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Reconciling forest product statistics for enhanced sector modeling: A recursive dynamic goal programming approach

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ABSTRACT

International forest product statistics contain measurement errors, missing values, and trade flow discrepancies. Our study presents a recursive dynamic goal programming approach to identify and reconcile these inconsistencies over the period from 2000 to 2022. Unlike traditional static reconciliation methods, this framework includes year-over-year consistency, optimizing deviations between reported and estimated values while adhering to technological constraints and trade balances. Results indicate substantial regional heterogeneity: Europe and North America exhibit high reported–reconciled agreement, while Oceania and Africa require larger adjustments. Export statistics consistently require the greatest corrections, with import–export reconciliation gaps often reaching 20–30 percentage points. Agreement rates vary widely across products, with residues (waste paper, chips and particles) requiring substantially more adjustment than other categories. The reconciled dataset reveals diverging trends in wood processing efficiency, characterized by gains in Europe and Asia contrasted against declining efficiency in South American sawnwood production. The reconciled price series captures major market dynamics, including the 2021–2022 pandemic-induced surge. Validation confirms elimination of all material balance violations present in raw data. This methodology improves resource potential evaluation and provides a robust, internally consistent foundation for future forest sector analysis.

1. Introduction

International trade in wood and paper products reached about USD 482 billion in 2023, representing around 1.5–1.6% of global trade in goods and services (FAO, 2024; UNCTAD, 2024). The Food and Agriculture Organization of the United Nations Statistics (FAOSTAT) Forestry Database serves as one of the primary sources of data for analyzing this sector worldwide, providing annual time series on production, imports, and exports of forest products dating back to 1961. This comprehensive global database, used by researchers and policymakers, forms the foundation for economic and environmental analysis through various forest sector models (Hurmekoski and Hetemäki, 2013; Latta et al., 2013; Toppinen and Kuuluvainen, 2010), including the Global Forest Product Model (Buongiorno et al., 2003) and the Forest Resource Outlook Model (Johnston et al., 2021). Recent applications of these models to evaluate trade disruptions (Nepal et al., 2024) illustrate the continued policy relevance of global forest sector modeling. Accurate and consistent assessment of forestry product prices, supply and demand quantities, and market forecasts is essential for understanding society's increasing dependence on forest resources, which provide crucial ecosystem services, including carbon sequestration (Pan et al., 2011), watershed protection (Millennium Ecosystem Assessment, 2005), biodiversity habitat (IPBES, 2019), and renewable materials (IPCC, 2019).

Despite their crucial role in assessment and analytical decision making, trade data and production data across multiple databases, including FAOSTAT, present persistent challenges in use (Chen et al., 2022; Jiang et al., 2022; Zhang et al., 2022). These include discrepancies between reported exports from the origin countries and imports by destinations (mirror statistics gaps), mismatches between production volumes and independently verified outputs, and temporal discontinuities that distort trend analyses (Kallio and Solberg, 2018; Pardo-Herrera, 2021). Such issues, often involving quantities exceeding millions of cubic meters (and involving values in trade of comparable magnitudes), arise from factors such as varying conversion factors, reporting lags, and misclassifications, leading to biased estimates of material flows and

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economic values (Ferrantino et al., 2012; Hamanaka, 2012). Although such data reporting challenges, particularly for international trade, have been long-recognized across traded products more generally (Buongiorno, 2018), these data quality challenges of FAOSTAT threaten the database's foundational role as a source of research data and in informing market, rural development, and climate policies.

While studies have explored factors driving data discrepancies (Hamanaka, 2012; Ferrantino et al., 2012; Gaulier and Zignago, 2010), studies specifically focused on the FAOSTAT Forestry Database remain limited. Existing literature has largely sought to document inconsistencies in agricultural trade statistics or other FAOSTAT domains, yet there is a dual gap: comprehensive time series analyses of forestry trade data discrepancies are rare, and methodological frameworks to reconcile these inconsistencies are even scarcer. To close the dual gap, our study presents a recursive dynamic goal programming (RDGP) approach to systematically identify and reconcile inconsistencies in the FAOSTAT Forestry Database over the period from 2000 to 2022. Our approach integrates several key steps to enhance data consistency. Initially, we implement a data screening process to pinpoint missing values, outliers, and logical inconsistencies across production, import, and export statistics. Next, we employ imputation techniques, using product-specific global means and standard deviations, to fill data gaps while preserving economic relationships. We then implement robust price assignment mechanisms to filter anomalous values and establish consistent pricing benchmarks. Finally, to reconcile residual inconsistencies, we apply a RDGP model that optimizes deviations between reported and estimated values while adhering to technological constraints, material balances, and temporal continuity. The recursive structure ensures that reconciled values from each period inform constraints for the subsequent period, imposing year-over-year consistency.

Our analysis yields insights into patterns of reported-reconciled agreement and market trends. Spanning 2000 to 2022, our findings reveal pronounced regional variations in data quality, with processed products requiring less reconciliation adjustment than raw materials or by-products. The reconciled dataset also highlights divergent regional trends in wood processing efficiency. While Europe and Asia showed modest efficiency gains (e.g., Europe's IRNC to SWNC coefficient improving from 2.0 to 1.8), South America exhibited declining efficiency, with its IRC to SWC coefficient increasing from 1.5 to 2.1 between 2002 and 2022. These regional disparities underscore the importance of region-specific analysis. Additionally, our reconciled price benchmarks capture market dynamics, such as the 2021–2022 pandemic-induced price surge and persistent regional price differences across product categories. These improvements enhance the dataset's utility for forest sector modeling and offer insights into refining data collection systems.

This study contributes to the literature by introducing a comprehensive methodology for addressing data inconsistencies in forest product statistics and by providing a reconciled dataset spanning over two decades of global forest product markets. In addition, this study contributes to a better understanding of cascading wood input-output flows, improves resource potential evaluation, and enables more reliable specification of coefficients for wood use in forest sector models. The remainder of the paper is organized as follows: Section 2 reviews relevant literature on data reconciliation methods and forest sector modeling; Section 3 details the enhanced methodology; Section 4 presents results and validation metrics; Section 5 discusses implications and limitations; and Section 6 concludes with recommendations for future research and applications.

2. Literature review

Data discrepancies in the forest sector are common in both trade and production statistics, arising from differences in transportation cost accounting (Cost, Insurance, and Freight versus Free on Board), reporting time lags, product misclassification, misattribution of origins, transshipment practices, and inconsistencies in conversion factors (Ferrantino et al., 2012; Hamanaka, 2012; Vincent, 2004). These challenges are not unique to forestry; similar issues have been documented in UN Comtrade, where researchers have developed approaches to address missing values (Zhang et al., 2022), outliers (Jiang et al., 2022), and bilateral asymmetries arising from differences in trade systems, monetary valuation, and partner attribution (Chen et al., 2022). Methodologies for detecting discrepancies in forest product statistics have evolved from simple mathematical formulations to optimization techniques. Early approaches relied on relative measures of discrepancies (Vincent, 2004), ratios between reported exports and imports (Ali et al., 2019; Hamanaka, 2012), or apparent demand calculations (Torres-Rojo, 2021). While these methods effectively identify inconsistencies—such as the under- and over-valuation in timber trade data demonstrated by Pardo-Herrera (2021)—they generally lack mechanisms to systematically reconcile conflicting data.

Reliable forest product statistics are fundamental to models that inform forest sector analysis and policy. Forest sector models range from global partial equilibrium frameworks to regional simulation tools, each with distinct data requirements (Latta et al., 2013; Mathieu and Roda, 2023; Toppinen and Kuuluvainen, 2010). Reviews of these modeling approaches highlight their evolution toward integrated frameworks addressing sustainability challenges (Nummelin et al., 2021; Rivière and Caurla, 2020; Riviere et al., 2020; Sjølie et al., 2015). Models such as the Global Forest Products Model (Buongiorno et al., 2003) and the Forest Resource Outlook Model (Johnston et al., 2021) rely heavily on FAOSTAT data, making data quality a critical determinant of model reliability. Buongiorno and Johnston (2018) further demonstrated that parameter and data uncertainty in such models leads to steadily increasing variability in long-term projections. Hurmekoski and Hetemäki (2013) emphasized that long-term outlook studies face particular challenges when market structures shift, as models based on historical data may fail to capture emerging patterns—underscoring the importance of maintaining plausible temporal trajectories in reconciled datasets.

To address data quality limitations, researchers have developed various frameworks to harmonize trade and production figures. The BACI database (Gaulier and Zignago, 2010) utilizes reliability-weighted averaging of mirror statistics to reconcile UN Comtrade bilateral flows. While effective for trade values, this approach does not ensure consistency with domestic production and consumption constraints, nor does it enforce material balance relationships between raw inputs and processed outputs—limitations relevant for the forest sector where input-output relationships are critical. Forest-specific Material Flow Analysis approaches offer an alternative perspective. Lenglet et al. (2017) applied consequential MFA to analyze forest-wood supply chains in France, while Rougieux et al. (2017) developed a reproducible tool for analyzing international forest products trade flows. Bösch et al. (2023) developed a physical accounting model using matrix algebra to trace wood-based products across 268 countries and 16 product categories, establishing production-consumption linkages at multiple processing levels and converting all flows into wood fiber equivalents. These MFA studies provide valuable insights into material movement and can identify implausible flows, though they focus on tracing physical flows rather than reconciling inconsistent statistics within an optimization framework that minimizes deviations from reported values while enforcing production, trade, and technological constraints.

