TiMBA - Timber market Model for policy-Based Analysis: Validation of a Partial Equilibrium Model

TI-FSM - Thünen Institute Forest Sector Modelling

Thünen Working Paper 282

TI-FSM

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Preface

The Timber market Model for policy-Based Analysis - TIMBA - is a partial economic equilibrium model for the global forest products market. The model endogenously simulates the production, consumption, and trade of wood and wood-based products across 180 countries. TIMBA computes the market equilibrium for each country and product in a given year by maximizing the social surplus in the global forest sector. During the equilibrium process, commodity production, consumption, and prices are recursively balanced for each simulation period. TiMBA is Python-based, with a modular structure built entirely using open-access libraries.

This validation report is the result of the collaborative efforts of the forest sector modeling team at the Thünen Institute of Forestry. Several people have made significant contributions to the development and validation of TiMBA. Without their support, reflection, and constructive criticism, this undertaking would not have been as successful as it is today. We want to express our gratitude to all of them. In particular, we would like to thank

- Lauri Pekkka and Fulvio di Fulvio for providing scenario data from simulations carried out with GLOBIOM
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- Johann Heinrich von Thünen Institute, and in particular the Institute of Forestry, and their representatives for providing financial resources, as well as acquiring third-party funding to support the development.

Summary

TiMBA (Timber market Model for policy-Based Analysis) is a partial economic equilibrium model that simulates the global forestry sector, capturing economic interactions from raw material extraction to the processing of intermediate and end products (TI-FSM et al. 2025). The model underwent an intercomparison to ensure its quality and functionality. Information about the validation process and results is published in this working paper. Model validation, as emphasized by Buchholz (2023), is a central, iterative component of model development that confirms the plausibility and reliability of model outputs. Distinct from verification (testing inputs, assumptions, and code) and calibration (adjusting parameters to improve fit), validation assesses the realism and accuracy of model outcomes through systematic comparison with empirical data or alternative models.

The validation of TiMBA was conducted using a model intercomparison approach, comparing its results with other established partial equilibrium models. On the supply side, validation draws on the intercomparison study by Daigneault et al. (2022) within the Forest Sector Model Intercomparison Project (ForMIP), which includes the Global Timber Model (GTM), the Global Biosphere Management Model (GLOBIOM), and the Global Forest Products Model (GFPM). On the demand side, comparisons are made against GFPM results from Morland and Schier (2020). Both studies are based on Shared Socioeconomic Pathways, providing a standardized scenario framework for assessing long-term developments in the global forest sector between.

Graphical analyses compare TiMBA's projections across regions and scenarios, focusing on key indicators such as forest area, industrial roundwood harvest, and wood product demand. Despite differences in baseline years and structural assumptions among models—such as in technological change, forest dynamics, and market elasticities—TiMBA shows a high degree of internal consistency and external plausibility. Globally, TiMBA's industrial roundwood harvest projections are in the middle of the multi-model range by 2100, while its forest area projections position it in the upper third of the scenario range, closely aligned with GFPM results. On the demand side, trends projected with TiMBA align closely with GFPM in the sawnwood sector, display mixed results for wood-based panels, and diverge somewhat in the paper sector. The differences are largely attributable to contrasting model structures and assumptions. Overall, TiMBA demonstrates strong credibility as a policy-analysis tool, with robust, plausible, and comparable results across global and regional levels. Its validation confirms that TiMBA provides a balanced and competitive representation of future developments in the forest sector, supporting informed decision-making in forestry policy and management.

Table 1: Model characteristics overview

Model type	**Dynamic and static equilibrium market model**
Geographical scope	Global (180 countries)
Temporal Dimension	Recursive long-term analyses
Products	Raw-, intermediate, end products
Data sources	FAOSTAT, FRA, WDI, Comtrade, WTO, IIASA-SSP
Software Implementation	Python 3.9, 3.10, 3.11
Current model version	TiMBA 1.3.0
Permanent link to code repository	https://doi.org/10.5281/zenodo.13842384
Code License	APGL3
Code versioning system used	GitHub, Zenodo
Solver environment and Solver	CVXPY, OSQP

Source: TI-FSM et al. (2024)

Keywords: Forest sector analysis, partial equilibrium model, wood product markets, forest-based production, international trade, Python, programming, model validation, policy impact assessment

Zusammenfassung

Um die Qualität und Funktionsfähigkeit des Modells sicherzustellen wurde TiMBA einem Validierungsprozess unterzogen. Informationen zum Validierungsprozess und den Ergebnissen sind in diesem Working Paper veröffentlicht. Dabei wird die Validierung des „Timber market Model for policy-Based Analysis" (TiMBA), ein partielles ökonomisches Gleichgewichtsmodells, das den globalen Sektor Forst und Holz und die Wechselwirkungen von Holzgewinnung bis hin zur Verarbeitung von Halbfertig- und Fertigwaren analysiert, präsentiert (TI-FSM et al. 2025). Buchholz (2023) lehrt, dass die Modellvalidierung ein zentraler und iterativer Bestandteil der Modellentwicklung ist, der dazu dient, die Plausibilität und Zuverlässigkeit der Ergebnisse zu bestätigen. Die Validierung zielt auf die Bewertung der Realitätsnähe und Genauigkeit der Modellergebnisse durch den systematischen Vergleich mit empirischen Daten oder alternativen Modellen ab. Die Validierung von TiMBA wurde mittels eines modellübergreifenden Vergleichs durchgeführt, bei dem die Ergebnisse mit anderen etablierten Gleichgewichtsmodellen verglichen wurden. Auf der Angebotsseite stützt sich die Validierung auf die Studie von Daigneault et al. (2022) die im Rahmen des „Forest Sector Model Intercomparison Project" (ForMIP) durchgeführt wurde und die Modelle „Global Timber Model" (GTM), „Global Biosphere Management Model" (GLOBIOM) und „Global Forest Products Model" (GFPM) umfasst. Auf der Nachfrageseite zeigen die mit TiMBA projizierten Trends im Schnittholzsektor eine weitgehende Übereinstimmung mit dem GFPM, während sich für Holzwerkstoffe gemischte Ergebnisse und im Papiersektor gewissen Abweichungen ergeben. Diese Unterschiede lassen sich überwiegend auf verschiedene Modellstrukturen und Annahmen zurückzuführen sind. Die Validierung bestätigt, dass TiMBA eine plausible Abbildung zukünftiger Entwicklungen im Forstsektor bietet und eine fundierte Entscheidungsfindung in der Forstpolitik und -verwaltung unterstützt.

Table 1: Modell Charakteristika

Model type	**Dynamic and static equilibrium market model**
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Code License	APGL3
Code versioning system used	GitHub, Zenodo
Solver environment and Solver	CVXPY, OSQP

Quelle: TI-FSM et al. (2024)

Schlüsselwörter: Analyse des Forst- und Holzsektors, Partielle Gleichgewichtsmodell, Holmärkte, Forstwirtschaftliche Produktion, Internationaler Handel, Python, Programmierung, Modell Validierung, Politikfolgeabschätzung

1 Introduction

Given the complexity of the forestry sector and its intersection with environmental and natural resource management, developing robust, reliable models is critical. Accurate modeling enables researchers, policymakers, and stakeholders to understand better both the economic and ecological consequences of forest-related decisions.

The Timber market Model for policy-Based Analysis (TiMBA) (TI-FSM et al. 2025) is a partial economic equilibrium model designed to simulate and analyse possible future developments in the forestry sector. Inspired by the Global Forest Product Model (GFPM) (Buongiorno et al. 2003), it captures the economic interactions and structural dynamics across multiple stages of forest-based production, ranging from resource extraction to the processing of semi-finished and finished wood products.

TiMBA is a newly developed, Python-based software tool (TI-FSM et al. 2025). This paper aims to assess the plausibility and validity of its modelling performance before broad application in market analysis and policy impact assessments. Model validation is a central activity in model development and underpins a robust, reliable, and credible analytical tool, whether for research, policymaking, or market applications (Buchholz 2023). At the same time, however, validation represents a demanding and resource-intensive step in the development process.

To assess a model's ability to generate robust and reliable outputs, several methodological concepts exist that are related yet conceptually distinct. Buchholz (2023), for example, teaches a useful distinction among three key concepts: verification, validation, and calibration. In this context, verification refers to confirming all model input variables and assumptions. These include structural assumptions, programming accuracy, and parameter values. The process is typically carried out through a series of test procedures, some of which (e.g., program verification) can even yield formal proofs. In contrast, validation focuses on confirming the plausibility and accuracy of the model outputs by comparing them with, e.g., observed data or established benchmarks. The objective of calibration is to identify and eliminate unintended model behaviour or discrepancies between the model and a benchmark system. This process involves adjusting the model, usually by altering parameters or making structural changes, to reduce behavioral discrepancies and improve the model's fit. Structural changes affect the model architecture by modifying the program code, adding new components, or altering existing processes, whereas parameter changes involve adjusting the values of individual model parameters.

In the context of TiMBA, all three concepts have been or are addressed:

Verification was supported through a structured external review process[1] as well as a scholarly review[2]. A test suite now complements the model: TiMBA is published as a ready-to-use Python package and includes automated tests that are executed as part of a continuous integration (CI) pipeline. Currently, this automatic CI pipeline tests approximately 85% of the model code. The single-period test runs and systematic output comparisons embedded in this process ensure that core model behaviour is continuously checked against reference results.

During its development phase, TiMBA was iteratively modified to calibrate model behavior: First, structural changes were repeatedly required to improve the program's functionality. These involved modifications to the model structure, such as changing the program code, adding new aspects, or altering existing processes. Second,

[1] See the TiMBA documentation (TI-FSM 2025): the codebase and model architecture were reviewed, reworked, and redesigned by an external professional services company. This external redesign supports a clean and maintainable architecture and reduces the risk of structural design flaws that might not be caught by tests alone.

[2] See the peer-review TI-FSM et al. (2025): the final model code and architecture have undergone a formal review process in the context of the Journal of Open Source Software (JOSS), which includes scrutiny of code quality, documentation, and testing practice

parameter changes, adjusting the values of individual model parameters such as market elasticities, were done. This work, however, is regarded as preparatory work and is not the subject of this report.[3]

In contrast to verification and calibration, the objective of this report is to complement these steps by validating the plausibility and performance of TiMBA's results, achieved through a systematic analysis of model outputs across a range of scenarios and comparable models.

This paper is organized as follows: Section 2 and Section 3 give a short model description and a summary of input data and model parameter calibration. Section 4 introduces the validation strategy. Then, Section 5 presents the results of the validation exercise, while Sections 6 and 7 discuss and conclude the work.

2 Model description

The Timber market Model for policy-Based Analysis (TiMBA) is a multi-periodic partial economic equilibrium model for the global forest sector (TI-FSM et al. 2025). The model simulates production, imports, exports, consumption quantities, and prices, as well as technological and forest development for 16 commodities and 180 countries. The market equilibrium is subject to market-clearing conditions and constraints that balance the required raw materials and the produced wood products and limit trade (Samuelson 1952). TiMBA is designed to assess the impacts of policy options and strategies, sector developments under shifting market patterns, and the outcome of alternative scenarios. The model structure distinguishes between raw, intermediate, and end products. It considers fuelwood, coniferous and non-coniferous roundwood, coniferous and non-coniferous sawnwood, wood-based panels, paper pulps, waste paper, and paper products (Figure 1).

The model assumes perfect competition, in which consumers are indifferent to product origin, implying perfect substitution across suppliers. As the optimization of the market equilibrium in a given year does not include elasticity of substitution, demand is merely shifted by changes in income and price (Murray et al. 2004). Production of intermediate and end products is modeled using input-output coefficients to determine the level of input needed to produce one unit of output. The production quantity depends on raw material prices, manufacturing costs, and commodity prices. While the prices of raw materials, intermediate products, and end products are simulated endogenously, the costs of manufacturing and transport are given exogenously. The model structure consists of two phases: a static phase, in which equilibrium is computed for a single period, and a dynamic phase, in which key model parameters are updated year to year to reflect exogenous developments such as policy changes, technological progress, and resource trends. Roundwood supply is determined by the growth dynamics of the forest stock, changes in forest area, and harvest volume. To estimate the supply-side roundwood production, a forest-specific module in TiMBA uses forest-related and socioeconomic variables to simulate global forest area and growing stock development at the national scale for the countries included in the model.

In TiMBA, each country imports from and to the world market. Trade occurs when the price of a product in a particular country exceeds the foreign price plus transport costs, or vice versa, is lower than the world price. Simultaneously, trade is necessary because of the scarcity of goods in one country. This dynamic consequently incentivizes international trade, as countries seek to balance production and consumption through imports and exports. The differences in production costs and prices across countries further reinforce the need for such trade interactions to optimize resource allocation and market equilibrium.

