and policy alternatives rather than being limited to post hoc consultation on predetermined results. Communities should be offered meaningful access to information and practical channels for disputing inaccurate geospatial classifications or unreasonable compliance obligations. Such safeguards recognise that environmental knowledge is jointly produced by scientific measurement and locally situated experience, neither of which should automatically silence the other.

Operationally, participation should include a documented response-to-comments register and a channel for growers or customary-rights holders to request revisions to land-cover assignments. Research on Indonesia's palm-oil supply chains and Brazil's soy governance confirms that exclusionary practices can persist despite stated sustainability objectives, while Peruvian value-chain experience reinforces the importance of implementation-sensitive rights protection. An independent reviewer should verify not only that consultation occurred but also whether it changed relevant assumptions, classifications or safeguards.

The sixth component is policy robustness. For high-stakes decisions, policymakers should request at least one plausible alternative model specification or independent assessment, harmonised scenario stress tests and explicit identification of decisions that change under credible assumptions. Particular attention should be paid to the size of shocks, baseline economic growth, crop yields, land mobility, carbon factors, peat assumptions and rates of international substitution. An assessment should distinguish decisions that are robust across scenarios from those requiring precaution, adaptive implementation or additional evidence. This is a decision process rather than a numerical certification label; value judgments and thresholds must remain visible.

Table 2 converts the proposed TJEMF from a normative argument into a practical disclosure and accountability checklist. It identifies minimum materials that reviewers should receive and the complementary safeguards needed when model-derived indicators have unequal consequences for producers or communities.

Table 2: Minimum Audit Evidence and Justice Safeguards Proposed for TJEMF Applications

TJEMF assessment gate	Minimum reproducibility evidence	Corresponding safeguard
Structural fitness	Version, closures, geographical/sectoral scope, excluded mechanisms	Explicit limits on the model's fitness for the policy decision
Environmental integrity	Land classifications, conversion matrix, peat/carbon factors, observation cross-checks	Separate monitoring of biodiversity, forest and peat outcomes
Transparency	Versioned baseline, input files, parameters, scripts, licences, model card	Independent audit or secured access where proprietary inputs prevent open release
Distributional justice	Affected group typology, livelihood/food-price effects, compliance cost assumptions	Proportionate assistance and differentiated smallholder pathways
Procedural recognition	Stakeholder register, dispute records, response-to-comments documentation	Rights-based participation and land-classification correction channels
Policy robustness	Harmonised alternatives, uncertainty ranges, sensitivity decisions, revision triggers	Adaptive rules, appeals and publicly stated precautionary thresholds

These requirements are designed as a proposal for future application, not as a claim that the TJEMF has already been validated empirically. A pilot implementation should test whether disclosed assumptions, independent scrutiny and community challenges materially improve decisions without imposing disproportionate administrative costs.

Implementation Priorities for Global South Institutions

Producer countries should not be positioned solely as data providers for externally constructed models. A practical reform agenda would fund regional laboratories capable of independently evaluating GTAP, GLOBIOM and related systems, maintaining national land-cover crosswalks and reviewing sustainability classifications. Universities, statistical agencies, agricultural ministries, forest authorities and community organisations could jointly identify the assumptions with greatest domestic relevance. International partnerships should support open training materials, interoperable geospatial infrastructure and the ability to commission independent sensitivity tests. Building this capacity would reduce epistemic dependence without requiring each country to invent an entirely separate global economic modelling system.

For importing jurisdictions and multilateral organisations, the corresponding duty is to avoid transferring all verification costs to producers. Transition periods, proportional reporting obligations, public technical assistance, credible grievance mechanisms and compatibility with diverse production systems can improve fairness while protecting environmental objectives. An equity-monitoring framework should be institutionalised at the time a regulation is designed, not constructed only after adverse effects have materialised. This principle follows from evidence that environmental value-chain policies can produce distributional and recognition-related risks at multiple scales. It also aligns incentives toward better conservation outcomes rather than strategic avoidance of a particular consumer market.

Figure 4 presents a sequenced pathway for operationalising the TJEMF in high-stakes environmental policy studies. It makes independent review and stakeholder involvement recurring requirements rather than optional final-stage consultations.