Goal programming has emerged as a promising framework for forest product data reconciliation. The foundational contributions of Buongiorno et al. (2001, 2003) established the methodological basis for subsequent work, and the present study draws directly upon their framework. Unlike conventional linear programming, goal programming allows weighted deviations from multiple targets rather than requiring strict equality constraints—essential when reconciling statistics containing measurement errors. This approach simultaneously enforces material balance constraints, accommodates reporting asymmetries through controlled deviations, and incorporates realistic conversion coefficients. A key insight from Buongiorno et al. (2003) was relating penalty weights to product prices, reflecting the assumption that statistics tend to be more accurate for higher-value products. Buongiorno (2018) subsequently applied this framework globally, revealing significant underreporting in major markets including China, while Kallio and Solberg (2018) used analogous principles to identify substantial inconsistencies between reported wood biomass volumes and production quantities across multiple countries.

Despite these advances, a limitation of prior goal programming applications lies in their treatment of time. Existing approaches have typically focused on static reconciliation, treating each time period independently. This approach balances materials within a single year but does not account for temporal dependence of production and trade capacities. Our study builds upon the goal programming framework of Buongiorno et al. (2001, 2003) by extending it from a static to a recursive structure. We address limitations of independent yearly estimation by introducing year-over-year consistency constraints that prevent unrealistic jumps in time series. This recursive approach ensures results from one period inform constraints of the next, imposing continuity on reconciled series. Additionally, we expand product coverage aligned with current FAOSTAT classifications and incorporate region-specific, time-varying conversion factors. The resulting framework aims to create a more internally consistent version of the FAOSTAT Forestry Database, improving the foundation for forest sector analyses and modeling applications.

3. Methodological framework

To transform the raw FAOSTAT time series into a single, internally consistent panel of production, trade, and price (unit value) observations that can be used without further manipulation in forest-sector models, we design a RDGP model. This model operates on the full 2000–2022 period by incorporating temporal constraints that ensure year-over-year consistency.

3.1. Data structure and problem setting

The reconciliation of forest product statistics presents a multi-dimensional optimization problem spanning n countries, k forest products, and T time periods. Each country c reports production $\widetilde{q}_{c,k,t}$, imports $\widetilde{m}_{c,k,t}$, and exports $\widetilde{x}_{c,k,t}$ for product k in year t, where tildes denote reported values containing measurement errors and inconsistencies.[1] A full list of the k forest product categories and their corresponding acronyms is provided in Appendix A.

Four primary data issues motivate our approach: (i) missing values that create spatial and temporal gaps, (ii) extreme outliers from reporting errors or methodological changes, (iii) mirror statistics discrepancies in bilateral trade flows, and (iv) material balance violations when processed product output exceeds feasible production from available inputs. Traditional static reconciliation treats each year independently, potentially introducing artificial volatility. Our dynamic formulation addresses this by simultaneously reconciling data across all dimensions while respecting technological constraints and limiting unrealistic temporal fluctuations. Issues (i) and (ii) are addressed through preprocessing steps prior to optimization, as detailed in Appendix B. Issues (iii) and (iv) are handled directly by the goal programming constraints described below.

Data preprocessing addresses systematic issues before optimization. Missing production values receive conservative imputation using $\widetilde{q}^{imp}_{c,k,t} = \max(\mu^q_k - \sigma^q_k, \epsilon)$ where μ^q_k and σ^q_k represent global production mean and standard deviation for product k, and $\varepsilon = 0.001$ is a small positive constant ensuring non-negativity. Outliers are capped at three standard deviations from global means. We derive implicit prices from trade values and quantities, filtering extreme observations while preserving legitimate market signals. Such preprocessing yields adjusted values ready for reconciliation while maintaining transparency about modifications. Forest product manufacturing follows well-established technological relationships that structure reconciliation. Conversion factors vary regionally. These relationships provide bounds on feasible input-output combinations while accommodating substitution possibilities such as recycled fiber replacing virgin pulp. These preparatory steps ensure the model is initialized with a clean, complete, and logically sound set of input data.

3.2. Dynamic goal programming formulation

The reconciliation problem seeks estimated values $Y_{c,k,t}$ for production, $\widehat{m}_{c,k,t}$ for imports, and $\widehat{x}_{c,k,t}$ for exports that minimize deviations from reported data while satisfying consistency constraints. Our goal programming formulation balances multiple objectives:

$$
\begin{aligned}
\min Z = \quad & \alpha_1 \beta \sum_c \sum_k w_{c,k} \left(Y^+_{c,k,t} + Y^-_{c,k,t} \right) \\
& + \alpha_2 (1-\beta) \sum_c \sum_j \sum_o \sqrt{w_{c,j} w_{c,o}} \left(I^+_{c,j,o,t} + I^-_{c,j,o,t} \right) \\
& + \alpha_3 \sum_c \sum_k w_{c,k} \left(p^+_{c,k,t} + p^-_{c,k,t} \right) \\
& + \alpha_4 \sum_c \sum_k w_{c,k} \left(\tau^+_{c,k,t} + \tau^-_{c,k,t} \right) \\
& + \alpha_5 \sum_c \sum_k w_{c,k} \left(\gamma^{q+}_{c,k,t} + \gamma^{q-}_{c,k,t} + \gamma^{m+}_{c,k,t} + \gamma^{m-}_{c,k,t} + \gamma^{x+}_{c,k,t} + \gamma^{x-}_{c,k,t} \right)
\end{aligned} \tag{1}
$$

The first term minimizes production deviations where $Y^+_{c,k,t}$ and $Y^-_{c,k,t}$ represent positive and negative deviations from reported values, weighted by penalty weights $w_{c,k}$. The second term ensures input-output consistency by minimizing deviations ($I^+_{c,j,o,t}$, $I^-_{c,j,o,t}$) from expected input usage $I_{c,j,o,t}$, which denotes quantities of input j used for output o, weighted by the geometric mean of their penalty weights $\sqrt{w_{c,j} w_{c,o}}$. The third term maintains price consistency by minimizing deviations ($p^+_{c,k,t}$, $p^-_{c,k,t}$) from reported prices. The fourth term captures trade balance adjustments ($\tau^+_{c,k,t}$, $\tau^-_{c,k,t}$). The fifth term, unique to our recursive approach, penalizes excessive year-over-year volatility in production, imports, and exports through variables $\gamma^{q\pm}_{c,k,t}$, $\gamma^{m\pm}_{c,k,t}$, and $\gamma^{x\pm}_{c,k,t}$. Two types of weights appear in our formulation: component weights (α_1 through α_5) and observation weights. Country-product specific weights reflecting data reliability, calculated using the methodology described in Section 3.4.

Production estimates relate to reported values through:

$$
Y_{c,k,t} + Y^-_{c,k,t} - Y^+_{c,k,t} = \widetilde{q}_{c,k,t} \quad \forall c, k, t \tag{2}
$$

where $Y_{c,k,t}$ is the reconciled production for country c, product k, and year t; $\widetilde{q}_{c,k,t}$ is the reported production; and $Y^+_{c,k,t}$, $Y^-_{c,k,t}$ are non-negative deviation variables.

Input usage aligns with production levels according to:

$$
I_{c,j,o,t} + I^-_{c,j,o,t} - I^+_{c,j,o,t} = Y_{c,o,t} \cdot \overline{a}_{j,o} \quad \forall c, j, o, t \tag{3}
$$

where $I_{c,j,o,t}$ denotes the quantity of input j used for output o in country c and year t, and $\overline{a}_{j,o}$ represents expected input requirements per unit output based on technological studies. The specific upper and lower bounds for these input-output relationships are detailed along with their sources in Appendix C.

[1] Tilde notation ($\widetilde{\cdot}$): Used for reported/observed values from the original FAOSTAT database. Hat notation ($\widehat{\cdot}$): Used for reconciled/estimated values that are outputs of the optimization model. Capital letters without marks (Y): Used for reconciled production specifically (equivalent to $\widehat{q}_{c,k}$)

Material balance constraints ensure supply meets demand:

$$Y_{c,j,t} - \hat{x}_{c,j,t} + \hat{m}_{c,j,t} = \sum_{o} I_{c,j,o,t} \quad \forall c, j, t \tag{4}$$

For final products without industrial uses:

$$Y_{c,k,t} + \hat{m}_{c,k,t} \geq \hat{x}_{c,k,t} \quad \forall c, k \in F, t \tag{5}$$

Technological feasibility bounds input-output relationships:

$$a_j^L \cdot Y_{c,o,t} \leq I_{c,j,o,t} \leq a_j^U \cdot Y_{c,o,t} \quad \forall c, j, o, t \tag{6}$$

$$a_{tot}^L \cdot Y_{c,o,t} \leq \sum_{j} I_{c,j,o,t} \leq a_{tot}^U \cdot Y_{c,o,t} \quad \forall c, o, t \tag{7}$$

where a_j^L and a_j^U are lower and upper bounds on individual input coefficients, and a_{tot}^L and a_{tot}^U bound total input requirements per unit output (see Appendix C).