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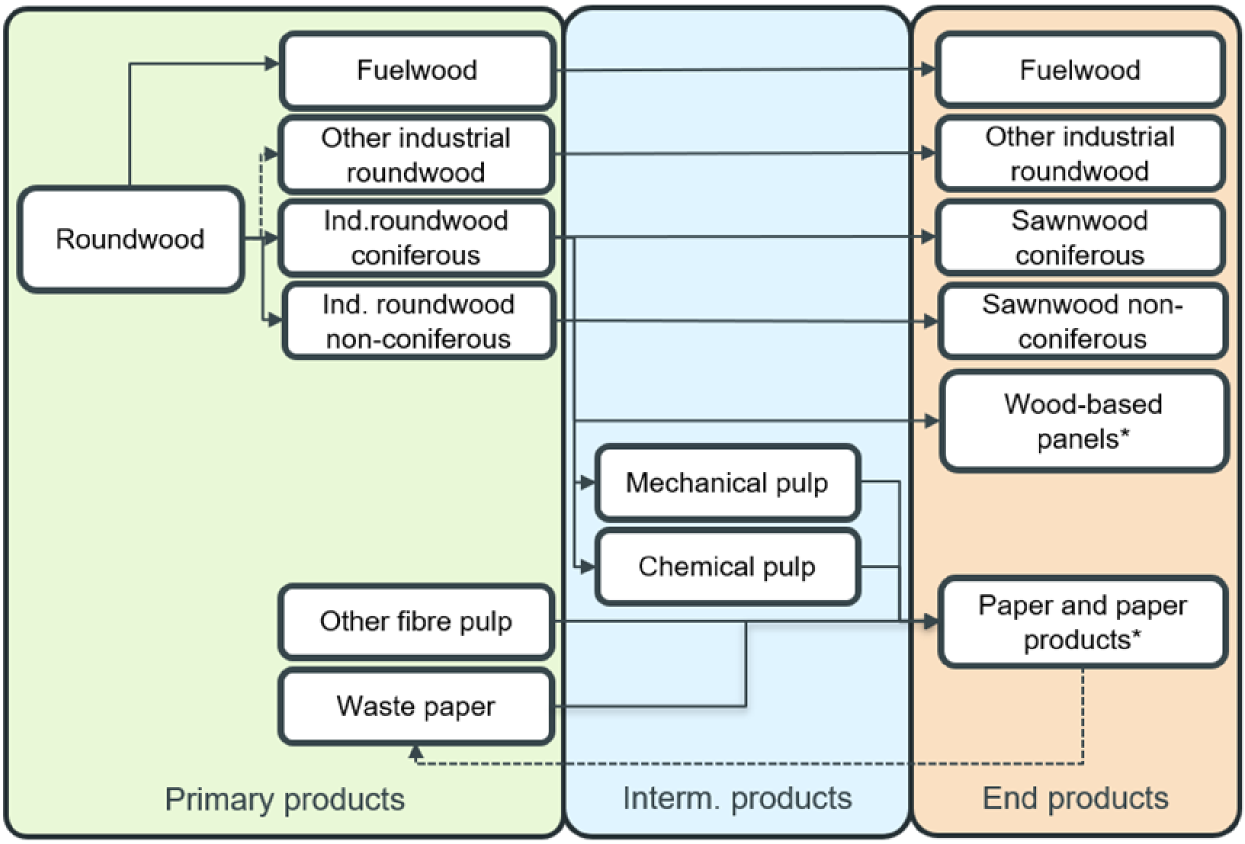
[3] Calibration in the sense defined by Buchholz (2023) should not be confused with the base year calibration of model input parameters, which is part of the TiMBA framework and described in TI-FSM (2025) and briefly summarised in Chapter 3.

Figure 1: **Material flow and product structure in TiMBA**



Source: own illustration

Note: The amounts of coniferous and non-coniferous other industrial roundwood are subtracted from the total amount of industrial roundwood and summed up as total other industrial roundwood for model simulation. Fuelwood is not further processed before being sold as the end product. Industrial and forestry wood residues used as inputs in the wood-based panel and pulp sectors are not explicitly modeled in TiMBA. However, they are implicitly accounted for through input-output coefficients. All products, except sawnwood, can be produced from a mix of raw materials. Thus, wood-based panels could be made from a single input or a mixture of coniferous and non-coniferous roundwood, while paper products could be made from a single input or a mixture of pulps and waste paper. Other fiber pulp and waste paper are inputs to the paper sector.

The input data used in TiMBA are obtained from freely accessible global databases including the FAO forestry statistics (FAOSTAT), the FAO Forest Global Resources Assessment (FRA), the World Bank, the WTO integrated database, and IIASA SSP database ((FAOSTAT 2022), (FAO 2022), (World Bank 2022), (WTO 2024), (Riahi et al. 2017)). The model output comprises, among others, information on supply, demand, and trade quantities, product prices, and the development of forest area and growing stock.

A detailed model documentation, including model specification and formulation, is given in (TI-FSM 2025).

3 Input data and model parameter calibration

Scenario simulations with TiMBA are guided by parameters and assumptions shaping future developments. Key socio-economic elasticities used for model simulations are either estimated using econometric estimations of panel data combining multiple countries over time (e.g., demand elasticities of income and price), derived from literature and databases (e.g., ad-valorem tax rates), or adapted based on expert knowledge (e.g., fraction of fuelwood that comes from the forest) to ensure consistent model behavior.

The supply of roundwood depends on wood prices and forest development, which, in turn, are primarily determined by the growth dynamics of the forest growing stock, changes in forest area, and harvest volumes. The GDP development, indicating national economic income, is an important driver of change. In TiMBA, demand for wood-based products is positively correlated to economic income. Thus, higher income increases demand. Forest area development and, thus, forest supply are coupled to developments in GDP per capita based on the concept of the environmental Kuznets curve (Panayotou 1993). In its basic version, TiMBA uses the assumptions made in the "Middle of the road" scenario described in "The Shared Socioeconomic Pathways" (the so-called SSP2 scenario) to model future GDP developments and population growth. This scenario describes a world of modest population growth, where social, economic, and technological trends continue similarly to historical patterns. (Riahi et al. 2017). Price and income elasticities of demand are taken from Morland et al. (2018). Further exogenous specifications for technological developments (input-output coefficients and manufacturing costs) are estimated using historical data from 1993 to 2020. Trade developments are constrained by constant trade inertia bounds, as defined in Buongiorno et al. (2003) and most recently applied in Buongiorno (2021).

For more details, the model documentation (TI-FSM 2025) provides a comprehensive overview of the different model components, the data and parameters used, and introduces the model structure and specifications.

In the TiMBA version used for this validation report, the model simulations are based on the year 2020. TiMBA uses input data and model parameters from various sources (see Section 2 and below). The input data used are calibrated using a goal-programming-based procedure that tackles data inconsistencies and determines initial input-output coefficients and manufacturing costs along the forest-based value chain. The calibration procedure is described in Buongiorno and Zhu (2014) and modified as described in Schier et al. (2018).

Data on country-specific production and trade volumes of raw, intermediate, and end products are taken from FAOSTAT (FAOSTAT 2022). Product consumption for the base year is then calculated as:

$$\text{consumption} = \text{production} + \text{imports} - \text{exports} \qquad (1)$$

Further, data on country-specific export values are used to compute the unit product prices in the base year as the total export volume divided by the total export quantity stated in constant US$ of 2018 using the GDP deflator (NY.GDP.DEFL.ZS) from the World Development Indicators database (World Bank 2022). Unit prices differ for net-importer and net-exporter countries. The unit price for net importers of a given commodity is the export unit price plus commodity-specific freight costs and tariffs. Tariffs are derived from the WTO Integrated Database (IDB) (WTO 2024)and computed as the average of ad valorem duties for the latest available year, aggregated by reporting country and product at HS-code level 4 to 6. Freight factors are taken from the Global Forest Sector Model (Buongiorno et al. 2003; Buongiorno 2021). Data extraction, as well as country- and product-specific tariff calculations, are provided by Schier et al. (2026). Data on GDP (“GDP in current US$”: NY.GDP.MKTP.CD) and population (“Population, total”: SP.POP.TOTL) for the base year are derived from the World Development database (World Bank 2022). Forest area and growing stock data are mainly taken from the FAO Global Forest Resources Assessment (FAO 2022) and compiled according to Schier et al. (2026).

4 Model validation strategy

Validation’s inherent goal is to confirm the plausibility and correctness of model results. According to Buchholz (2023), validation is model-specific and individualized, while no universally valid or prescriptive framework exists. Instead, validation is a gradual process that evolves over time alongside the model’s maturity and can be seen as a continuous, project-accompanying activity that may never fully conclude. Consequently, validation is inherently iterative and should be understood as the outcome of an ongoing process. Accordingly, the modeling literature discusses a variety of validation approaches, reflecting the diversity of modeling frameworks and objectives. The following approaches serve to illustrate the range of methodological possibilities rather than a uniform set of applicable procedures.

- Backtesting, as a form of model validation, examines how well a model would have performed in the past (Terzic and Milojevic 2016). By comparing historical model estimates to the respective historical data base, backtesting assesses whether the model can reproduce existing data and/or known effects of past policies and market interruptions. To measure a model's accuracy, this approach compares model outputs with observed market responses using a data series that includes both estimated model values and empirical observations (Terzic and Milojevic 2016). Financial institutions widely use backtesting to ensure regulatory compliance and evaluate market risk of, e.g., investment strategies (Arakelian et al. 2024; Du et al. 2024). A key limitation of this approach, especially for long-term projections spanning several decades, is the path dependency. By extrapolating the future from the past, this approach locks the model systems into a specific trajectory.
- Out-of-sample prediction assesses the model's predictive performance by measuring its accuracy on data excluded from model training and evaluating generalizability (Bergmeir and Benítez 2012; Tashman 2000). This method is commonly used in machine learning contexts (e.g., gravity models and neural networks), where models are trained on one dataset and tested on another. Out-of-sample testing is crucial for understanding how a model performs on unseen data and for accurate projection. However, this approach is generally less applicable to partial equilibrium (PE) models, which are typically calibrated to structural economic relationships rather than predictive tasks.
- Assessing model fit via cross-validation is a common approach in machine learning and mixed-effects models for model selection, evaluating a model's performance and generalization on unseen data to prevent overfitting and selection bias. Model input data are split into training and validation sets to train the model on the training sets, and test it on the validation sets (Yates et al. 2023). This approach is unsuitable for PE models such as TiMBA, which are theory- and structure-driven rather than data-driven.
- Models intercomparison involves comparing and evaluating the outputs of the model under study with those from models of a similar type and characteristics, using a common analytical framework (Tinumbang et al. 2023; Daigneault et al. 2022). This approach enhances the model's generalizability, particularly in contexts where empirical data are limited or where future developments lack alternative benchmarks. The model intercomparison methodology can thus provide valuable insights into the model's robustness and plausibility.
- Sensitivity analysis assesses how uncertainties in model inputs affect model output (Campolongo et al. 2011). It entails systematically varying selected model parameters and analyzing the model's economic logic and response behavior. By adjusting one or several model parameters, researchers can observe the resulting changes in model outputs and, e.g., identify which parameters exert the greatest influence on model predictions. Even though sensitivity analysis is an important methodology for evaluating the overall quality and plausibility of a model (Saltelli et al. 2000; Ferretti et al. 2016), identifying key parameters and unexpected dependencies is particularly useful for model calibration and adjustment to improve the model fit and behaviour (Ravalico et al. 2010).

For testing TiMBA's behaviour and the plausibility of its outcomes, in theory, three of these approaches could be considered: (1) backtesting, (2) model intercomparison, and (3) sensitivity analysis. However, a key limitation of the backtesting approach is that its path dependency implies that the historical pattern holds for future predictions. Therefore, this method is less suitable for long-term projections spanning several decades. The main goal of sensitivity analyses is to detect key parameters and dependencies within the model to improve the fit and behaviour. While it can partly be useful for distinct validation exercises, it is not suitable for validating the overall model performance. Thus, among these possibilities, we focus on a model intercomparison approach, as it allows TiMBA to be embedded within an international modeling environment of structurally comparable models. This approach is particularly suitable given the shared theoretical foundation of PE modeling and the availability of harmonized outputs from other economic PE models.

4.1 Model validation approach

This validation paper aims to assess the overall plausibility of TiMBA's modelling outcomes. To validate TiMBA's supply-side projections, we draw on Daigneault et al. (2022), who published the first intercomparison of global forest-sector models. Within the Forest Sector Model Intercomparison Project (ForMIP), Daigneault et al. (2022) simulated the development of the global forest sector under future socioeconomic change using the SSPs (O'Neill et al. 2017; Riahi et al. 2017). Three well-established partial equilibrium models were included in ForMIP: the Global Timber Model (GTM), the Global Biosphere Management Model (GLOBIOM), and the Global Forest Products Model (GFPM).

The model intercomparison of Daigneault et al. (2022) is limited to the forest-based supply side. To validate the demand side, we therefore rely on GFPM results from Morland and Schier (2020). However, as in Daigneault et al. (2022), socioeconomic developments in Morland and Schier (2020) are derived from the SSPs.
The SSPs define five distinct pathways for the development of future socioeconomic conditions in the absence of explicit climate mitigation or adaptation policies (O'Neill et al. 2017; Riahi et al. 2017). The "business-as-usual" pathway (SSP2) reflects a continuation of historical trends and represents a so-called middle-of-the-road trajectory relative to the other SSPs. The remaining pathways span a broad spectrum of futures, ranging from a "sustainable and highly adaptive" world with low socioeconomic challenges (SSP1), to a "fragmented" world characterized by weak global institutions and high population growth (SSP3), an "unequal" world marked by pronounced disparities in global development (SSP4), and a "fossil-fueled development" world with rapid economic growth and technological change (SSP5).

