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RESEARCH

From simulation to sustainability: using forest growth models for indicator-based bioeconomy monitoring

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Abstract
The transition from a fossil-based economy to a bioeconomy (BE) is crucial for sustainable production and consumption. Yet, growing demand for bio-based resources challenges sustainability, underscoring the need for indicator-based monitoring. Forests play a central role by providing carbon sequestration, timber, biodiversity, habitats, and other ecosystem services but are vulnerable to overuse and conflicting management goals. This study proposes a framework for indicator-based BE monitoring in the German forest sector, combining empirical data with forest growth models (FGMs) to reconcile resource use with ecosystem protection and to support policy development. The framework emphasizes ecological aspects and synergies among societal demands to optimize trade-offs between competing needs. Developed through literature review and expert consultations, the framework defines selection criteria ensuring concise, evidence-based indicators: they must (i) provide quantitative feedback on target achievement, (ii) draw on historical datasets, and (iii) be represented in FGMs for future projections. FGMs simulate interactions between management and ecological factors driving tree growth, mortality, disturbances, regeneration, and stand development. They track forest development via parameters assessing biomass, ecosystem state, and resilience. We identified 11 FGMs suitable for BE monitoring in Germany and propose five indicator groups: biomass carbon stocks, biodiversity, soil, water, and biomass extraction. Carbon and biomass indicators are well integrated into FGMs, while biodiversity indicators remain only partially represented. Soil indicators are hampered by database gaps and process simplifications. Water indicators focus on drought stress quantification and require high temporal resolution process representation and meteorological input for accurate soil-plant-atmosphere interactions. These challenges highlight the need for further FGM development to improve and standardize indicator representation for BE monitoring.

Keywords Forest growth models (FGMs) · Forest-based bioeconomy · Bioeconomy monitoring framework · Ecological indicators · Carbon stocks · Biodiversity indicators · Soil and water indicators

Introduction

The fossil-based economy and its impacts on climate, environment, and natural resources are increasingly recognized as unsustainable (Helm 2017; Kircher 2022; Sharma and Malaviya 2023; Aguilar et al. 2018). Consequently, transitioning to a biomass-based economy (bioeconomy, short: BE) is widely seen as a pathway towards more sustainable production and consumption systems (Aguilar et al. 2018). The BE relies on biological resources to generate products, drive processes, and provide services across diverse economic sectors (EC 2022), aiming to balance sustainable resource use with protecting biodiversity and ecosystem services (Queiroz-Stein and Siegel 2023; IPBES 2018; Jitendra 2024).

However, increasing demand for bio-based resources exerts growing pressure on ecosystems, threatening the sustainability goals that the BE pursues. To avoid negative environmental impacts, monitoring of affected ecosystems is essential for sustainable management and continued productivity (Bringezu et al. 2021). This need is amplified by climate change, which increases uncertainty in bio-based

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production and underscores the importance of adaptive, evidence-based management.

Forests are a cornerstone of the BE, contributing to climate change mitigation through carbon sequestration, supplying timber and non-timber products, and providing ecosystem services such as water regulation, air purification, soil stabilization, recreation, and local climate regulation (Brockerhoff et al. 2017; Acharya et al. 2019; Krieger 2001; Bonan 2008). They also support biodiversity conservation by offering habitats for a wide range of species. These socio-economic, cultural, and ecological values must be central to forest-related decision-making (Ninan and Inoue 2013).

Forest-based BE research has focused on sustainable development, bioenergy production, and climate change mitigation (Ilaria et al. 2020). Yet, conflicts among ecosystem services can arise, e.g., between maximizing carbon sequestration, intensifying resource use (Lin and Ge 2020), and the need for adaptation measures that enhance forest resilience under climate change (Ibáñez et al. 2019; Forzieri et al. 2022; Gregor et al. 2022). However, well-designed management strategies can yield synergies, e.g., by increasing timber production while reducing vulnerability to climate-related risks (Giana et al. 2023; Collalti et al. 2018).

Germany's national BE strategy (BMBF and BMEL 2020) envisions establishing a comprehensive monitoring system to assess the BE's contribution to the UN Sustainable Development Goals (SDGs) of the Agenda 2030 (UN General Assembly 2015), with a focus on food security, climate-neutral production, and biodiversity conservation (Bringezu et al. 2020). Forest policy in Germany must reconcile diverse and sometimes competing objectives across multiple governance levels: at the European Union level, policies include renewable energy targets and biodiversity protection commitments (EU 2024), while at the national level, initiatives such as the "Aktionsprogramm Natürlicher Klimaschutz" (BMUV 2023) support enhanced natural carbon sinks in line with ambitious net removal targets under the LULUCF Regulation (German federal government 2021; EU 2018). Additional federal state and regional measures—such as timber construction incentives and biodiversity programs (e.g., StMB 2022; BMWE 2024)—add further layers of complexity to forest sector governance. This multifaceted policy landscape highlights the need for effective monitoring frameworks that optimize synergies and manage trade-offs among competing societal demands in the forest-based bioeconomy.