Temporal consistency constraints limit year-over-year changes:

$$Y_{c,k,t} - Y_{c,k,t-1}^{rec} = \gamma_{c,k,t}^{q+} - \gamma_{c,k,t}^{q-} \quad \forall c, k, t > t_0 \tag{8}$$

$$\gamma_{c,k,t}^{q+} \leq \delta_q \cdot Y_{c,k,t-1}^{rec} \quad \forall c, k, t > t_0 \tag{9}$$

$$\gamma_{c,k,t}^{q-} \leq \delta_q \cdot Y_{c,k,t-1}^{rec} \quad \forall c, k, t > t_0 \tag{10}$$

where $Y_{c,k,t-1}^{rec}$ denotes the reconciled production from the previous year (a fixed parameter in the current year's optimization), $t_0 = 2000$ is the initial year, and $\delta_q = 0.15$ permits 15% annual changes based on observed historical volatility in FAOSTAT production series. These constraints are expected to be non-binding for large producers with complete, consistent reporting and primarily serve to stabilize reconciled series for smaller countries where data gaps or preprocessing adjustments may otherwise introduce artificial year-over-year volatility. Similar constraints apply to imports and exports. We note that alternative temporal specifications exist for addressing year-over-year consistency. Within-transformations using deviations from period means, or autoregressive specifications incorporating multiple lags, e.g., AR(2), AR(3), represent well-established econometric approaches that could provide extensions to our framework.

Trade balance adjustments track through:

$$\left(\hat{m}_{c,k,t} - \hat{x}_{c,k,t}\right) + \tau_{c,k,t}^{-} - \tau_{c,k,t}^{+} = \left(\tilde{m}_{c,k,t} - \tilde{x}_{c,k,t}\right) \quad \forall c, k, t \tag{11}$$

where $\tau_{c,k,t}^{+}$ and $\tau_{c,k,t}^{-}$ capture deviations of reconciled net trade from reported net trade.

3.3. Assessment metrics

Following reconciliation, we assess data quality through multiple complementary metrics. Production Reconciliation Deviation Index (PRDI), quantifies agreement between reconciled and reported values:

$$PRDI_{c,k,t} = 100 \cdot \left(1 - \min\left(0.5 \frac{\left|Y_{c,k,t} - \tilde{q}_{c,k,t}\right|}{\max\left(\tilde{q}_{c,k,t} \varepsilon\right)}\right) \cdot 2\right) \tag{12}$$

where $Y_{c,k,t}$ represents reconciled production, $\tilde{q}_{c,k,t}$ represents reported production, and $\varepsilon = 0.001$ prevents division by zero for countries with negligible or unreported production. This index ranges from 0 (maximum disagreement, where relative deviation $\geq 50\%$) to 100 (perfect alignment). High-agreement records are defined as country-product pairs where RIS falls below 0.20, indicating minimal reconciliation was required.

The Import Reconciliation Deviation Index (IRDI) and Export Reconciliation Deviation Index (ERDI) follow similar constructions:

$$IRDI_{c,k,t} = 100 \cdot \left(1 - \min\left(0.5 \frac{\left|\hat{m}_{c,k,t} - \tilde{m}_{c,k,t}\right|}{\max\left(\tilde{m}_{c,k,t} \varepsilon\right)}\right) \cdot 2\right) \tag{13}$$

$$ERDI_{c,k,t} = 100 \cdot \left(1 - \min\left(0.5 \frac{\left|\hat{x}_{c,k,t} - \tilde{x}_{c,k,t}\right|}{\max\left(\tilde{x}_{c,k,t} \varepsilon\right)}\right) \cdot 2\right) \tag{14}$$

where $\hat{m}_{c,k,t}$ and $\hat{x}_{c,k,t}$ represent reconciled imports and exports, and $\tilde{m}_{c,k,t}$ and $\tilde{x}_{c,k,t}$ represent reported imports and exports, respectively.

Beyond point-wise metrics, we developed a comprehensive Reconciliation Intensity Score (RIS) synthesizing multiple dimensions. Coverage completeness measures data availability across the time series by tallying instances of missing reported values:

$$Comp_{c,k} = \frac{\sum_{t=1}^{T} \mathbb{I}\left(\tilde{q}_{c,k,t} \neq \text{missing}\right)}{T} \tag{15}$$

where $\mathbb{I}(\cdot)$ denotes the indicator function and T represents the total number of years. Consistency of magnitude captures average alignment between reconciled and reported values:

$$Cons_{c,k} = 1 - \frac{1}{n_{c,k}} \sum_{t=1}^{T} \frac{\left|Y_{c,k,t} - \tilde{q}_{c,k,t}\right|}{\max\left(\tilde{q}_{c,k,t}, Y_{c,k,t}, \varepsilon\right)} \tag{16}$$

where $n_{c,k}$ is the number of non-missing observations for country c and product k, normalizing by the maximum to handle cases where reconciled values exceed reported ones.

Volatility of discrepancies indicates whether differences between original and reconciled data remain stable or fluctuate erratically:

$$Vol_{c,k} = \frac{\sigma\left(\delta_{c,k,t}\right)}{\bar{\delta}_{c,k}} \tag{17}$$

where $\delta_{c,k,t} = \left|Y_{c,k,t} - \tilde{q}_{c,k,t}\right|$ represents the absolute deviation for country c, product k, and year t, and $\bar{\delta}_{c,k}$ represents the mean deviation. High volatility suggests inconsistent reporting practices or model difficulty in reconciling conflicting constraints.

We assess systematic drift by regressing absolute differences on time, with the coefficient of determination R^2 indicating trend strength. Outlier frequency counts observations exceeding 3.5 median absolute deviations, identifying countries or products with persistent reconciliation challenges.

The composite Reconciliation Intensity Score aggregates these metrics:

$$\begin{aligned} RIS_{c,k} = \; & 0.30 \times \left(1 - Comp_{c,k}\right) + 0.40 \times \left(1 - Cons_{c,k}\right) \\ & + 0.15 \times Vol_{c,k} + 0.10 \times R^2 \\ & + 0.05 \times OutlierFreq_{c,k} \end{aligned} \tag{18}$$

Weights derive from expert consultation and sensitivity analysis, with consistency (40%) and completeness (30%) as primary indicators. Higher RIS values indicate greater reconciliation intensity—that is, more adjustment was required due to lower completeness, lower consistency, higher volatility, stronger systematic drift, or more frequent outliers. This composite score enables systematic identification of data segments requiring improved collection methods or additional validation. We emphasize that there is no universal rule for weight selection in goal programming reconciliation. Our primary objective is to provide a flexible methodological framework for balancing inconsistent datasets, and researchers applying our GAMS code can incorporate additional information to construct weights tailored to their research questions and data contexts.

3.4. Weight selection

The model employs a systematic weight selection methodology combining variance-based reliability weights with price-based weights. Observation weights for each country-product pair are determined by data characteristics including reporting consistency (measured by coefficient of variation across years) and product value (following Buongiorno, 2003). Component weights (α) determine relative importance of different objective function terms. Complete documentation of the weight calculation methodology is provided in the annotated GAMS demonstration code available in the repository.

3.5. Validation procedures

We assess model performance through three complementary validation approaches. First, a starting year sensitivity analysis tests path dependency by re-solving the model from different initial years (2000, 2003, 2006, 2010) and comparing results over common evaluation periods. Second, Monte Carlo simulation introduces controlled data quality problems (random measurement error, systematic bias, missing values) to test the model's ability to recover known true values. Third, temporal cross-validation (5-fold) assesses out-of-sample performance by holding out consecutive years for testing. Results are presented in Section 4.6 with detailed tables in Appendix D.

3.6. Implementation

The model is implemented using a sequential reconciliation approach that solves the goal programming problem for each year in the analysis period from 2000 to 2022 (note: 2023 data were not complete at the time of analysis). This temporal methodology enables the incorporation of year-over-year continuity constraints while maintaining computational tractability for the large-scale optimization problem encompassing all countries and products in the FAOSTAT database. For each year in the sequence, the model initializes with current year data and applies temporal constraints based on the previous year's reconciled solution. The goal programming model is then solved to minimize the weighted objective function subject to all economic, technological, and temporal constraints. Results are stored and serve as the foundation for initializing the subsequent year's optimization, ensuring that the entire time series maintains both internal consistency and realistic temporal evolution.

The complete model was implemented in the General Algebraic Modeling System (GAMS) using the XPRESS solver for the linear programming components. The framework encompasses 20 forest product categories across all countries and regions in the FAOSTAT database, producing a comprehensively reconciled dataset that maintains economic consistency, respects technological constraints, and exhibits plausible temporal behavior. This sequential approach enables the model to adapt to structural changes in forest product markets over time while maintaining the continuity essential for longitudinal analysis and forecasting applications.