Population and gross domestic product (GDP) growth are key elements of the scenario pathways and constitute a common denominator for this model validation based on the intercomparison. All three forest-sector models, as well as TiMBA, rely on the same population and GDP projections (Riahi et al. 2017), which facilitates a systematic comparison of model behavior. While Daigneault et al. (2022) provide results for SSPs 1–5 through 2100, Morland and Schier (2020) present results for SSPs 1, 2, and 4 through 2050. Therefore, TiMBA's supply- and demand-side projections are benchmarked against different SSP scenarios and across different time horizons.

4.2 Models used for the intercomparison

This section summarizes the key characteristics of the three forest-sector models used to benchmark and validate TiMBA's results.

- GTM is an intertemporal, price-endogenous economic model that covers 16 global regions and three major forest products (Daigneault et al. 2022). It endogenously simulates forest area dynamics and management intensity, distinguishing among up to 302 forest types, depending on the region. Transitions between forest and agricultural land are modeled based on agricultural land rents. GTM does not include bilateral trade (Sohngen et al. 1999).
- GLOBIOM is a recursive dynamic, price-endogenous model that distinguishes 59 global regions and 35 forest products. It endogenously simulates land use and forest management, accounting for both forest and agricultural sectors. Land-use decisions are based on maximizing economic surplus, non-linear land-use change costs, feasible land area constraints, and explicit rules governing permissible land-use transitions. Due to differences in data availability, the supply side is modeled at varying levels of spatial disaggregation: for some regions (e.g., the European Union), supply projections are generated at the grid level, whereas for others, they are provided at the national scale. Demand and trade are resolved at the regional level, and GLOBIOM includes bilateral trade flows (IBF-IIASA 2023).

- GFPM is a recursive dynamic, price-endogenous partial equilibrium model of global forest product markets. It covers 180 countries and 14 forest-based products, including raw materials, intermediate products, and end products. National forest areas are not further differentiated by forest type or management regime. The model endogenously simulates industrial roundwood harvest and supply, as well as trade and demand for all included products and countries. Land-use transitions are represented using an Environmental Kuznets Curve framework (Buongiorno et al. 2003; Buongiorno 2015).

4.3 Model intercomparison methodology

The validation approach in this paper builds upon the framework used for the model intercomparison by Daigneault et al. (2022) and examines model results for the period 2020–2100. In TiMBA, technological change and manufacturing cost developments are held constant after 2050, whereas GDP and population evolve according to the pathways defined by SSP1–5 (Riahi et al. 2017). The model intercomparison consists of two components: the supply side and the demand side.

On the supply side, we compare the projections of forest area and industrial roundwood harvest across all four models (GTM, GLOBIOM, GFPM, and TiMBA). The results are displayed as ranges across the five SSPs at both global and regional levels. The regional analysis distinguishes six regions: Africa, Asia, Europe, the Former Soviet Union, Latin America, North America, and Oceania. Industrial roundwood harvest comprises the supply of industrial roundwood and other industrial roundwood, as defined by the FAO (FAOSTAT 2022).

Although the analysis primarily uses data from Daigneault et al. (2022), the model results used for this validation of industrial roundwood harvest differ from those in GLOBIOM. For this model intercomparison, we draw on updated GLOBIOM results reported in Lauri et al. (2021), which were recommended by the GLOBIOM modeling team for comparative analyses.

On the demand side, the TiMBA model structure is inspired by GPFM (Buongiorno 2015), featuring a similar representation of intermediate and end products in the wood product market as well as comparable product transformation processes. This structural similarity enables a detailed comparison of individual wood product categories based on projected demand developments across both models. Data for the intercomparison of wood product demand were retrieved from Morland and Schier (2020), which provides results for three SSP scenarios: SSP1, SSP2, and SSP4 (Riahi et al. 2017). Demand projections are compared at the global level and for five regions: Africa, Asia (including the Russian Federation), the EU27, North America, and South America.

Although TiMBA distinguishes between coniferous and non-coniferous sawnwood, both product categories are aggregated and presented as total sawnwood to facilitate the comparison with GPFM results (Figure 6). Wood-based panels comprise plywood and veneer sheets, particle board (including OSB), and fibreboard in both models. Similarly, paper and paperboard include newsprint, printing and writing paper, and other paper and paperboard. All product categories follow FAO definitions (FAOSTAT 2022).

The figures presented in Section 5.1 are generated using TiMBA Charts[4], a toolkit for analysing TiMBA's simulation results (Morland et al. 2025). TiMBA Charts includes a validation dashboard for comparing data across different scenarios and models.

[4] https://github.com/TI-Forest-Sector-Modelling/TiMBA_Charts

5 Results

The model intercomparison illustrates the extent to which TiMBA's model outputs align with those of the other models.

Figure 2 and Figure 4 illustrate the development of forest area and industrial roundwood harvest across the SSP scenarios at an aggregated level. and further present the relative changes in forest area and industrial roundwood harvest across the SSP scenarios.

The global and regional developments in the simulated demand for fuelwood, sawnwood, wood-based panels, and paper and paperboard are illustrated in Figure 6 to Figure 9, respectively.

5.1 Forest-based supply

Forest area development influences industrial roundwood harvest, which, in turn, is a key input for the production of wood-based commodities in the supply chain modelled in TiMBA. They therefore play a critical role in the model framework.

The differences in the start year of 2020 arise because TiMBA simulations are based on smoothed and calibrated FAOSTAT data for 2019–2021, whereas the simulations carried out for the study by Daigneault et al. (2022) start in 2015. The regional levels used reported in Figure 2 to Figure 5 are those used by Daigneault et al. (2022) where Africa comprises Africa and the Middle East, Asia entails Asia and Oceania, Europe the EU28 and the Rest of Europe, the Former Soviet Union Russia and the Rest of Former Soviet Union Countries, and Latin America Central and South America as well as the Caribbean.

5.1.1 Forest area

Across the SSPs, TiMBA projects a mean increase in global forest area to 4,304 million hectares (mil ha) by 2100, corresponding to an average increase of 6% between 2020 and 2100. The largest and smallest increases in forest area are projected under SSP2 (+8%) and SSP4 (+5%), respectively. At the global level, TiMBA's mean forest area projections fall within the range of other forest-sector models. Compared to GLOBIOM and GTM, TiMBA's forest area projections are more stable across the SSPs. Like GFPM, TiMBA projects a higher mean increase in forest area than GLOBIOM and GTM (Figure 2 and Figure 3). Compared to GTM, the influence of socioeconomic drivers underlying the SSP scenarios appears to have a smaller effect on forest area projections.

Consistent with other forest-sector models, TiMBA projects a decline in the mean forest area in Africa until 2050. While GFPM and GTM projects continued to decrease after 2050, TiMBA projects a subsequent increase, reaching 636 million ha in 2100. Overall, TiMBA projects a mean decline in forest area in Africa of 3% over the entire simulation period. However, forest area projections for Africa vary substantially across SSPs: under SSP4, forest area declines by 15%. It increases by 5% under SSP1, highlighting the strong influence of SSP assumptions on GDP and Population growth on forest area dynamics in TiMBA (Figure 2 and Figure 3).

In Asia, TiMBA projects a steady increase in mean forest area, reaching 865 mil ha by 2100. While GFPM projects stronger increases than TiMBA over the simulation period, GLOBIOM and GTM show largely stable trajectories of forest area. GFPM, GLOBIOM, and TiMBA project a similar range of forest area developments across the SSP scenarios considered. The largest and smallest increases in forest area are projected under SSP3 (+22%) and SSP5 (+10%), respectively (Figure 2 and Figure 3).

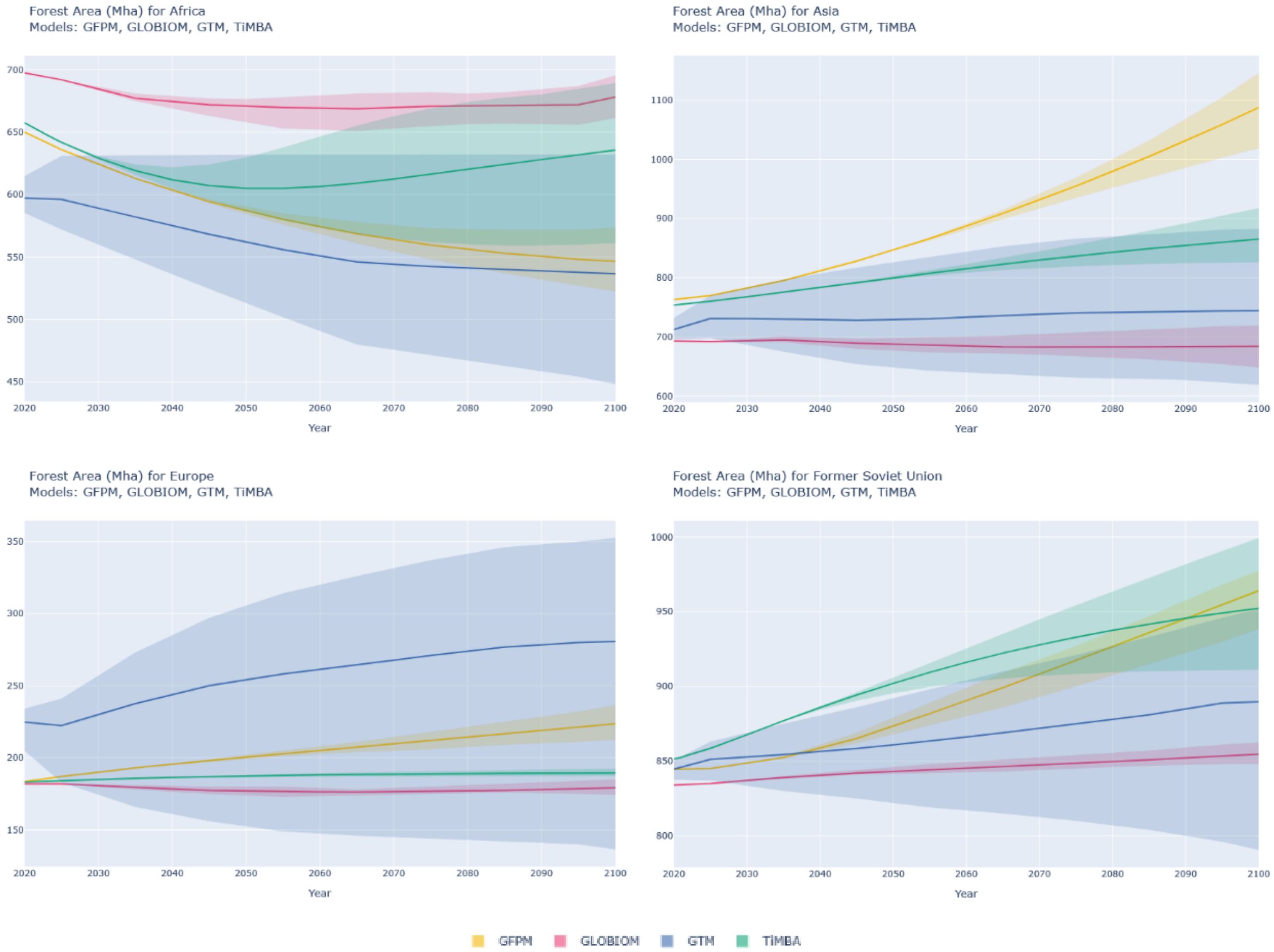
In Europe, TiMBA projects a largely stable mean forest area between 2020 and 2100, with a slight overall increase of 3% to 189 million ha by 2100, and shows only limited variation across the SSP scenarios. GLOBIOM projects similar forest area dynamics. In contrast, GFPM and GTM project larger increases in forest area, accompanied by a wider spread across the SSPs (Figure 2 and Figure 3).