Indicators and Forest Growth Models in bioeconomy monitoring

A forest BE monitoring framework should support target setting and adaptive adjustment amid economic, environmental, and societal challenges (Fig. 1). Such a framework requires specific indicators to quantitatively monitor ecosystem states and services. Well-chosen indicators distill complex information into comparable, evidence-based metrics that aid policy formulation, evaluation, and adaptive management (Wolfslehner et al. 2016). They can guide resource planning, identify risks and trade-offs, and serve as early warning systems by enabling long-term tracking of historical trends and future projections (Bringezu et al. 2021; Robert et al. 2020).

Relevant indicators can be derived from forest inventories, remote sensing, field surveys, experiments, and economic statistics (e.g., timber construction quotas, fuelwood demand; see, e.g., Iost et al. 2025). However, such empirical data usually have limited temporal coverage, irregular spatial resolution, and are inherently retrospective.

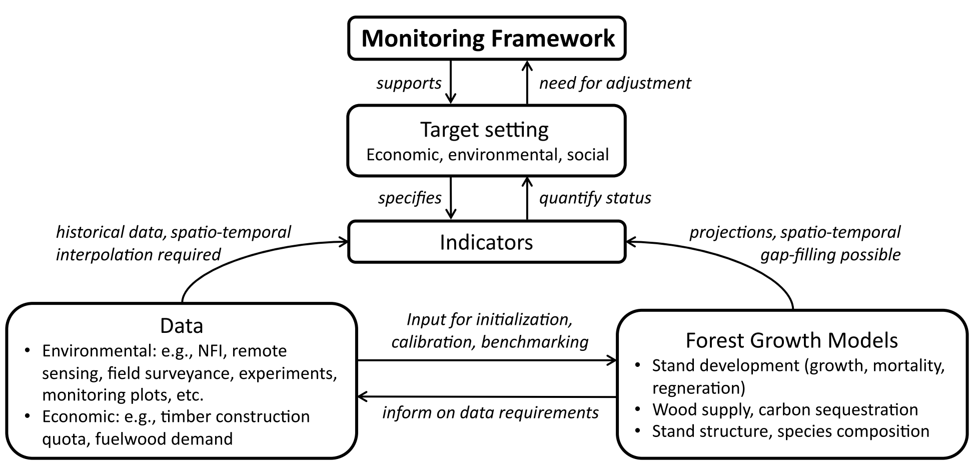

Fig. 1 Flowchart illustrating a forest bioeconomy monitoring framework, where economic, environmental, and social objectives specify which indicators are required. Suitable indicator selection is based on empirical data and output from Forest Growth Model (FGM) simulations. Data harmonization and model calibration ensure accuracy, while feedback loops enable adaptive management. This integrated system supports evidence-based assessment and projection of forest BE development

Forest growth models (FGMs) complement data by simulating forest dynamics under variable management practices, climate scenarios, and disturbances (Weiskittel et al. 2011; Gutsch et al. 2018; Pfeiffer et al. 2023). FGMs integrate mathematical process representations with empirical data, tracking variables such as growth, mortality, biomass, and stand structure, which can directly serve as ecological indicators (Albrich et al. 2020; Forzieri et al. 2022; Gregor et al. 2022; Ibáñez et al. 2019; Seidl et al. 2014; Tarasewicz and Jönsson 2021). Scenario-based simulations by FGMs enable spatiotemporal gap filling and projection of future forest developments but require environmental input data for model initialization, calibration, and benchmarking. Interactions between data sources, indicators, and FGMs are illustrated in Fig. 1. Feedback loops allow monitoring results to inform adaptive governance and management adjustments.

FGMs encompass empirical models using statistical relationships derived from observations, and process-based models that simulate biophysical and biogeochemical processes (Korzukhin et al. 2024; Lindeskog et al. 2021). Empirical models excel at reproducing current and short- to medium-term conditions, whereas process-based models are also well suited for assessing long-term responses to drivers such as climate change, nitrogen deposition, and elevated CO_2 (Hickler et al. 2015). Combining both model types leverages their respective strengths for BE monitoring.

Applications of FGMs include resource assessment and scenario analysis (Pfeiffer et al. 2025), policy evaluation (Jose et al. 2023), supply chain management (Pretzsch et al. 2008), the development of sustainability strategies (Tarasewicz and Jönsson 2021), biodiversity conservation (Augustynczik et al. 2020), and climate change mitigation and adaptation (Gregor et al. 2022). Using ecological and environmental data, FGMs project potential forest development across various time scales. However, FGMs only marginally cover economic indicators, which therefore require complementary modeling approaches.