4. Results

Applying our multi-stage methodology to the FAOSTAT data from 2000 to 2022 uncovers persistent patterns in adjustment requirements and reveals underlying trends in forest product markets once inconsistencies are reconciled. We start by examining regional patterns in the magnitude of adjustments, then explore quality variations across product categories, followed by insights into processing efficiency, global quality distributions, and price trends.

4.1. Regional Forest product data reconciliation analysis (2000–2022)

The Production Reconciliation Deviation Index (PRDI) demonstrates substantial variability in reported-reconciled agreement across regions over the past two decades (Fig. 1). Europe consistently maintains the high PRDI (90–93%), with values hovering around 92% at both the beginning and end of the period, reflecting data requiring minimal adjustment and well-established reporting infrastructure. North America exhibits similarly strong performance (91–95%), starting at approximately 91% in 2000, peaking around 95% in 2012, and settling at 92% by 2022. Asia shows moderate PRDI (83–86%), beginning at 85% in 2000 and ending at approximately 83% in 2022. South America displays good initial agreement at 91% in 2000 but experiences notable fluctuations, declining to approximately 88% by 2022. Africa maintains relatively stable but lower PRDI (75–80%), starting at 79% and ending around 77%. Oceania exhibits the lowest and most volatile values (68–80%), beginning at 74% in 2000 and dropping to approximately 72% by 2022, with significant year-to-year variations throughout the period.

Note: Scores range from 0 to 100%, with higher values indicating greater agreement between reported and reconciled data. Shaded areas represent ±1 standard error of the mean, calculated from the variability of country-level scores within each region, indicating statistical uncertainty in the regional estimates. The same methodology applies to Figs. 2 and 3.

The Import Reconciliation Deviation Index (IRDI) shows a general downward trajectory across all regions, indicating systematically increasing adjustments required for import data over time (Fig. 2). Oceania experienced the steepest decline, falling from approximately 91% in 2000 to 80% by 2022, representing an 11% drop. Asia's IRDI declined from 88% to approximately 85%, while South America fell from 88% to 78%. Europe started at 85% in 2000, experienced a sharp decline around 2010 to 80% coinciding with changes in reporting methodologies and economic disruptions following the global financial crisis, before partially recovering to 83% by 2022. North America's IRDI decreased from 86% to approximately 82%, while Africa showed a more modest decline from 79% to 76%.

The Export Reconciliation Deviation Index (ERDI) presents the most problematic dimension of forest product reporting, with consistently lower indices compared to both production and import data (Fig. 3), indicating that export statistics require the largest adjustments to achieve consistency. South America shows the most dramatic decline, falling from 82% in 2000 to approximately 65% by 2022. North America maintains relatively higher ERDI values, though still declining from 81% to 73%. Europe's ERDI decreased from 77.5% to approximately 72.5%. Oceania experienced a catastrophic decline from 73% to 49%, representing a 24% drop. Asia's ERDI fell from 60% to 53%, while Africa shows the lowest overall performance with extreme volatility, starting at 56% in 2000 and ending at approximately 45% in 2022.

4.2. Analysis of reconciliation by Forest product categories

Fig. 4 reveals variation in agreement rates across forest product categories. Fuelwood non-coniferous (FWNC) shows the highest share of high-agreement records (68.2%), while sawnwood coniferous (SWC) and industrial roundwood non-coniferous (IRNC) also rank near the top (60.0% and 58.8%, respectively). Industrial fuelwood non-coniferous (FWNCI) follows at 58.1%, newsprint (News) at 57.0%, and mechanical pulp (MP) at 56.9%. Products such as industrial fuelwood coniferous (FWCI) at 53.9%, fuelwood coniferous (FWC) at 53.8%, wood pellets (PEL) at 53.4%, plywood (PW) at 52.0%, and sawnwood non-coniferous (SWNC) at 51.8% occupy the middle range. Fibreboard (FB) at 49.8%, printing and writing paper (PWP) at 49.2%, particle board (PB) at 48.5%, and industrial roundwood coniferous (IRC) at 46.5% show

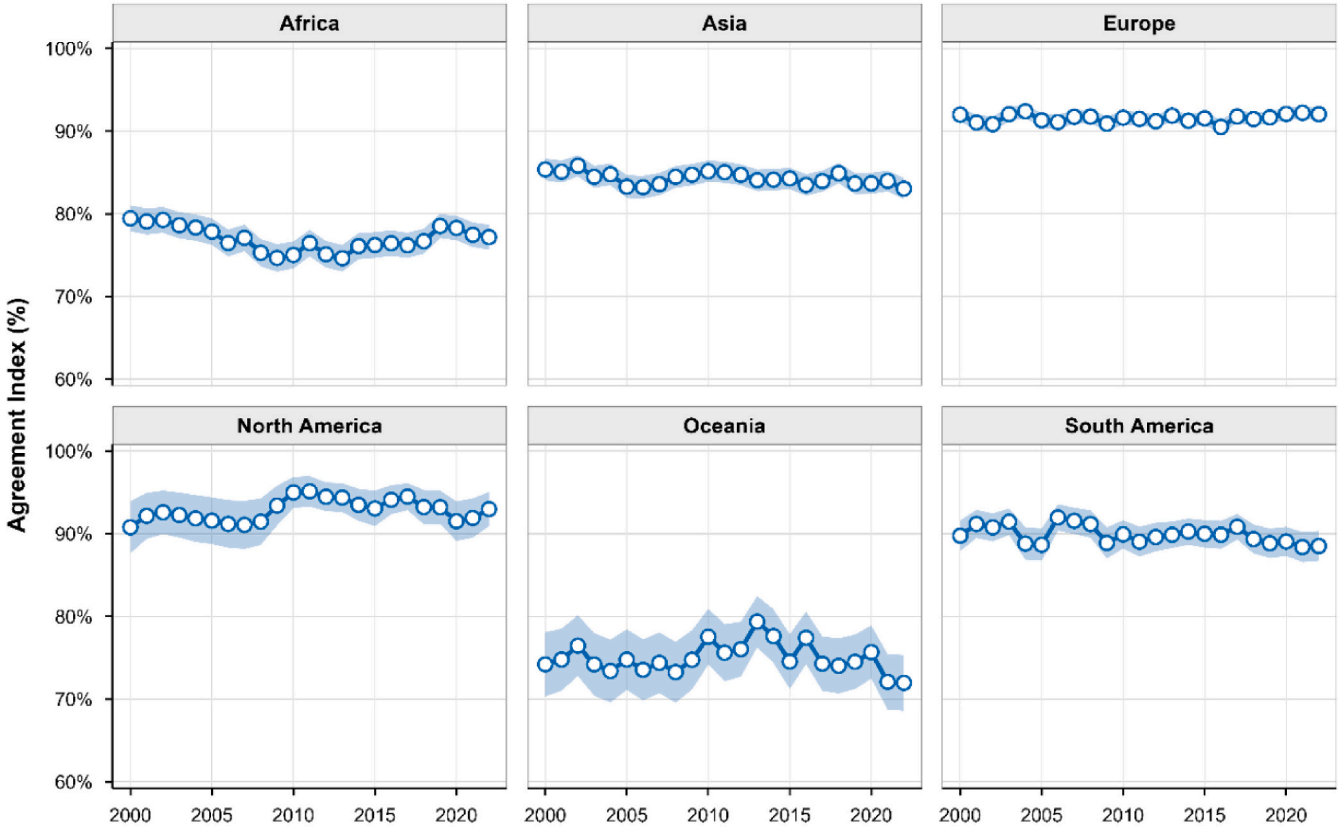

Fig. 1. Production Reconciliation Deviation Index (PRDI) by Region (2000–2022).

moderate values. Other pulp (OP) at 45.4%, chemical pulp (CP) at 44.7%, and other paper and paperboard (Opap) at 41.4% fall in the lower-middle range. Residual products show the lowest agreement by a wide margin: chips and particles (CPR) at 21.1% and waste paper (WP) at 17.5%. Agreement rates appear related to trade characteristics and market structure. Products with high trade volumes and well-established international markets—such as sawnwood coniferous and newsprint—exhibit relatively high agreement, likely benefiting from standardized measurement and customs documentation. In contrast, residual products present the greatest challenges: waste paper and chips and particles show rates less than half those of any other category, reflecting informal collection channels and heterogeneous definitions across countries.

4.3. Weighted average IO coefficients by region

Fig. 5 compares the weighted average input-output (IO) coefficients for two key wood conversion processes—IRC to SWC on the left, and IRNC to SWNC on the right—across major global regions, contrasting 2002 with 2022. Lower IO coefficients imply greater efficiency, as fewer cubic meters of roundwood are needed to produce one cubic meter of sawnwood.