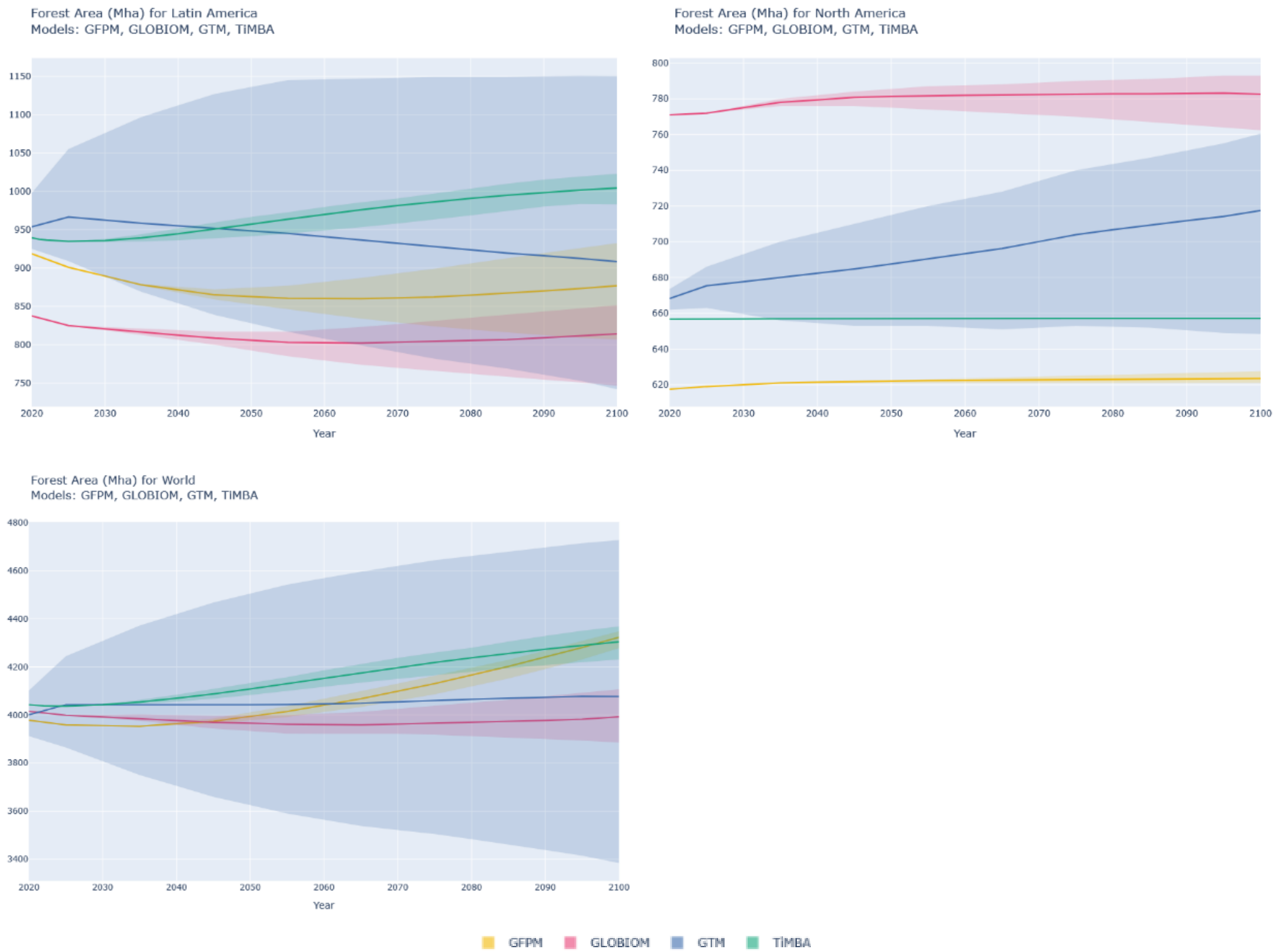
In the countries of the former USSR, TiMBA projects a 11% increase in mean forest area to 952 million ha by 2100. All forest-sector models included in the cross-model validation indicate increasing forest area in this region, although the magnitude of the increase varies across models. Until 2090, TiMBA sets the upper bound for the projected forest area range across models, while after 2090, GFPM projects the highest forest area. In contrast, GLOBIOM and GTM project more moderate increases in mean forest area (Figure 2 and Figure 3).

In Latin America, TiMBA projects an initial decrease in mean forest area until 2030, followed by an increase to 1,004 million ha by 2100. Over the full simulation period, this corresponds to a net increase of 7% in mean forest area. A similar initial decline is projected by GLOBIOM and GFPM, continuing until 2050, after which mean forest areas remain largely stable. GTM shows the largest variation in forest area projections across the SSPs in Latin America, with a mean decrease of 9% by 2100 (Figure 2 and Figure 3).

In North America, similar to Europe, TiMBA projects a largely stable mean forest area between 2020 and 2100, with only minor variation across the SSP scenarios. In TiMBA, the mean forest area increases by 0.1% to 657 million ha by 2100. Stable mean forest area trajectories are also projected by GLOBIOM and GFPM, although at different absolute forest area levels. In contrast, GTM projects an increase in mean forest area with substantial variation across the SSP scenarios (Figure 2 and Figure 3).

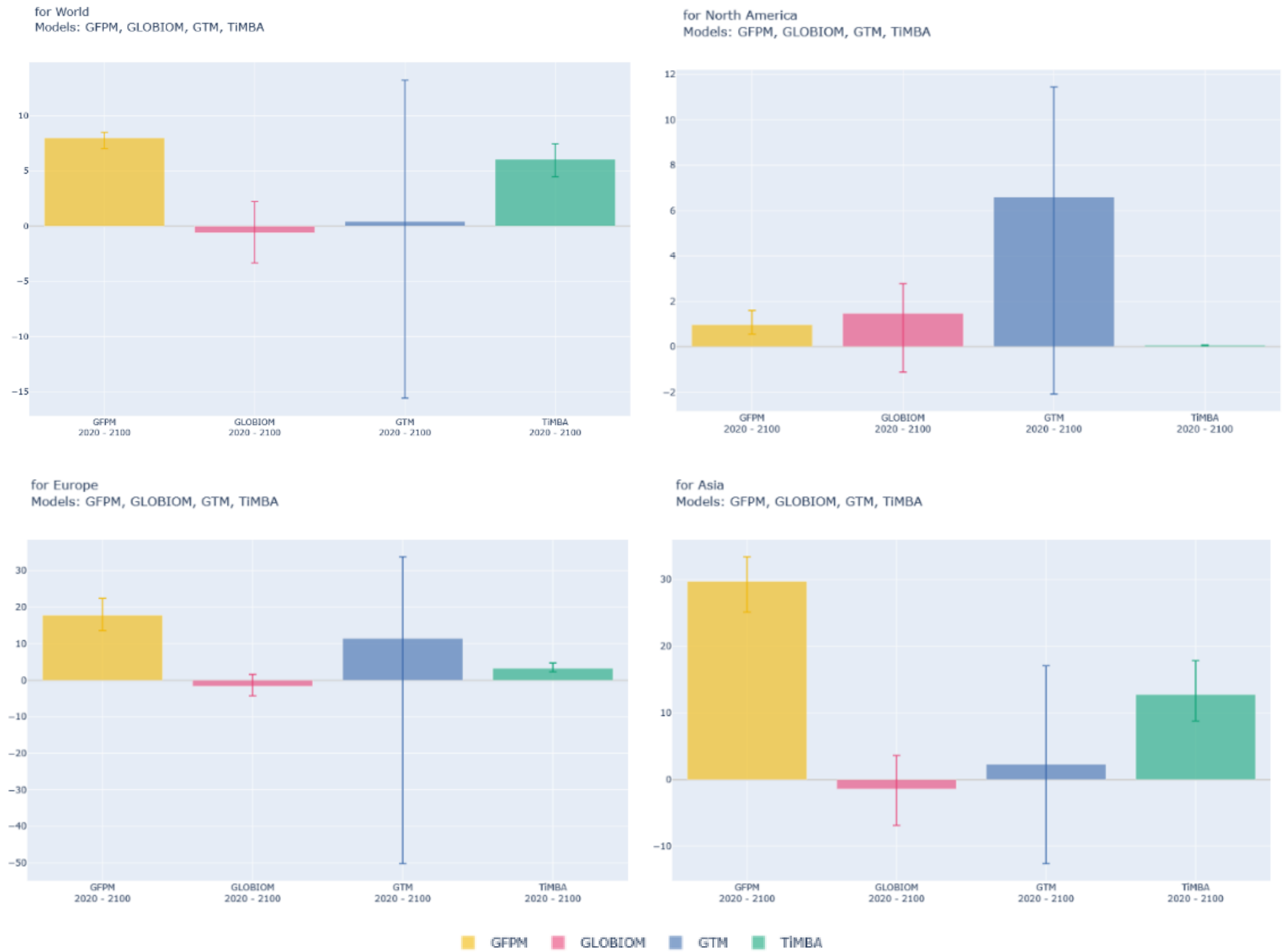
Figure 2: Forest area projections





Note: Forest area is reported on the x-axis in Mil ha for continental aggregates estimated with the models TiMBA, GPFM, GTM, and GLOBIOM and the SSP scenarios 1-5 for the period 2020 - 2100. TiMBA data were generated by the author's collective. Data of GTM, GFPM, and GLOBIOM are extracted from Daigneault et al. (2022). Source: own illustration.

Figure 3: Relative changes in forest area projections



Note: Relative forest area changes reported on the x-axis in % for continental aggregates estimated with the models TiMBA, GPFM, GTM, and GLOBIOM and the SSP scenarios 1-5 for the period 2020 – 2100. TiMBA data were generated by the author's collective. Data of GTM, GFPM, and GLOBIOM are extracted from Daigneault et al. (2022). Source: own illustration.

5.1.2 Industrial roundwood harvest

At the global level, all forest-sector models, including TiMBA, project increasing mean industrial roundwood harvests up to 2100. However, the magnitude of these increases differs across models, with GLOBIOM and GFPM representing the upper and lower bounds, respectively. TiMBA projects a 46% increase in mean industrial roundwood harvest by 2100, reaching 2,951 Mil m^3/yr. In TiMBA, the mean industrial roundwood harvest increases until approximately 2075, after which it stabilizes. Industrial roundwood harvest projections also vary across SSP scenarios. The highest industrial roundwood harvest is projected under SSP5, with an increase of 77% (3,580 Mil m^3/yr). In contrast, under SSP3, industrial roundwood harvest increases by only 26% (2,528 Mil m^3/yr) (Figure 4 and Figure 5).

These global trends emerge from heterogeneous regional developments, which differ markedly across world regions.

In Africa, TiMBA projects a 31% increase in the mean industrial roundwood harvest by 2100, reaching 567 Mil m^3/yr. While the range of projected industrial roundwood harvest levels across the SSPs remains relatively narrow until 2080, it widens substantially thereafter. By 2100, the highest and lowest harvest levels are reached under SSP2 and SSP4, with increases of 148% and 5%, respectively. In comparison, GFPM and GTM project largely stable industrial roundwood harvests with only minor differences across SSP scenarios. In contrast, industrial roundwood harvest levels modelled by GLOBIOM increase by 371% by 2100, exhibiting considerable variation across the SSPs (Figure 4 and Figure 5).

In Asia, TiMBA projects an increase in mean industrial roundwood harvest until 2045, followed by stabilization at about 862 Mil m^3/yr through 2100. Industrial roundwood harvest levels exhibit a substantial spread across the SSP scenarios, consistent with other forest-sector models. The highest and lowest increases in industrial roundwood harvest are projected under SSP5 (+95%) and SSP3 (+53%), respectively. Overall, the industrial roundwood harvest development simulated by TiMBA lies within the range projected by the other forest-sector models (Figure 4 and Figure 5).

In Europe, TiMBA projects a mean industrial roundwood harvest peak in 2060 at 593 Mil m^3/yr, which is followed by a decline to 485 Mil m^3/yr by 2100. Over the entire simulation period, this corresponds to an overall increase of 19% in industrial mean roundwood harvest. GLOBIOM projects a similar mean harvest level in 2100. In contrast, GTM and GFPM project higher mean industrial roundwood harvest levels in 2100, accompanied by larger spreads across the SSP scenarios (Figure 4 and Figure 5).