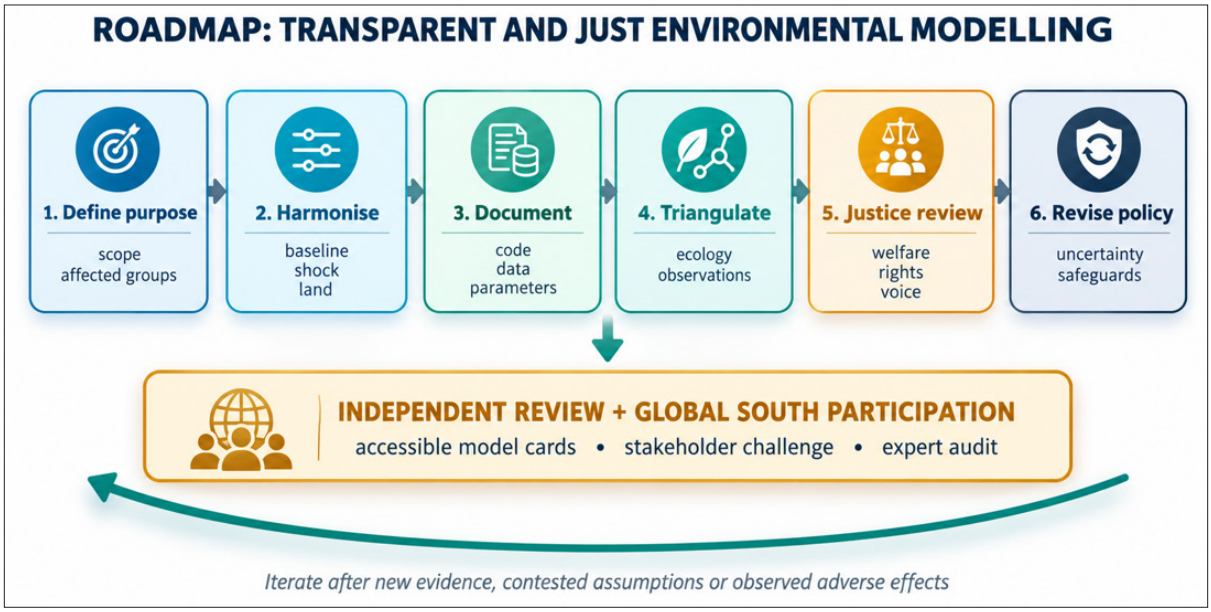


Figure 4: Proposed Transparent and Just Environmental Modelling Framework (Tjemf) Implementation Roadmap

Figure 4 translates these components into a practical sequence. The roadmap begins with agreeing on the policy question and comparable scenario, then moves through data harmonisation, transparent simulation, ecological validation and distributional review before producing a conditional policy decision with scheduled revision. A feedback arrow indicates that the exercise is iterative: contested assumptions, new environmental observations and stakeholder evidence should lead to updated simulations and, where appropriate, corrected regulatory conclusions.

Research Limitations and Future Testing

The present review synthesises heterogeneous research rather than reproducing or recalibrating either model. Its thematic conclusions are therefore strongest where they concern identifiable structural differences, documented uncertainty mechanisms and well-supported governance needs; they are more tentative when projecting the net distributive effect of a hypothetical policy in any individual country. A useful next research phase would run harmonised GTAP-BIO and GLOBIOM scenarios for palm-based biofuels, soybean biodiesel and deforestation-free supply chains with shared baselines and emissions accounting. Independent land observations, household-level distributional analysis and documented local stakeholder review would provide complementary tests, making clear where models agree, where disagreement remains and what the policy consequences of that uncertainty are.

A second avenue is to test the TJEMF itself. Pilot assessments could evaluate whether its reporting template improves reproducibility, whether participatory scrutiny changes material scenario assumptions, and whether distributional safeguards lower compliance burdens without increasing deforestation. The results should be reported transparently, including failures, costs and trade-offs. A successful framework would not eliminate political disagreement; rather, it would make the factual basis, normative choices and rights implications of disagreement inspectable. That is a more realistic standard for credible environmental modelling than an expectation of universally agreed predictions [48-57].

Conclusion

The comparison of GTAP and GLOBIOM demonstrates that environmental modelling is fundamentally an exercise in selecting analytical boundaries, specifying behavioural assumptions and interpreting uncertain counterfactuals. GTAP's general-equilibrium orientation offers valuable insight into trade, prices and economy-wide adjustments, while GLOBIOM's land-sector and spatial emphasis is useful for exploring agricultural, forestry and bioenergy competition. Neither architecture can claim universal superiority, and model-based policy conclusions should never be presented as stronger than the evidence and accounting conventions that support them. Differences in outcomes are meaningful only when scenarios and environmental boundaries are sufficiently comparable.

For Global South countries, the consequences of model selection can extend into market access, rural incomes, food security, forest governance and the legitimacy of sustainability requirements. These outcomes are not determined by model architecture alone; they depend on the rules, institutions and safeguards through which model findings become policy. An environmental policy may pursue an important conservation objective and still impose unnecessarily unequal compliance costs. Equally, concerns about equity should not be invoked to dismiss documented deforestation, peat degradation or biodiversity loss. Responsible policy must take both environmental integrity and social justice seriously.

The proposed Transparent and Just Environmental Modelling Framework links six requirements: structural fitness, ecological integrity, reproducibility, distributive appraisal, meaningful participation and policy robustness. Its purpose is to make model-informed decisions more auditable and revisable rather than to replace scientific models with subjective judgments. Comparative studies should publish their assumptions, harmonise scenarios wherever feasible, retain uncertainty information and consult stakeholders who would bear the costs of implementation. Producer-country expertise and community knowledge should enter the assessment process early enough to influence it.

The principal recommendation is that governments, research institutions and international standard setters treat model-derived environmental indicators as conditional evidence embedded within a wider decision architecture. Transparent multi-model appraisal, independent ecological verification and proportionate

social safeguards should become normal requirements for high-stakes trade and climate rules. Future empirical work should evaluate the proposed framework using controlled multi-model experiments and participatory country studies. The resulting goal is not merely more technically sophisticated modelling but environmental governance that is scientifically credible, institutionally accountable and compatible with fair development pathways.

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