For IRC to SWC conversion, Africa consistently shows the highest coefficients (2.3 in both 2002 and 2022), suggesting little or no improvement in conversion efficiency over the two-decade period. Asia maintains stable efficiency at 1.4 in both years, representing the most efficient conversion rates among all regions. Europe shows improvement from 1.9 to 1.8, demonstrating modest efficiency gains. North America remains stable at 1.6 for both periods. Oceania shows slight improvement from 2.1 to 2.0. South America exhibits the most concerning trend, with its coefficient rising markedly, from 1.5 to 2.1, pointing to a significant decline in efficiency and increased roundwood requirements per unit of sawnwood produced. The world average remains stable at 1.7 for both years, suggesting that efficiency gains in some regions are offset by losses in others.

For IRNC to SWNC conversion, Oceania maintains the highest coefficients overall (2.4 in both years), with no observable improvement over the two decades. Africa remains stable at 2.2 in both periods. Asia shows notable improvement from 1.8 to 1.6, representing one of the more significant efficiency gains. Europe demonstrates improvement from 2.0 to 1.8. North America maintains the best efficiency at 1.4 in both years, representing the most efficient IRNC to SWNC conversion globally. South America again shows deterioration, moving from 1.9 to 2.2, mirroring the decline observed in its coniferous sector. The global coefficient for IRNC to SWNC shows modest improvement from 1.8 to 1.7, reflecting efficiency gains particularly in Asia and Europe.

4.4. Global distribution of reconciliation intensity scores

The global map of country-level Reconciliation Intensity Scores (Fig. 6) reveals a notable contrast between regions requiring minimal versus substantial adjustment. Higher RIS values indicate greater reconciliation intensity, meaning more adjustment was required to achieve data consistency. Most of Europe and North America shows low RIS values (below 0.24), indicating that reported production and trade data in these areas exhibit relatively high completeness and consistency, thus requiring less adjustment. The United States, Canada, and Australia show particularly low scores in the Very Low category (below 0.17), reflecting well-established reporting infrastructure. Western European countries and Russia display scores predominantly in the Low range (0.17–0.24). Parts of East Asia, including China, also fall within the Low category, suggesting relatively consistent data reporting. South America shows generally low scores, with Brazil and Chile in the Low range. By contrast, many regions in Africa show High to Very High scores (above

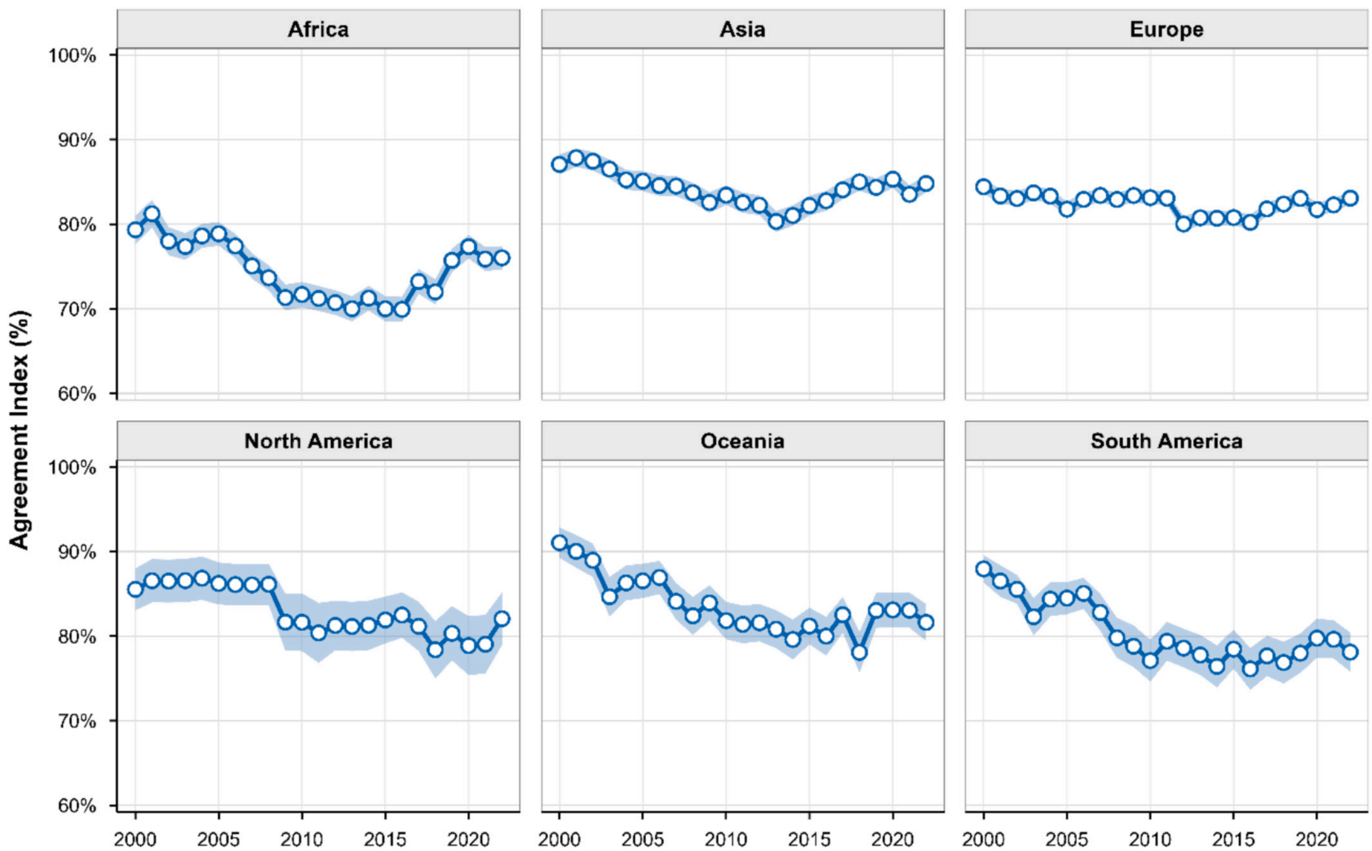

Fig. 2. Import Reconciliation Deviation Index (IRDI) by Region (2000–2022).

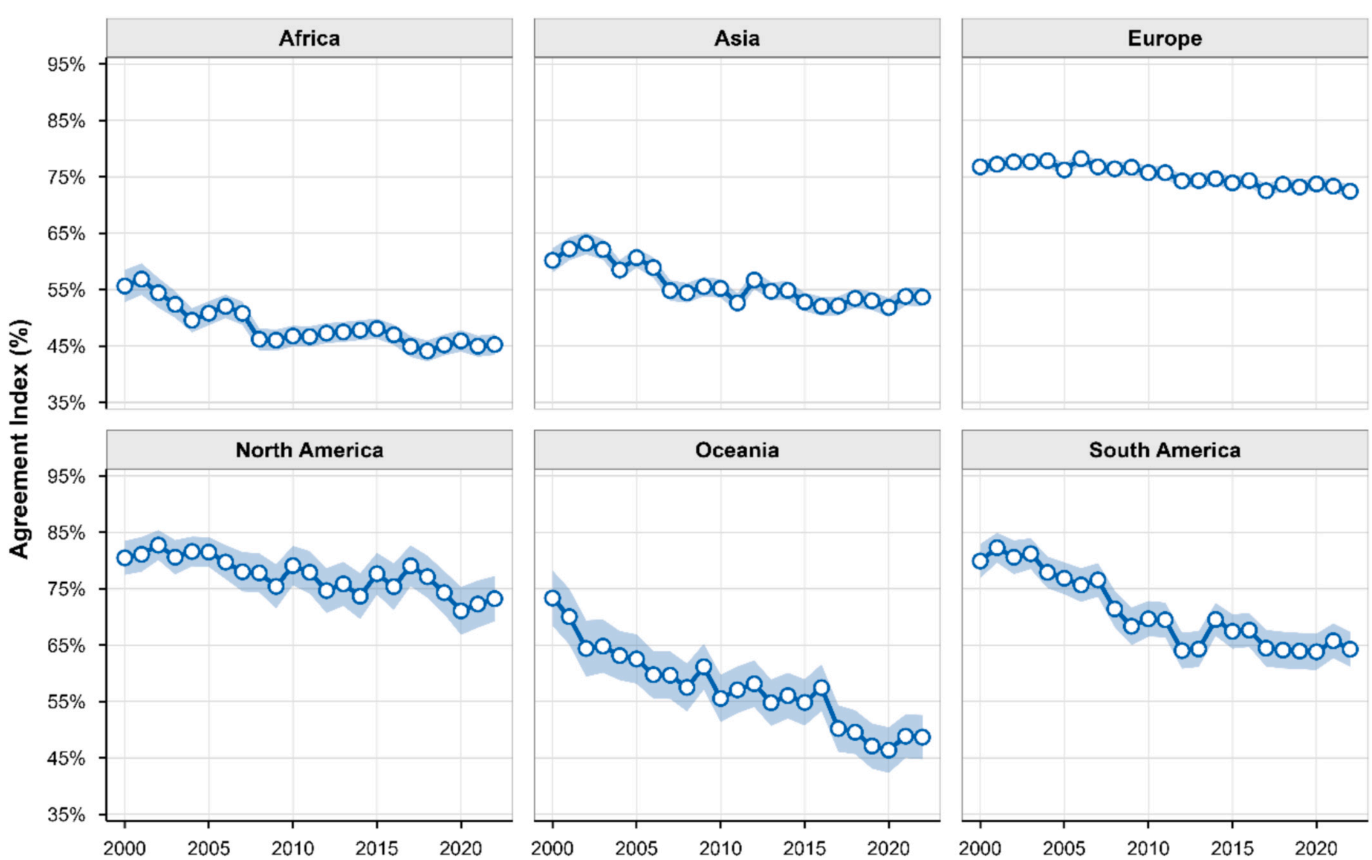

Fig. 3. Export Reconciliation Deviation Index (ERDI) by Region (2000–2022).