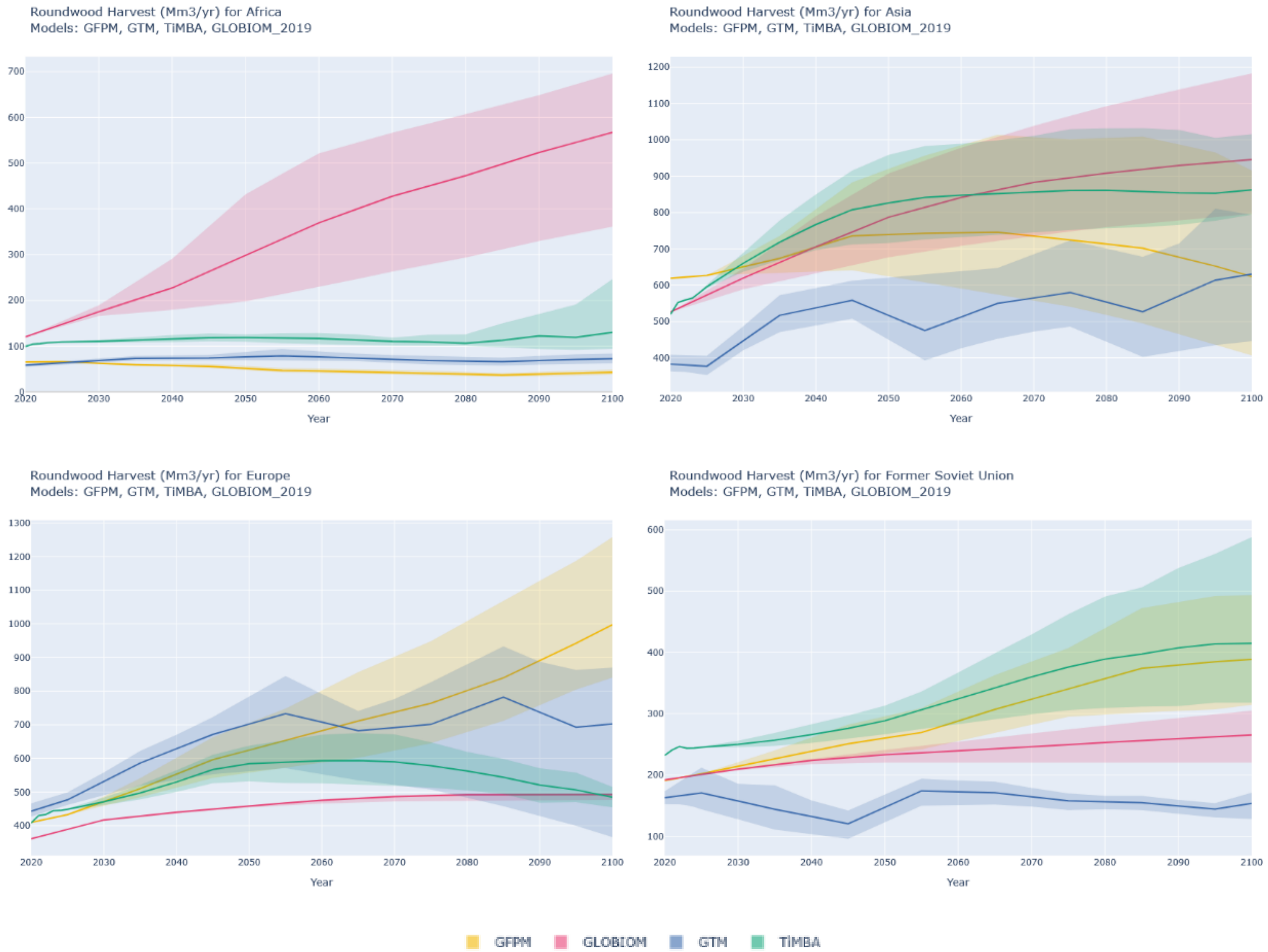
For the countries of the former Soviet Union, the mean industrial roundwood harvest projected by TiMBA serves as the upper bound in the model intercomparison. It shows a large spread across the SSP scenarios. TiMBA projects an increase in mean industrial roundwood harvest of 79% by 2100, reaching 415 Mil m^3/yr. The highest and lowest increases are projected under SSP5 (+153%) and SSP3 (+37%), respectively. While GFPM and GLOBIOM also project increasing mean industrial roundwood harvests, though with lower magnitudes, GTM indicates a slight decrease in mean industrial roundwood harvest over the simulation period (Figure 4 and Figure 5).

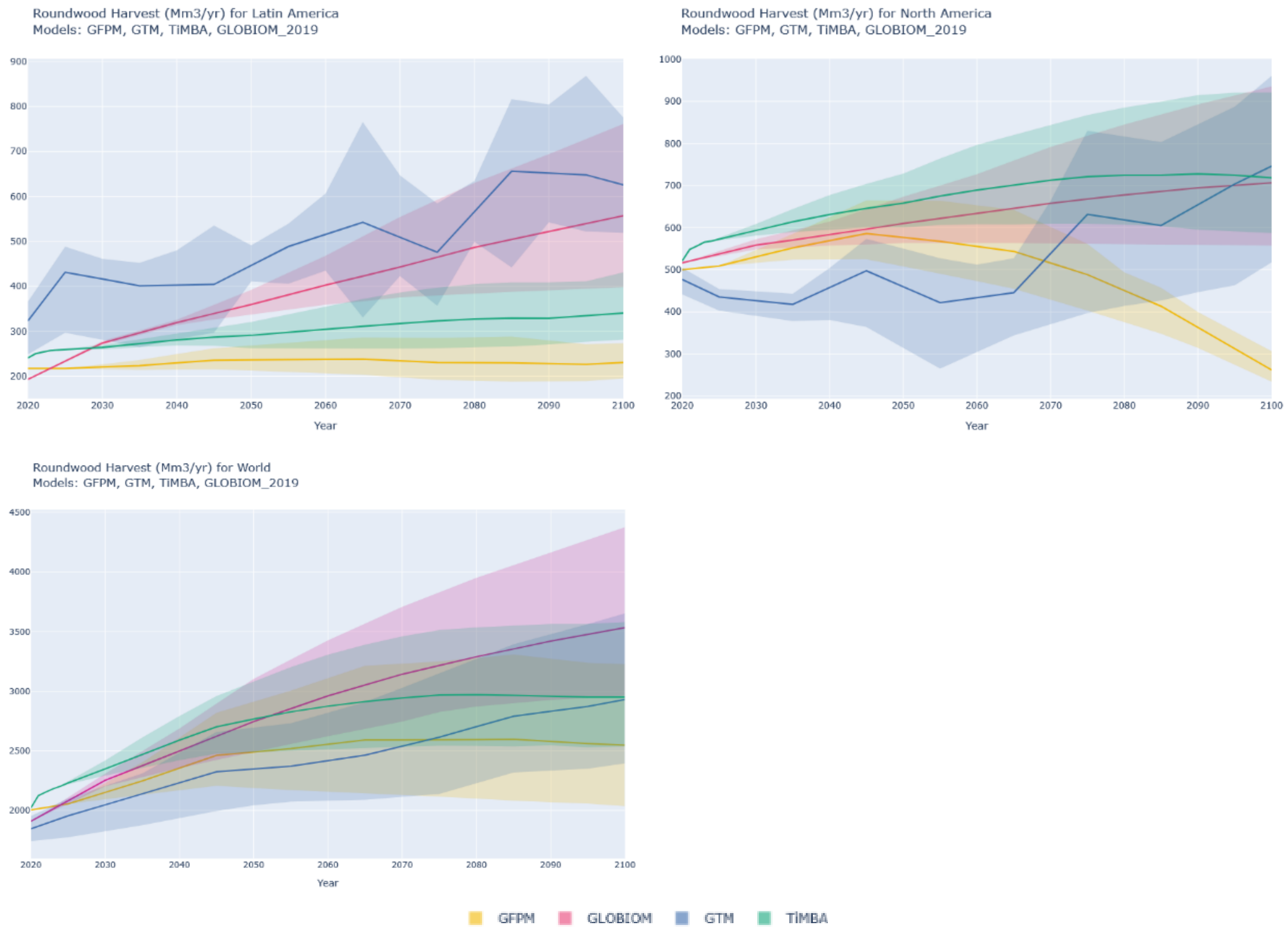
In Latin America, the mean industrial roundwood harvest is projected to increase by about 100 Mil m^3/yr, according to TiMBA, reaching 340 Mil m^3/yr by 2100. Across the SSP scenarios, increases in projected industrial roundwood harvests range from +17% under SSP3 to +79% under SSP5. These industrial roundwood harvest projections fall within the range of the other forest-sector models, with results from GTM and GFPM at the upper and lower bounds, respectively. GLOBIOM shows the highest spread of industrial roundwood harvest across the SSP scenarios (Figure 4 and Figure 5).

Projections of the mean industrial roundwood harvest for North America differ across forest-sector models. TiMBA simulates an increase in the mean industrial roundwood harvest of 38% until 2100, but depicts a wide spread across the SSP scenarios. In SSP3, industrial roundwood harvest increases by 13% until 2100, representing

587 Mil m³/yr. In contrast, roundwood harvests increase up to 921 Mil m³/yr (+77%) until 2100 under SSP5. The mean industrial roundwood harvest in GLOBIOM follows a similar trajectory. GTM is reaching an equivalent industrial roundwood harvest level by 2100, but projects a decreasing trend until 2055. The mean industrial roundwood harvest in North America peaks in GFPM by 2045 and declines sharply until 2100 (-48%). Despite differences in projected trends, the mean industrial roundwood harvest development in TiMBA remains in a similar order of magnitude to that in the other forest sectors (Figure 4 and Figure 5).

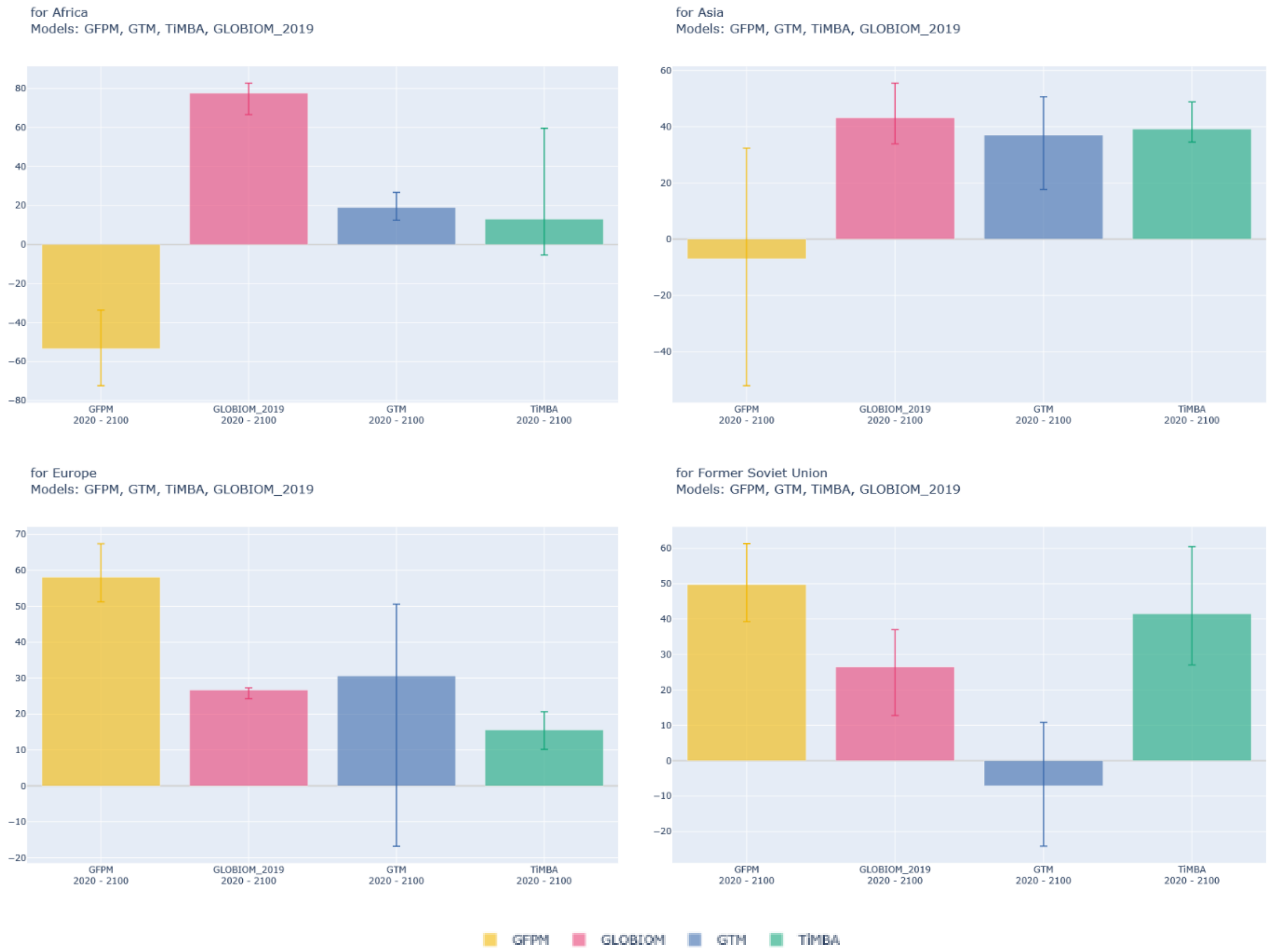
Figure 4: Roundwood harvest projections

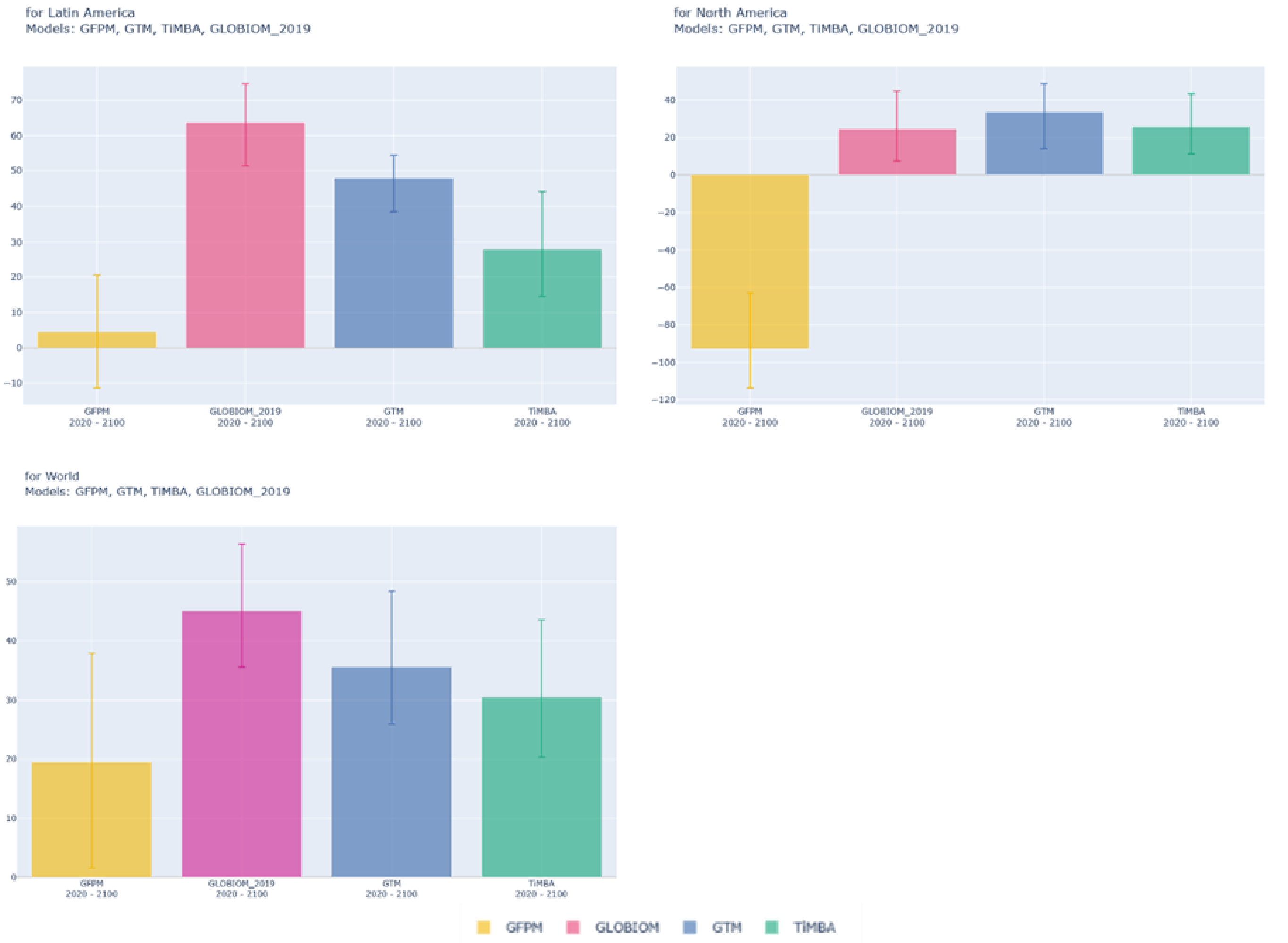




Note: Roundwood harvest reported on the x-axis in Mil m³/yr for continental aggregates estimated with the models TiMBA, GPFM, GTM, and GLOBIOM and the SSP scenarios 1-5 for the period 2020 - 2100. TiMBA data were generated by the author's collective. Data of GTM and are extracted from Daigneault et al. (2022). GLOBIOM dat are extracted from Lauri et al. (2021). Source: own illustration.

Figure 5: Relative changes in roundwood harvest projections





Note: Relative changes in roundwood harvest reported on the x-axis % for continental aggregates estimated with the models TiMBA, GPFM, GTM, and GLOBIOM and the SSP scenarios 1-5 for the period 2020 - 2100. TiMBA data were generated by the author's collective. Data of GTM and are extracted from Daigneault et al. (2022). GLOBIOM data are extracted from Lauri et al. (2021). Source: own illustration

5.2 Forest products demand

Figure 6 to Figure 9 illustrate projected demand for fuelwood, sawnwood, wood-based panels, and paper products across continents from 2020 to 2050 for the two models, GFPM and TiMBA. The regional levels reported in Figure 6 to Figure 9 are the aggregation levels used behind the TiMBA charts (Morland et al. 2025).

It should be noted that the GFPM simulations are based on project-specific scenario projections, as described in Morland and Schier (2020), and use 2015 as the initial year. Consequently, the comparison between GFPM and TiMBA is structurally biased by different base years and by the incorporation of additional scenario assumptions in the simulations, in addition to the SSP data on GDP and population development. Therefore, the graphs may primarily reflect the relative scales of the two modelling approaches and illustrate how demand from TiMBA simulations compares with that from a well-established model such as the GFPM.

5.2.1 Fuelwood

Figure 6 illustrates regional and global projections of fuelwood demand from 2020 to 2050. Across most continents, both models indicate a general increase in fuelwood demand, although the magnitudes and growth rates differ considerably. The demand for fuelwood in Africa is projected to rise substantially. TiMBA anticipates a markedly stronger increase compared to GFPM, with demand exceeding 2,000 Mil m^3/yr by 2050. GFPM forecasts a more moderate growth rate, peaking slightly above 1,000 Mil m^3/yr.

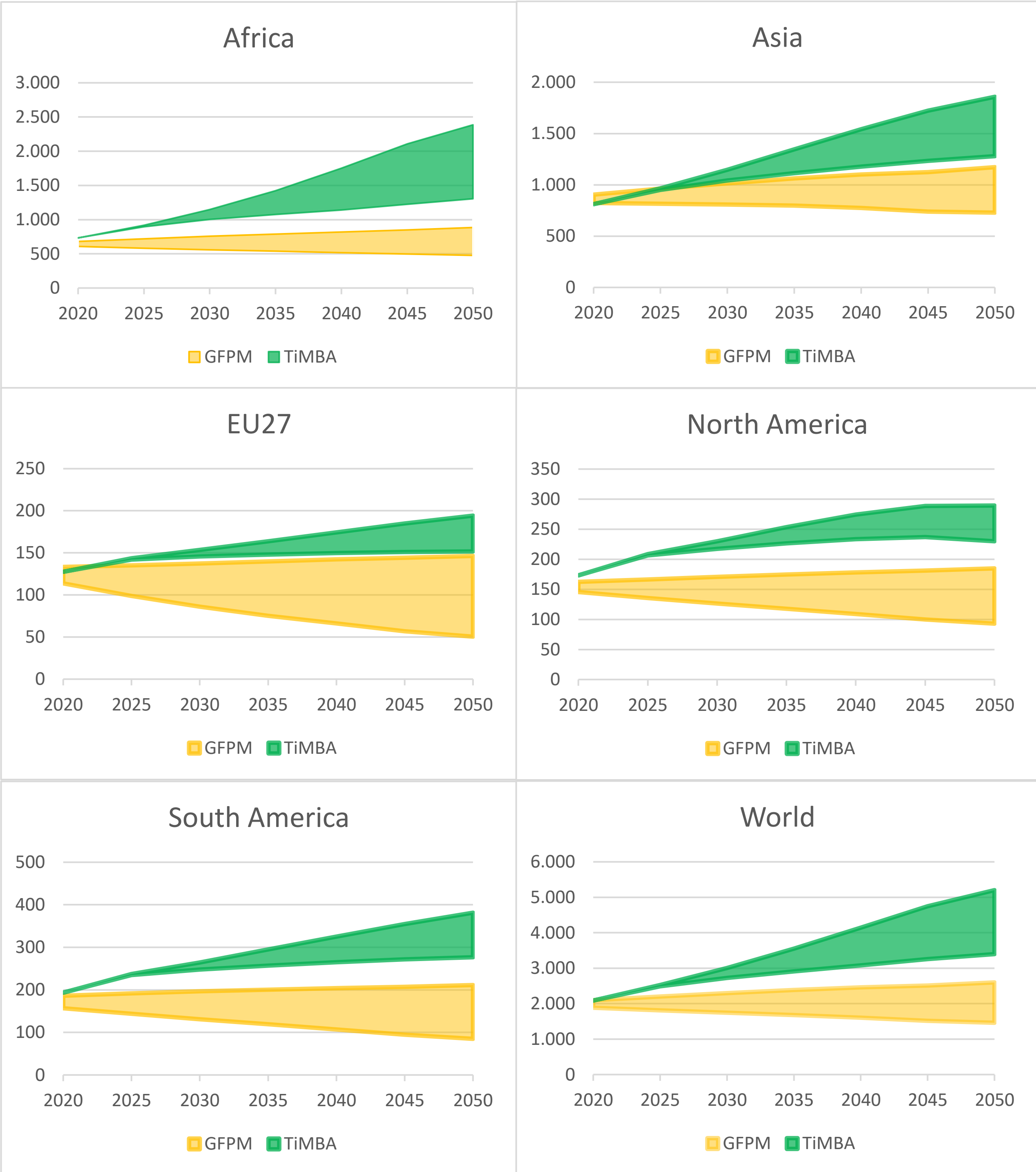
Both models predict continued growth of fuelwood demand in Asia, although TiMBA projects higher future demand. By 2050, TiMBA reaches up to 1,800 Mil m^3/yr, whereas GFPM reaches a maximal demand at around 1,200 Mil m^3/yr.

Differences between the models are particularly notable for the EU27 and North America. GFPM suggests a decline in fuelwood demand to a range of 50-150 Mil m^3/yr by 2050 for the EU27. In contrast, TiMBA projects moderate growth, ranging from 150 to 200 Mil m^3/yr for the EU27. For North America, the GFPM projects decreasing demand, whereas TiMBA suggests a gradual increase, culminating at around 250 Mil m^3/yr by 2050. The initial divergence becomes more pronounced in the long term.

For South America, the demand is expected to increase in both models. TiMBA again projects significantly stronger growth, reaching a range of 300-400 Mil m^3/yr by 2050, while GFPM projects demand stabilizing at 100-200 Mil m^3/yr, followed by a slight decline.

On the global scale, fuelwood demand is projected to increase notably. TiMBA predicts a substantial expansion, ranging from around 3,000 to 5,000 Mil m^3/yr by 2050, depending on the scenario. Whereas GFPM shows more moderate growth, stabilizing at around 2,000 Mil m^3/yr.

Figure 6: Fuelwood demand (in Mil m³/yr)



Source: own illustration

5.2.2 Sawnwood

Figure 7 shows the development of sawnwood demand under three different SSP scenarios and the two models, TiMBA and GFPM. On the global level, TiMBA simulations show a rise in sawnwood demand across all scenarios, primarily driven by growth in Asia and other emerging economies. GFPM projections, on the other hand, show a more moderate to stagnating development on a global scale over time (see Figure 7). At the global level, demand rises from approximately 500 Mil m³/yr in 2020 to around 600-700 Mil m³/yr by 2050 under TiMBA, while GFPM simulates a more moderate development, ranging between 450 and 550 Mil m³/yr in 2050.

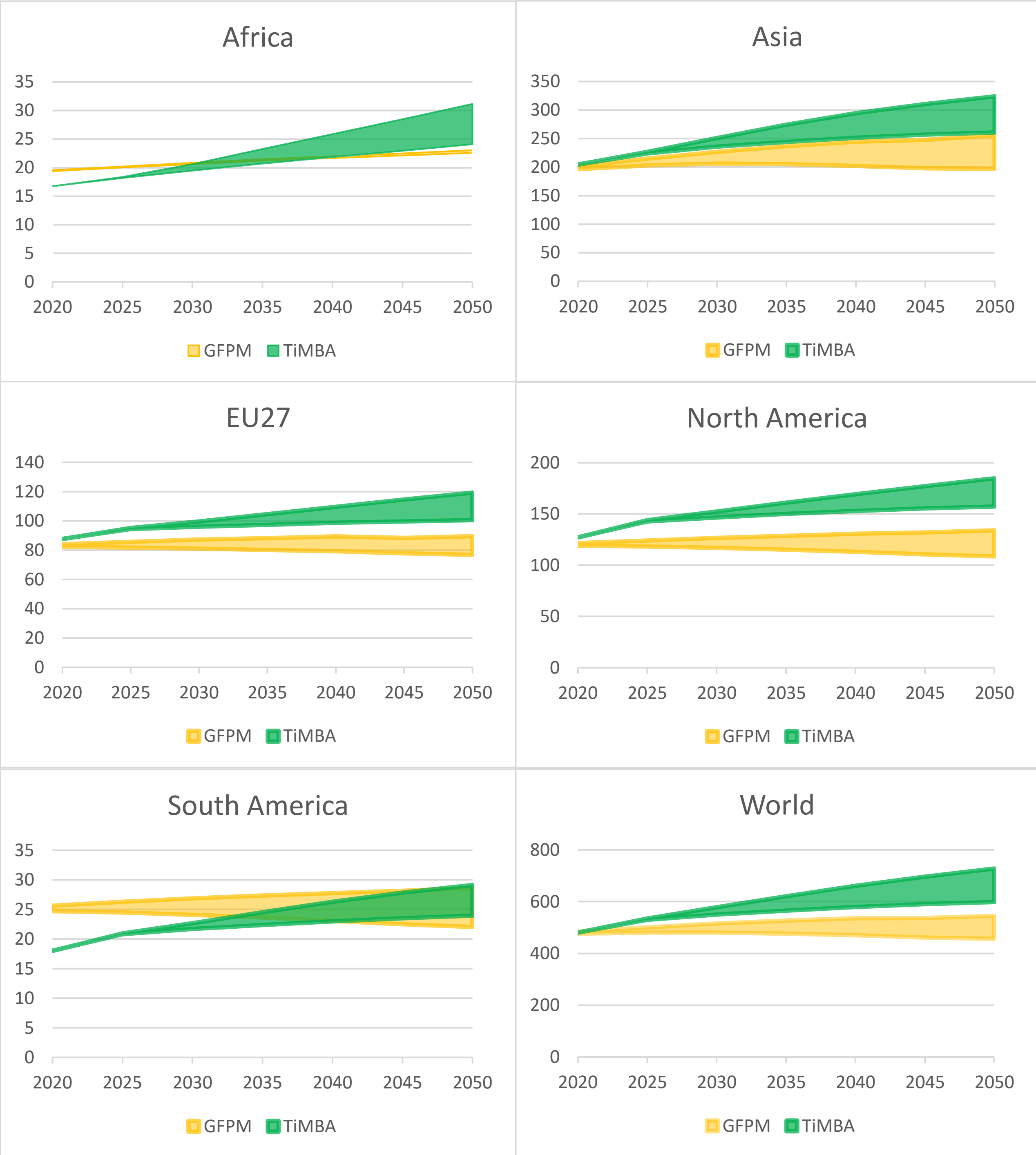
Among the regions, Asia shows the strongest growth in sawnwood demand in TiMBA, with demand projected to rise from approximately 200 Mil m³/yr to a range of 250-325 Mil m³/yr by 2050. Thus, compared to the GFPM, TiMBA simulates significantly higher demand growth across all scenarios, reaching 200-250 Mil m³/yr in 2050.