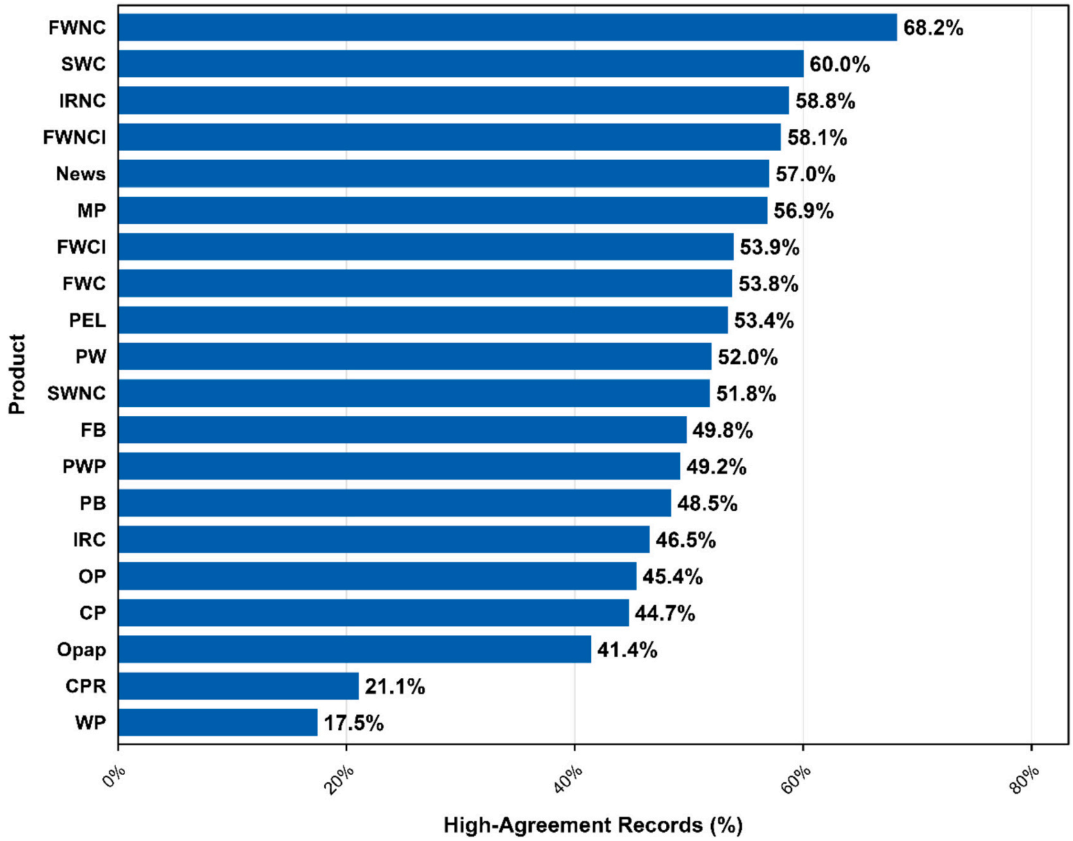

Fig. 4. Product Ranking by Percentage of High-Agreement Records.

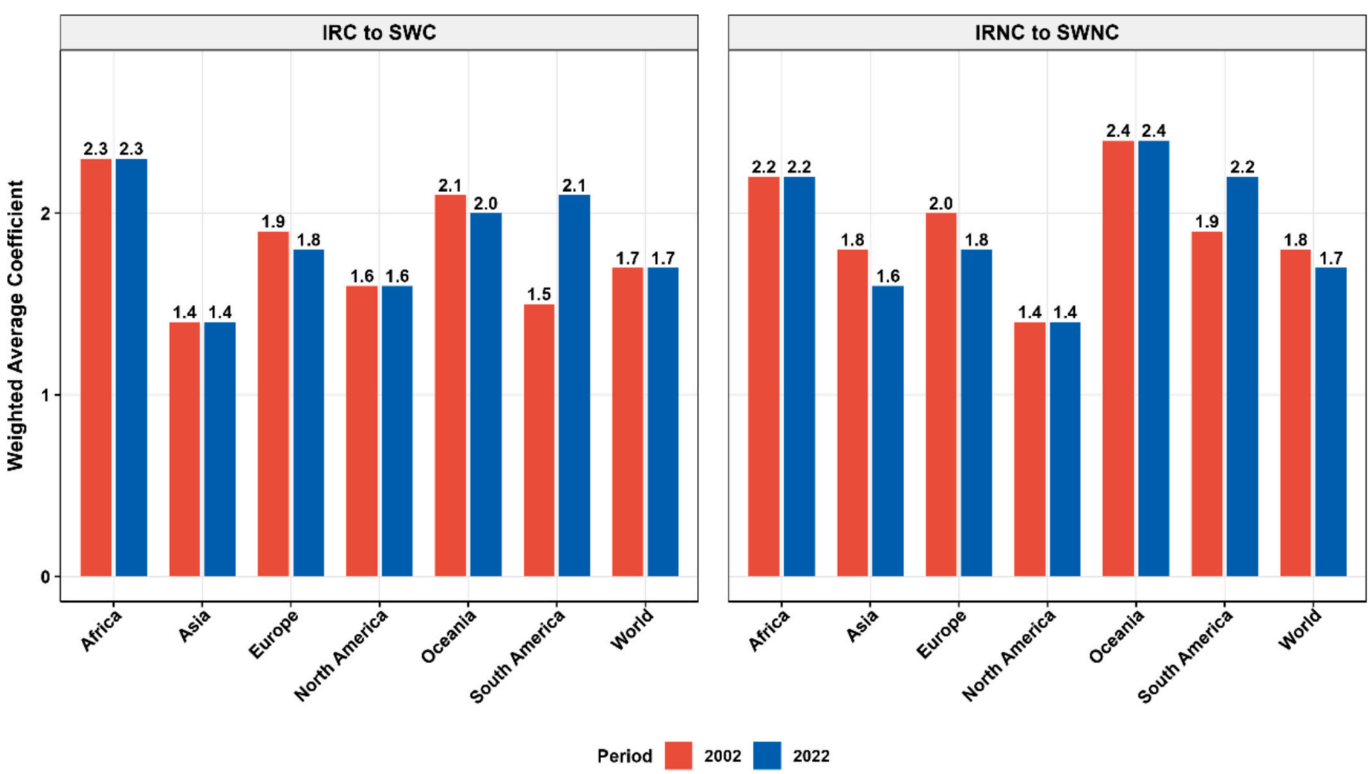

Fig. 5. Weighted Average Input-Output Coefficients by Region (2002 vs. 2022).

0.27), with several countries exceeding 0.30, indicating substantial data gaps, inconsistent reporting, or higher year-to-year fluctuations that required more reconciliation. Parts of the Middle East and Central Asia also reflect elevated scores in the Moderate to High range (0.24–0.30).

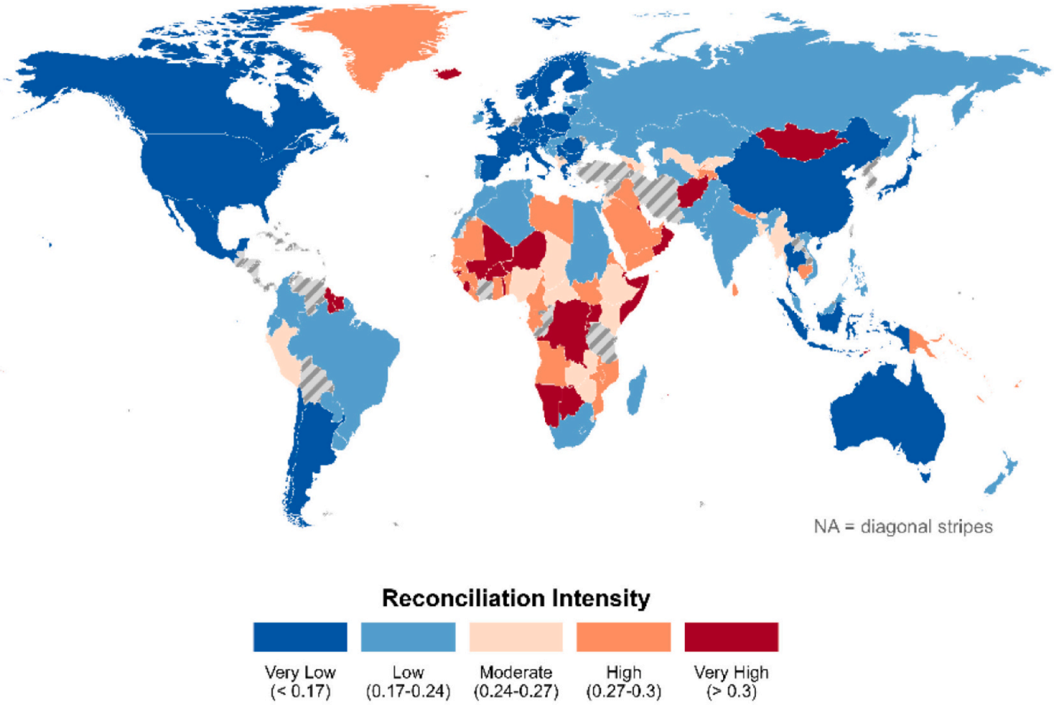

Fig. 6. Global Distribution of Reconciliation Intensity Scores.