Starting below the demand level of GFPM, TiMBA indicates considerably higher demand growth for sawnwood in Africa until 2050. In TiMBA, demand can almost increase fivefold to more than 30 Mil m³/yr, while in the GFPM, the increase accounts for about 4–5 Mil m³/yr until 2050. At the same time, the spread of the scenario ensemble obtained with TiMBA is much wider than that of the GFPM, which shows nearly no variation across scenario results.

Even though sawnwood demand growth is stronger in TiMBA, projections for South America are within the GFPM scenarios' range. Since in GFPM the demand for sawnwood remains either constant at 25 Mil m³/yr or even decreases to nearly 20 Mil m³/yr, the latter observation is mainly due to the lower starting level of TiMBA simulations in 2020 at approximately 18 Mil m³/yr.

North America and the EU27 exhibit increasing demand across the scenario ensemble in TiMBA, especially in the first simulation periods, while GFPM projects a stagnating to declining development of sawnwood demand for both regions. However, the variation across the scenarios remains limited compared to both models.

Figure 7: Sawnwood demand (in Mil m³/yr)



Source: own illustration

5.2.3 Wood-based panels

Figure 8 presents the projected demand for wood-based panels across global regions from 2020 to 2050 under the GFPM and TiMBA modelling frameworks. As for the sawnwood projections, demand for wood-based panels increases across all regions in TiMBA. Globally, demand under GFPM is expected to develop from approximately 500 million m³ in 2020 to a range of 400-1,200 Mil m³/yr by 2050, while TiMBA results are roughly the middle of the ranges simulated by the GFPM. The range in TiMBA, however, is not as large as that in the GFPM.

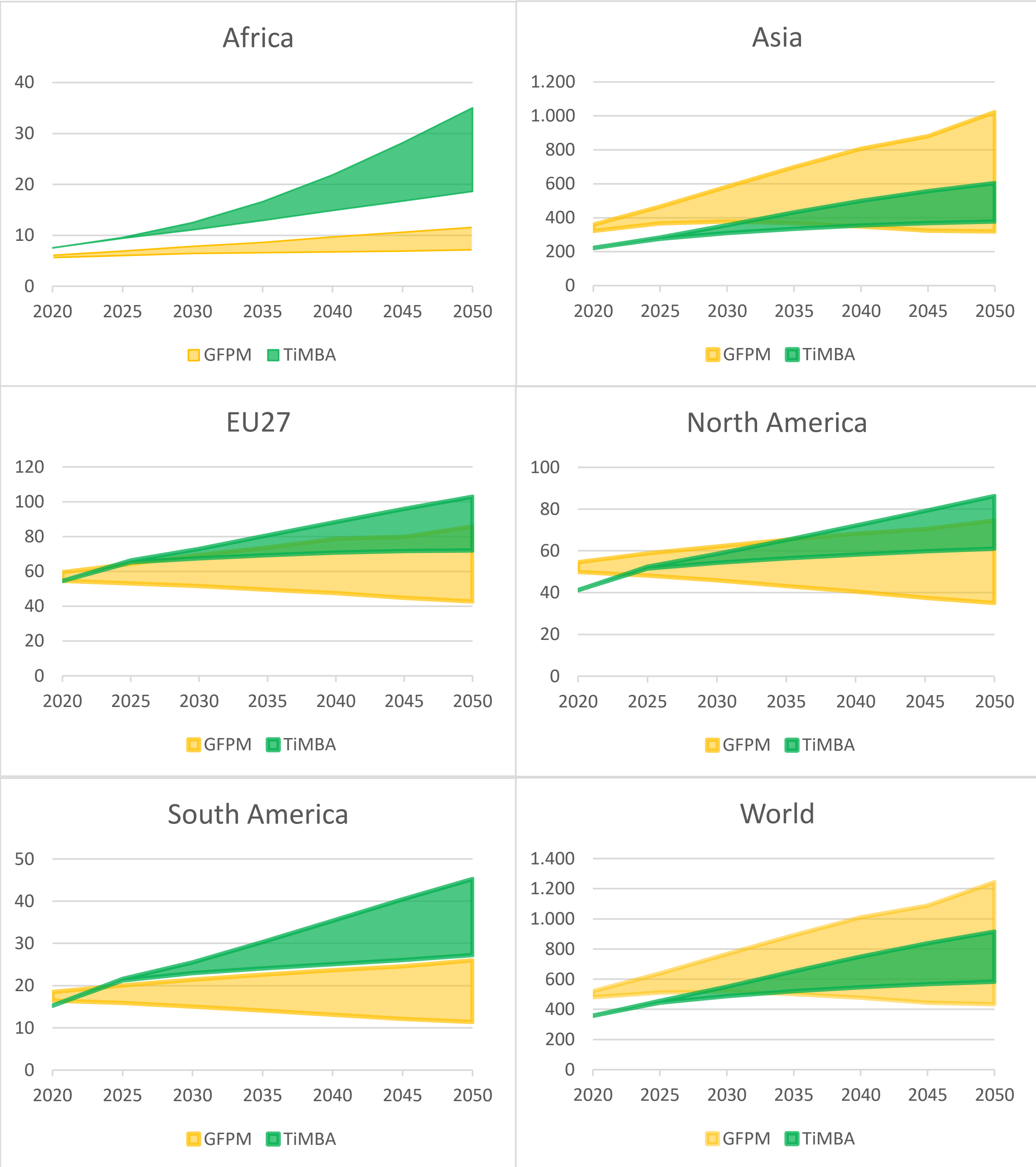
In most regions, TiMBA projects a steeper rise in demand compared to GFPM, especially in the first years of the simulation. The global trend is substantially driven by developments in Asia, which are showing substantial expansion in wood-based panel demand.

However, especially for Asia, the GFPM projects a broader range of possible future developments than TiMBA. Under the GFPM, Asia exhibits strong demand growth, with values potentially exceeding 1,000 Mil m³/yr by 2050 under SSP1. This growth, however, cannot be seen under other SSPs, where one scenario even projects a decreasing demand for wood-based panels of only 400 Mil m³/yr for Asia in 2050. TiMBA, on the other hand, projects a less pronounced but more consistent rise with lower variation across scenarios.

Africa and South America show a strong increase in demand for wood-based panels under TiMBA, with values projected to reach three (South America) to five (Africa) times the 2020 levels in 2050, and at least twice as high in the lowest-growth scenario. The GFPM estimates a more moderate increase – or even a decrease in the case of South America - with the gap between models widening over time. While the spread across scenarios is comparably wide for South America, GFPM exhibits much less variation for Africa than TiMBA.

North America and the EU27 show slower demand growth in both models, with GFPM even projecting declining demand for North America beyond 2035, whereas TiMBA indicates a continued upward trend. Thus, the ensemble of scenario outcomes generated with TiMBA lies at, and in parts extends beyond, the upper boundary of the scenario space spanned by GFPM. For these two regions, the spread of scenario results is wider in the GFPM simulations.

Figure 8: **Wood-based panels demand (in Mil m³/yr)**



Source: own illustration

5.2.4 Paper and paperboard

Figure 9 presents regional and global projections of paper and paperboard demand from 2020 to 2050 under different SSP scenarios simulated with the GFPM and TiMBA models. Global demand for paper and paperboard in TiMBA falls within the GFPM's projected range, though it exceeds the GFPM's simulations after 2040.

Thus, at the global scale, TiMBA projects a gradual increase in demand from roughly 410 million tonnes per year (Mil t/yr) to approximately 550 Mil t/yr by 2050. The GFPM scenario ensemble shows a stagnating-to-declining trend, decreasing to approximately 300 Mt/yr over the same period.

TiMBA, on the other hand, predicts a moderate and steady increase across all regions. The TiMBA simulations position themselves at the upper boundary of the GFPM scenario space (e.g., Asia) or exceed it. Though regional projections highlight substantial differences:

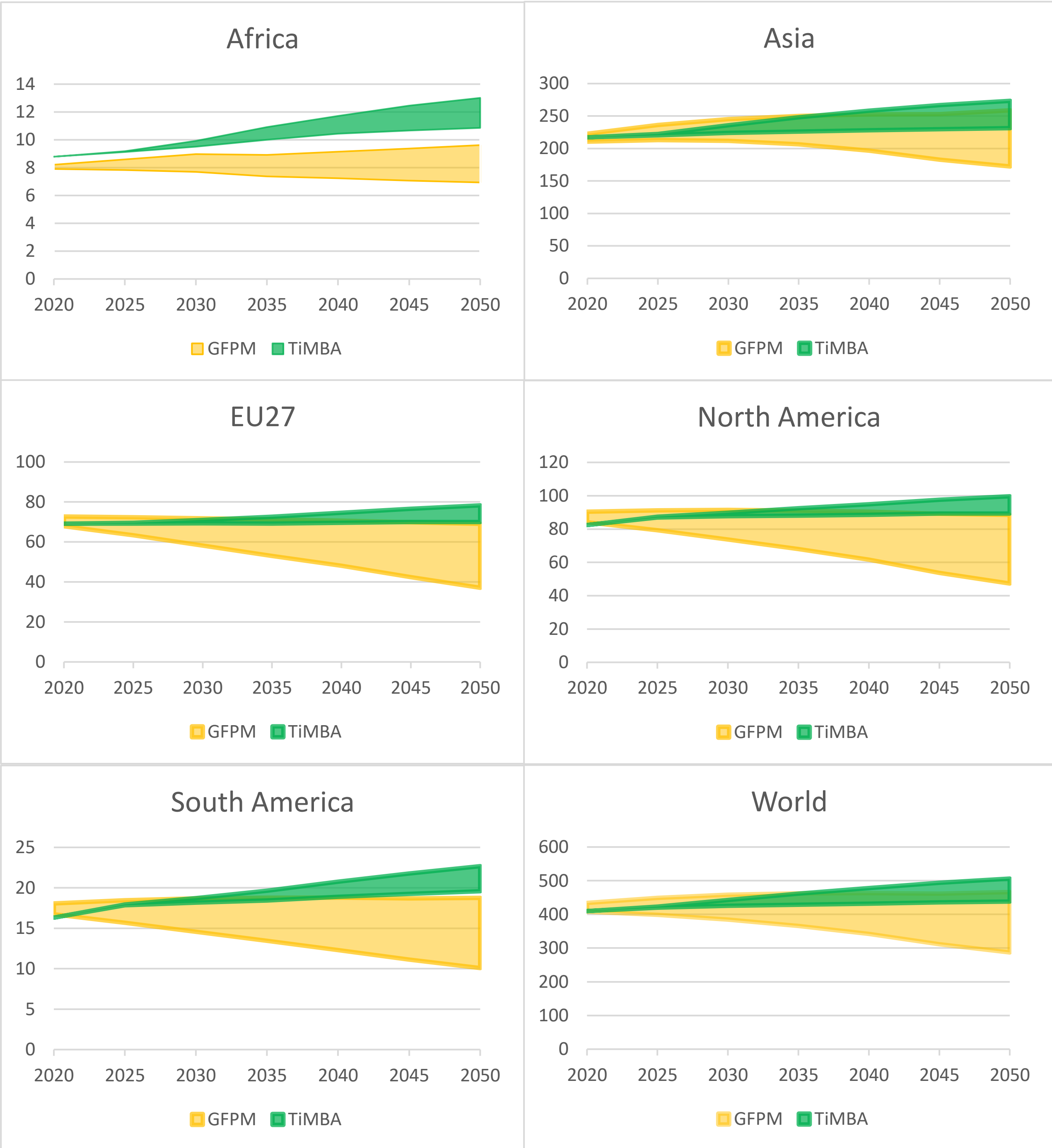
Asia, currently the largest demand region, shows stable growth under TiMBA, reaching around 270 Mil t/yr by 2050. GFPM, however, projects stable to declining trends after 2030, depending on the scenario.

However, in North America and the EU27, the range of TiMBA exceeds that of the GFPM in 2050. EU27 and North America exhibit strong downward trends under GFPM, with demand falling by roughly 40–50% by 2050. In contrast, TiMBA suggests slight growth or stabilization.

For Africa and South America, growth is again more pronounced under TiMBA. This is particularly true for Africa, even though the total volume remains low compared to the demand levels on other continents.

Globally, the contrast between models underscores the high uncertainty associated with long-term demand projections for paper products. While TiMBA projects continued market expansion, GFPM suggests a strong contraction for mature economies.

Figure 9: **Paper and Paperboard demand (in Mil t/yr)**



Source: own illustration

6 Discussion

6.1 Results discussion

In the following, we discuss where the model diverges from the observed behavior of other forest-sector models and the potential causes.

6.1.1 Forest-based supply

The representation of forest area developments differs across the forest-sector models included in this analysis. GLOBIOM and GTM simulate changes in forest areas using land rents, which account for the competition between different land uses (IBF-IIASA 2023; Favero et al. 2020). While GLOBIOM includes different land use types and related products, GTM does not explicitly model these products but instead assumes exponentially increasing land conversion costs with increasing forest area (Favero et al. 2020). Following a different approach, GFPM and TiMBA rely on the development of the GDP and population to model forest area development. Grounding on the concept of the environmental Kuznets curve, both models account for land-use competition indirectly (TI-FSM 2025; Buongiorno 2015). As countries develop, forest loss increases because economies rely heavily on wood for energy and materials, agricultural expansion, and other land-intensive activities. During mid-development, deforestation peaks as industrialization and urban expansion intensify land clearing. At higher income levels, forest loss slows or reverses because economies shift toward less land-intensive sectors and societies demand stronger environmental protection (Tandetzki et al. 2022).

Looking at the results, TiMBA falls roughly in the middle of the range of possible model outcomes. In contrast, the forest area projections of GTM span the upper and lower bounds of the possible outcomes. Given that the forest module and its parameterization in TiMBA are quite similar to that of the GFPM - and in part rely on the same factors - it is not surprising that their results are closely aligned. In fact, this can be interpreted as a validation mark for the consistency and performance of TiMBA's forest area module. Another strength of the intercomparison approach is that the model incorporates socio-economic drivers such as income growth, land-use pressures, and policy responses that strongly influence long-term forest area trends and are essential for generating realistic national-level projections.

Nevertheless, this approach comes with two key weaknesses: First, the national forest area is treated as a single, homogeneous category, ignoring differences in forest types, management regimes, and their distinct growth and regeneration dynamics, which can reduce accuracy, especially in countries where natural forests, plantations, and secondary forests follow divergent trajectories. Second, biophysical aspects are mostly ignored in TiMBA's projections of forest area development. Integrating these biophysical aspects would allow refining forest area projections, especially in light of the increasing impact of climate change on forest dynamics. The compared forest-sector models incorporate forest responses to climate change at different intensities, which might also explain differences in forest area development.

All forest-sector models project increasing mean industrial roundwood harvests throughout 2100. However, the magnitude of these increases differs across models and scenarios, with GLOBIOM and GFPM representing the upper and lower bounds, respectively. The GTM model displays a volatile development pattern, characterized by pronounced up-and-down fluctuations in industrial roundwood harvest, particularly evident for North and South America, Europe, and Asia. This contrasts with the smoother trajectories produced by the other models. The spread of TiMBA results across SSP scenarios is generally lower than for the other forest-sector models, except in countries that were part of the Former Soviet Union, where higher variability is observed.

Among all models, TiMBA exhibits the second-lowest variation in global industrial roundwood harvest, following GFPM.

However, the development of industrial roundwood harvest differs markedly across world regions and models. Overall, the results of the model intercomparison confirm a consistent projection pattern for TiMBA, which aligns with the range of other global forest-sector models. While all compared forest-sector models rely on production and trade data from FAOSTAT (FAOSTAT 2022), they differ in their approaches to model market-driven production developments, demand shifts, and trade changes (Daigneault et al. 2022). This heterogeneity of approaches might drive the differences in roundwood projections.

6.1.2 Forest products demand

TiMBA projects higher future fuelwood demand than GFPM across all continents and SSP scenarios. While GFPM projections indicate potential declines in fuelwood use in developed regions (e.g., EU27 and North America), TiMBA projects a more stable development, with a tendency toward rising demand and strong growth, especially in developing regions (e.g., Africa and Asia). A deeper analysis will be undertaken in an additional sensitivity analysis to systematically explore and refine parameter settings for fuelwood supply and demand.

For the other projections, both models are generally close, with TiMBA mostly located at the upper boundary of the GFPM projections. While GFPM exhibits a wider range of possible outcomes, including more negative developments linked to declining wood-based industries, TiMBA shows lower variation across SSP scenarios. It offers a more optimistic outlook, suggesting a growing forest sector. In TiMBA, the high roundwood supply observed previously aligns well with strong cross-sectoral market demand along the forest-based value chain, leading to higher production levels than under GFPM. This pattern is particularly pronounced in the sawnwood sector, where TiMBA projects robust expansion.

TiMBA projects sawnwood demand to increase worldwide from 2020 to 2050 in all SSP scenarios (see Figure 6). The GFPM projections are more conservative, so across the scenario ensembles sawnwood demand either moderately grows or even declines. Compared to that, growth is more dynamic in TiMBA across scenarios and continents, except for South America, where the demand for sawnwood peaks in both models by 2050. This is mainly due to the lower starting point for TiMBA simulations in 2020. As shown for Asia, North America, and the EU27, similar levels of demand in 2020 translate into higher demand quantities across all scenarios in TiMBA. Despite higher production levels, the overall directional trends between the two models remain broadly comparable, except for South America.

Demand for wood-based panels through 2050 spans a wide range in the GFPM, whereas TiMBA generally projects a narrower range of results. TiMBA’s demand projections lie in the lower to middle part of the GFPM range at the global level, while still reproducing the overall growth trend. In Africa and South America, TiMBA’s projections exceed GFPM's upper bound, reflecting stronger growth. In contrast, in the EU27 and the USA, TiMBA aligns more closely with GFPM's upper end. In Asia, by contrast, the GFPM projects substantially higher production by 2050 and, in general, exhibits a broader and thus more uncertain scenario space for this region. The systematic differences between the two model-specific scenario ranges likely arise from divergent assumptions regarding income and price elasticities, input–output coefficients, and their temporal evolution in each modelling framework.

For the paper sector, TiMBA consistently presents a more optimistic outlook than GFPM. While GFPM projects a stagnating to declining industry, TiMBA suggests a stagnating to slightly growing paper sector at both the continental and global levels.

Despite these differences, TiMBA’s results remain internally consistent and mostly cluster around the central tendencies represented by GFPM, suggesting a high degree of comparability and robustness across both models. While interpreting the results, it is important to keep in mind that the GFPM simulations are based on project-specific scenario projections as described in Morland and Schier (2020) and use 2015 as the initial starting year. Thus, the comparison primarily reflects how demand from TiMBA simulations behaves in comparison to a well-established model such as the GFPM.

6.2 Methodological discussion

The compared models (GLOBIOM, GTM, GFPM, and TiMBA) differ in their structural design and parameterization. Even when structural features and parameter sets appear similar, as in the case of GFPM and TiMBA, the model behaviour remains unique due to, e.g., the characteristics of the solver environment and individual parametrization from prior calibration steps of the model version. This involves model input data and baseline parameters such as market elasticities, input-output coefficients, and manufacturing costs. Beyond internal model specifications, differences in initial conditions such as resource endowments, market demand, and trade activities in the base year have a significant influence on simulation outcomes. Consequently, the results of seemingly comparable models can diverge due to these differences in context and calibration.

Heterogeneity has important implications for the intercomparison of models and interpretation of their results, particularly when simulations are initiated in different base years or rely on differing empirical datasets. While comparing the results from 2020 to 2100, projections provided by Daigneault et al. (2022) start in 2015, whereas scenarios simulated with TiMBA begin in 2020. The difference in the projection start might have led to differences in the projections. The interplay of model-specific assumptions, data limitations, and calibration choices introduces layers of uncertainty that can affect not only the magnitude but also the direction of simulated effects. Models' sensitivity to baseline assumptions can amplify discrepancies between models that aim to represent similar phenomena. Thus, divergent calibration baselines and structural differences reduce the direct comparability of outcomes, even when models are designed to represent similar economic or sectoral processes.

Small variations in elasticities, cost parameters, or trade assumptions can propagate through the model, yielding disproportionately large differences in results. In addition, model outcomes may be context-specific rather than generalizable, reflecting underlying base-year conditions that may overlay economic relationships. Therefore, a validation should focus not only on point estimates or magnitudes but also on patterns, directions of change, and qualitative consistency between models. This is in particular true for the exercise carried out in this report. Since TiMBA was compared with an existing model intercomparison, harmonizing input data, model parametrization, and base-year assumptions across all models can help reduce uncertainty, and systematic biases could further improve the robustness of this exercise.

7 Concluding remarks and outlook

The exhaustive validation of partial equilibrium models, such as TiMBA, enables scientists and policymakers to more accurately assess the reliability of model forecasts, thereby supporting more informed decision-making. TiMBA demonstrates robust reliability in the intercomparison, aligning well with projections from other global sectoral models. This is evidenced by comparing key domains such as forest area and roundwood supply.

Differences in the start year 2020 arise because TiMBA simulations are based on smoothed and calibrated FAOSTAT data for 2019–2021, whereas the simulations carried out for the study by Daigneault et al. (2022) start in 2015. Hence, the 2020 value is a projection. Variations in the development of the models can further be attributed to differences in the modelling structures and parameterization, particularly regarding forest development and use, technological change, and market elasticities (Daigneault et al. 2022).

In conclusion, TiMBA projections demonstrate a high degree of internal consistency and robustness across regional and global contexts. Overall, TiMBA provides a good representation of the range of possible future forest area development and industrial roundwood harvest, and performs competitively compared to other global forest-sector models.

At the global level, TiMBA's simulations of industrial roundwood harvest in 2100 fall in the middle of the solution space across the various models. Regarding global projections of forest area development, TiMBA's results lie at the upper end of the range depicted by the forest-sector model intercomparison, closely aligned with the GFPM results. For Africa, Asia, North America, and Europe, the TiMBA-projected mean forest area development lies between the projections of the other three models. For North America and Europe, the GFPM and TiMBA projections show remarkably little variation around their respective means. However, the relative positioning differs by region: in Europe, GFPM projects a higher forest area than TiMBA, whereas in North America, the opposite is true. These characteristics, together with plausible scenario results on industrial roundwood harvest levels, confirm that TiMBA provides a balanced and competitive representation of potential future pathways in forest area development and timber supply within the global forest-sector modeling landscape. To a certain extent, differences in supply-related outputs across the included forest-sector models can be attributed to their modeling approaches.

Regarding wood products demand, the GFPM and TiMBA trends are similar in the sawnwood sector. In contrast, developments in the wood-based panels sector are more mixed and partly oppose the patterns in the paper sector. These discrepancies reflect the different model specifications and assumptions applied within each framework. Despite these differences, TiMBA's projections for wood product demand remain internally consistent and generally cluster around the central tendencies of GFPM, indicating a high level of comparability and robustness between the two modeling approaches.

However, integrating TiMBA's results into an existing intercomparison of forest-sector models demonstrates alignment of its core outputs with those of well-established models and strengthens confidence in the reliability of its projections. The projection ranges provided by the compared models, including TiMBA, offer more robust information for science and policymakers on how the forest sector may evolve in the future, while accounting for methodological differences and the specific strengths and limitations of each model.

Outlook

Comparing the results of TiMBA and GFPM, a notable divergence was observed in the fuelwood sector. This divergence should therefore be addressed through a dedicated sensitivity analysis to systematically explore and refine parameter settings for fuelwood supply and demand, thereby improving the reliability of TiMBA's fuelwood sector projections.

To some extent, the models used in this exercise incorporate biophysical conditions into their forest-area projections. While this aspect is limited in TiMBA for now, data from dynamic global vegetation models could help improve the linkage between forest area development and biophysical conditions and their changes over time. This further development of TiMBA remains subject to future work.

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Annex

Supplementary data for the working paper are provided in TI-FSM (2026) and are publicly available via the following repository: [https://doi.org/10.5281/zenodo.18606156]. The dataset contains detailed information on products and countries used in the TiMBA model. It includes the input file (Excel format) for simulations of five SSP scenarios up to 2100, along with the corresponding output files (PKL format).

Model outputs can be visualized using the TiMBA_Charts package (Morland et al. 2025), which is available at [https://github.com/TI-Forest-Sector-Modelling/TiMBA_Charts]. Instructions for installation and usage are provided in the repository's README file.

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