Mongolia and Greenland show High scores, while some countries in Central and East Africa register Very High scores (above 0.30).

Note: Scores represent country-level averages of Reconciliation Intensity Scores (eq. 18). Higher scores (warmer colors) indicate greater reconciliation intensity, meaning more adjustment was required. Lower scores (cooler colors) indicate better agreement between reported and reconciled values requiring minimal adjustment. Diagonal stripes indicate countries with insufficient data for computation.

4.5. Global production-weighted Price trends analysis

Fig. 7 displays the reconciled price trends for key forest products across major regions from 2000 to 2022. These series reveal significant market dynamics, including pronounced volatility and distinct regional and product-specific patterns. A prominent feature across numerous categories, notably sawnwood products, is the sharp price surge during 2021–2022, reflecting global supply chain disruptions and heightened demand following the COVID-19 pandemic, before partial retracements in 2022. The reconciled data also capture the impact of previous economic cycles, such as the price dips corresponding to the 2008–2009 global financial crisis, demonstrating the ability of the reconciled dataset to reflect major market shocks while filtering noise.

Sawnwood products (both coniferous and non-coniferous) exhibit the most dramatic pandemic-related price spikes, with SWC prices rising from approximately $200–250/m^3$ to peaks around $350/m^3$, while SWNC shows greater regional variation with prices ranging from $250–600/m^3$. North America consistently maintains higher price levels for both products throughout the period. Plywood (PW) demonstrates similar patterns, rising from around $500–550/m^3$ to approximately $700/m^3$ during the pandemic surge, with North America showing the highest peak values.

Panel products (Particle Board and Fibreboard) demonstrate varying degrees of price convergence over time across regions. Particle Board shows considerable volatility, particularly for Africa and Oceania, with prices ranging from $150–350 throughout the period. Fibreboard exhibits a gradual upward trend from $200–250 in 2000 to $400–500 by mid-period, before spiking to $550–600 during the pandemic. Both products show more moderate pandemic effects compared to solid wood products.

Paper products show diverse patterns reflecting structural market changes. Newsprint exhibits declining trends from approximately $650 to $500 through 2010–2015 due to shifting media consumption patterns, before surging to over $800 during the pandemic. Printing and Writing Paper (PWP) maintains relatively high and stable price levels around $900–1000/ton through most of the period, before spiking to $1200-1400/ton in 2021–2022. Other paper and paperboard (Opap) follows similar patterns, ranging from $800–1000 before reaching $1100–1250 during the pandemic surge. Wood Pellets display particularly high volatility throughout the entire period, with prices fluctuating between $125–225, reflecting the emerging nature of this market and its sensitivity to renewable energy policy interventions.

4.6. Validation analysis

To assess whether reconciliation improves data usability for forest sector analysis, we conducted validation through multiple approaches. First, the reconciliation process eliminates the material balance violations present in the raw data. In the original FAOSTAT data, we can find country-product-year observations exhibited material balance violations where processed product output exceeded feasible production from reported inputs. After reconciliation, all observations satisfy material balance constraints by construction. Similarly, the reconciled dataset eliminates all instances of negative apparent consumption. Second, the reconciled price series captures major market events including the 2008–2009 financial crisis price decline and the 2021–2022 pandemic-induced surge in sawnwood prices. These patterns suggest that the reconciliation process maintains legitimate market signals.

To address concerns about path dependency in recursive models, we conducted three additional validation analyses. A Starting Year Sensitivity Analysis re-solved the complete model from four different starting years (2000, 2003, 2006, 2010); near-perfect correlations (>0.9997)

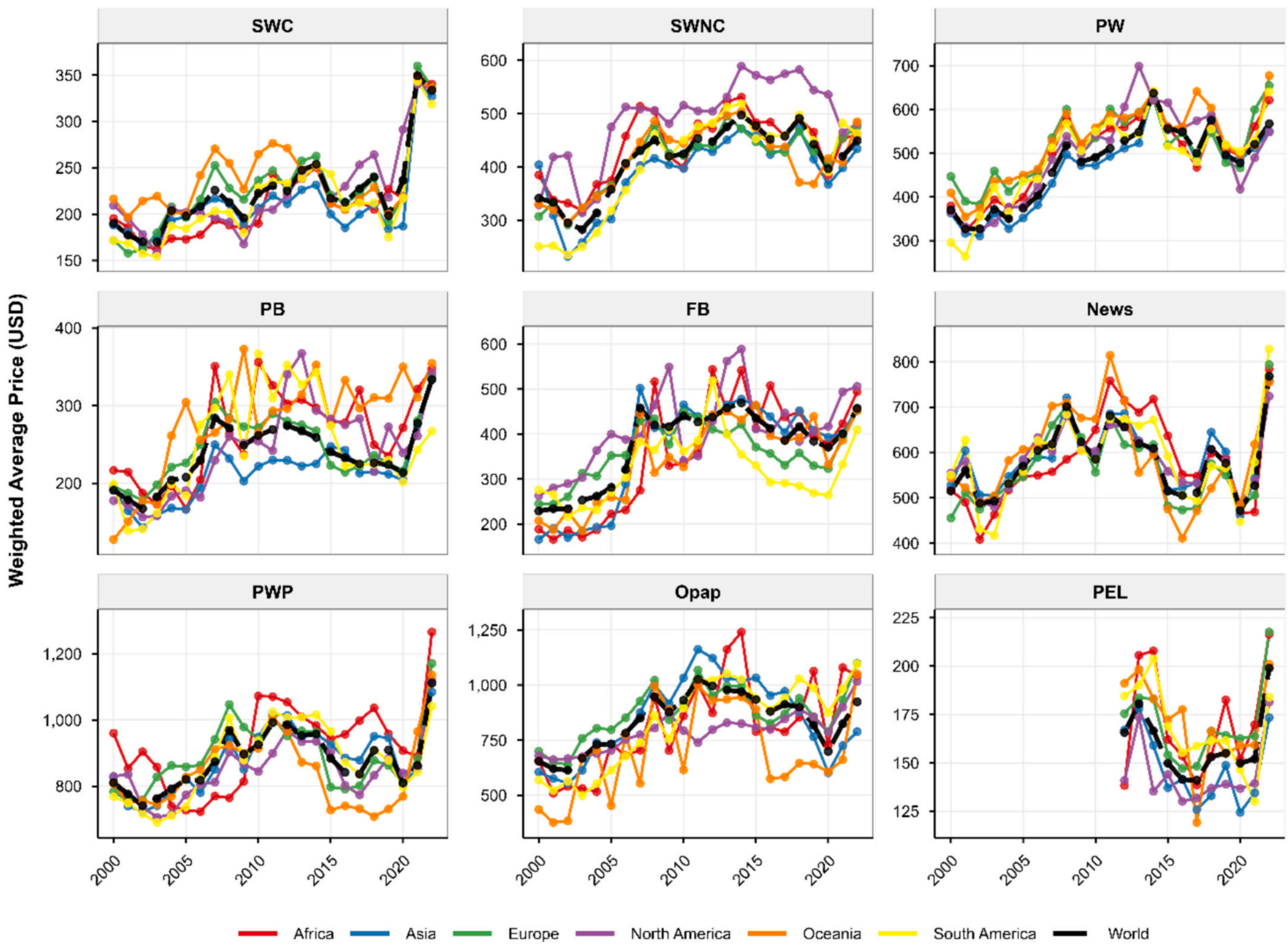

Fig. 7. Global Price Trends for Key Forest Products (2000–2022).

across starting years confirm that reconciled values reflect underlying constraints rather than initial condition artifacts. Monte Carlo simulation tested recovery of known true values by introducing controlled data quality problems to data from eight countries with reliable statistics; R^2 remained above 0.90 even under severe noise conditions, with improvement ratios of 1.38–1.44×. Five-fold temporal cross-validation demonstrated stable out-of-sample performance with mean R^2 of 0.9896 (standard deviation 0.0056). To examine temporal stability, we computed Table D.6 metrics for each year from 2000 to 2022. Production R^2 ranges from 0.964 to >0.999, import R^2 from 0.941 to 0.999, and export R^2 from 0.702 to 0.990, with agreement highest in early years and declining gradually as FAOSTAT coverage expanded to include additional smaller producers. The complete year-by-year table is available in the repository. Stage contribution analysis indicates preprocessing accounts for 44.9% of total adjustment, with goal programming contributing 55.1%. Detailed results are provided in Appendix D.

We also tested the robustness of results to key parameters and model specifications through three analyses. First, regarding weight specification, we tested variations in objective function penalty weights (α) by adjusting trade versus production deviation weights by ±10%. Results indicate that while increasing weights on specific components reduces their respective deviations, the aggregate global trends and regional rankings of Reconciliation Intensity Scores remain stable across specifications. Second, to assess potential error propagation in the recursive structure, we compared the dynamic approach (which uses the previous year's reconciled values as the baseline for temporal constraints) against an alternative specification using the previous year's raw reported data as the reference point. The RDGP approach yielded lower year-over-year volatility across production, import, and export categories, indicating that the method tends to smooth rather than amplify noise in the underlying data. Third, we verified result consistency across different FAOSTAT database versions (2023 versus 2024 downloads).

5. Discussion

Our study developed and applied a recursive dynamic goal programming framework to reconcile the FAOSTAT Forestry Database from 2000 to 2022. The approach builds on the foundational goal programming work of Buongiorno et al. (2001, 2003) and the inconsistency analysis of Kallio and Solberg (2018). The main methodological contribution is the integration of temporal constraints that link each period to the previous one. By enforcing year-over-year consistency, the model produces reconciled time series for production, trade, and prices that are suitable for longitudinal analysis and forecasting. This dynamic consistency enforcement differs from static approaches that treat each year as an independent optimization problem and may therefore produce unrealistic volatility between periods. While starting-year sensitivity tests confirm negligible path dependency, the practical advantages of the recursive formulation are most evident for the heterogeneous quality of global data. For major producing nations, year-over-year changes generally fall within expected bounds, making temporal constraints largely non-binding. However, for smaller countries with sparse data or missing values, the recursive layers act as a vital stabilizing mechanism against erratic fluctuations that static reconciliation can generate. The recursive structure also bridges structural breaks in the evolving FAOSTAT database, such as the introduction of wood pellets around 2012, by enforcing continuity rather than treating classification-driven changes as genuine production shifts. From an optimization perspective, identifying a feasible LP solution under strict temporal constraints provides assurance of mathematical robustness.

The regional patterns in reconciliation requirements are consistent with prior literature. The PRDI and IRDI results align with Kallio and Solberg (2018), who identified inconsistencies between apparent wood supply and forest industry production that sometimes amount to millions of cubic meters. The declining IRDI and persistently low ERDI values reflect the challenges documented by Ferrantino et al. (2012) and Hamanaka (2012), including differences in transportation cost accounting, reporting time lags, product misclassification, and misattribution of origins or destinations. The gap between import and export indices, often 20–30 percentage points, highlights the mirror statistics problem where reported exports frequently fail to match corresponding import records. The relatively higher ERDI for North America may partly be attributed to the 1987 US-Canada Memorandum of Understanding, under which each country derives export statistics from the other's import data since 1990 (United States Department of Commerce, 2011). The concentration of low RIS values in Europe, North America, and parts of East Asia, compared with higher values in Africa, Oceania, and parts of South America, reflects differences in institutional data infrastructure and the presence of formalized reporting systems.

The product-level results show that residual products—waste paper (17.5%) and chips and particles (21.1%)—require the largest adjustments, with agreement rates less than half those of any other category. This finding is consistent with Kallio and Solberg (2018), who identified residues as particularly problematic for material balance accounting. These low rates likely reflect informal collection channels and heterogeneous definitions across countries. Agreement rates correlate with market characteristics: products with high trade volumes and standardized definitions tend to exhibit higher agreement. Chemical pulp (44.7%) and other pulp (45.4%) show intermediate agreement rates, while mechanical pulp exhibits notably higher agreement (56.9%), possibly reflecting its more standardized production processes and established trade channels. Non-coniferous products consistently show higher agreement than their coniferous counterparts across fuelwood, industrial fuelwood, and industrial roundwood categories. Our analysis quantifies the persistent challenge of trade data discrepancies. Export statistics consistently required the largest adjustments across all regions, as indicated by the low Export Reconciliation Deviation Index values. This pattern is consistent with the mirror statistics problem documented in the broader trade literature by Ferrantino et al. (2012) and Hamanaka (2012). Our results show that these discrepancies persist within the forest products sector over the study period.

A key output of the reconciled dataset is the set of evolving input-output coefficients. The analysis revealed regional differences in implied processing efficiency. While Europe and Asia showed modest efficiency gains, the most notable trend was the apparent decline in efficiency for sawnwood production in South America. These divergent patterns may reflect a combination of resource base changes, technological differences, and varying reporting practices across regions. Comparing reconciled and original data, the input-output coefficients derived from reconciled data show fewer extreme outliers and reside more consistently within technologically feasible bounds. The coefficient of variation for key transformation ratios, such as roundwood to sawnwood, decreases when calculated from reconciled data compared to coefficients derived from original reported data. It is worth noting that the input-output coefficients derived in this framework are not directly comparable to those in survey-based publications such as UNECE (2020). Our model calculates implied coefficients based on the material balance of aggregate industrial roundwood required to produce reported sawnwood, while survey-based factors typically report sawlog-to-sawnwood conversions. Because industrial roundwood includes but is not limited to sawlogs, the coefficient magnitudes differ in scope and definition.

The reconciled price series provide consistent benchmarks across regions and time periods. The series capture major market events including the 2008–2009 financial crisis price decline and the 2021–2022 pandemic-induced surge in sawnwood prices. Regions with lower raw data quality, such as Oceania and Africa, display smoother price trajectories after reconciliation, indicating that the price assignment mechanism handles outliers effectively. These price benchmarks are linked with reconciled production and trade quantities, ensuring coherence across the dataset.

Several limitations of this study should be noted. The reconciliation process relies on the initial FAOSTAT data structure and cannot eliminate unknown systemic biases present in originally reported figures, such as consistent underreporting of fuelwood or timber illicitly harvested but laundered into formal processing channels. The specific penalty weights used within the goal programming model involve assumptions that influence the final reconciled values, though sensitivity analysis suggests robustness to reasonable weight variations. Ideally, validation against independent, high-quality national or industry datasets would strengthen confidence in the reconciled values, though such data are often scarce or difficult to harmonize.

6. Conclusion

Inconsistencies within the FAOSTAT Forestry Database present a longstanding challenge for global forest sector analysis. This study addressed this challenge by developing and implementing a multi-stage, RDGP framework to systematically reconcile production, trade, and price statistics for forest products from 2000 to 2022. By integrating data validation, imputation, robust price assignment, and temporal continuity constraints, this methodology generates a complete, internally consistent dataset that eliminates material balance violations and negative apparent consumption cases found in the raw data.

The analysis yielded several insights into the state of global forest product data and market trends. First, there is significant variability in the magnitude of adjustments required across regions and products. Data consistency is generally higher for processed goods compared to raw materials and by-products, and higher for production data than for trade data. Geographically, Europe and North America demonstrate more consistent reporting, whereas regions like Oceania, Africa, and parts of South America required more substantial reconciliation.

Second, the reconciled dataset revealed important trends in material efficiency. Globally, wood processing efficiency for sawnwood showed modest improvement between 2002 and 2022. However, this aggregate trend masks significant regional differences, most notably declining implied efficiency in South America and little change in Africa. These patterns may reflect changes in resource conditions, evolving reporting practices, or some combination of both. Third, the reconciled price benchmarks are able to capture major market dynamics, including the 2021–2022 pandemic-related surge, while providing smoother price trajectories than the raw data.

Future research could extend this work in several directions. First, incorporating auxiliary data sources such as remote sensing estimates of harvest volumes, detailed industry surveys, and customs data where available could reduce reliance on reported statistics and help detect systematic biases. Second, exploring machine learning techniques for more sophisticated imputation of missing values could improve initial data quality before reconciliation. Third, developing formal uncertainty quantification metrics for reconciled values through bootstrap or Bayesian approaches would provide users with confidence intervals for modeling applications. Finally, this reconciliation methodology provides a scalable template applicable to other natural resource databases facing similar consistency challenges.

CRediT authorship contribution statement

Jinggang Guo: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Craig Johnston:** Writing – original draft, Software. **Jeffrey P. Prestemon:** Writing – review & editing, Writing – original draft, Methodology, Investigation.

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The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2026.103775.

Data availability

The FAOSTAT Forestry data used in this study are publicly available from the Food and Agriculture Organization of the United Nations at https://www.fao.org/faostat/en/#data/FO/ The annotated GAMS demonstration code, solver solution reports, and year-by-year validation tables are available at [https://osf.io/qnajd]. The reconciled dataset generated by this study will be made available upon reasonable request to the corresponding author.

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