This study focuses on indicators that (1) FGMs can represent and (2) characterize ecological implications of the forest-based BE, targeting the following questions:

1. What are suitable ecological indicators for effectively monitoring a forest-based BE in Germany? How should they be grouped and defined within a conceptual framework?
2. Which existing FGMs can represent these ecological indicators?
3. What deficiencies and gaps exist in the representation of indicators by current FGMs, and how can these gaps be addressed?

To answer these, we conducted a comprehensive literature review and expert consultation to develop a conceptual monitoring framework for the German forest sector based on FGM-derived indicators. We propose key environmental indicator groups and specific indicators represented by existing FGMs and discuss potential development needs to enhance comprehensive model-supported indicator-based monitoring.

Materials and methods

Literature review

We first conducted a comprehensive literature review to support the development of a conceptual monitoring framework for forest-based BE in Germany. This review aimed to identify relevant ecological indicators that are compatible with forest growth models (FGMs) and to select FGMs suitable for assessing these indicators at a national scale.

The review process involved screening publications on existing certification systems, bioeconomy monitoring schemes, and model descriptions, focusing particularly on indicators represented in FGMs operating at the national level in Germany. Sources included peer-reviewed scientific literature, technical reports, and grey literature relevant to FGMs applicable at the national level.

While we did not strictly apply all items of the PRISMA 2020 Checklist (https://www.prisma-statement.org/prisma-2020-checklist), we predefined clear search terms and platforms. Searches were performed predominantly between April 2022 and December 2022 using keywords such as "forest growth model," "forest model," "forest simulator," "forest management model," and their German equivalents, combined with geographical terms such as "Germany" and "Central Europe." Searches were conducted using Google Scholar, Web of Science, and Google Search. Additionally, we included publications describing models cited in the reviewed literature, and literature brought to our awareness during expert exchange rounds. To structure the screening process, we created an Excel database containing 20 checklist items covering essential model characteristics and meta-information on models, including model name, reference publications/websites for the model, contact information of scientists developing/using the model, theoretical geographical region of model applicability, adjustability to Germany, spatial extent (stand-level vs. national), temporal resolution, implemented forest management routines, climate sensitivity, type of stand representation, model type (process-based vs. empirical), representation of distance-dependent competition, mixed stand representation, implemented types of management measures, mortality representation, deadwood representation, model modules, and required input data. Papers matching search keywords were screened using full-text PDFs of articles focusing on abstracts, model descriptions, and figure data. Materials not providing relevant data on these items were discarded but not formally tracked. In total, 100 papers were collected and stored.

This approach ensured the selection of indicators and models that align with policy needs and are feasible for long-term ecological monitoring within the German forest sector.

Development of a conceptual monitoring framework and selection of indicator groups

To establish essential indicator groups for forest BE monitoring in Germany, a conceptual framework was developed using a top-down approach. Target for this framework was to integrate societal demands with forest governance and management actions, and to link policy targets to quantifiable forest conditions through indicators. We specifically aimed to incorporate feedback loops where monitoring results inform adaptive management and regulatory adjustments.

To ensure that the monitoring framework is robust, policy-relevant, and aligned with current international and European standards and practices, we reviewed recognized concepts and frameworks to (1) determine which framework concepts most closely matched the needs of our targeted monitoring framework and (2) draw on existing structures and indicator sets rather than designing an entirely new framework. By synthesizing established concepts, we aimed to design a framework that combines formal policy requirements with conceptual clarity and applied research experiences to define relevant indicator groups for effective forest BE monitoring.

Criteria for selecting suitable indicators for forest-based bioeconomy monitoring

Building upon the conceptual monitoring framework developed in the preceding section, the selection of indicators for monitoring of the forest-based BE in Germany was guided by a set of criteria to ensure their strategic relevance, operational feasibility, and scientific robustness.

First, indicators were required to align closely with policy and management objectives embedded in key national and international frameworks, including the United Nations Sustainable Development Goals (SDGs), the EU Bioeconomy Strategy, the EU Biodiversity Strategy, and the LULUCF Regulation (Bogdanski et al. 2021; EC 2024). This alignment ensures the relevance of selected indicators within prevailing regulatory and strategic contexts, facilitating their use in policy evaluation and decision-making.

Second, we aimed to adhere to the SMART criteria (Doran 1981) to promote clarity and practicality: indicators must be Specific, Measurable, Accessible, Relevant, and Timely. This ensures that indicators yield precise, quantifiable, and actionable information capable of supporting consistent progress tracking towards BE objectives by informing forest policy frameworks and management practices.

Third, indicators needed to be quantifiable using available data and established methodologies, allowing for consistent monitoring across temporal and spatial scales and under varied management scenarios. We specified that metrics were preferably to be expressed in standardized units (e.g., tons per hectare), with spatial and temporal resolutions consistent with ecological process dynamics and decision-making requirements.

For model-based monitoring, compatibility with FGMs was a key consideration, ensuring that indicators could be accurately represented by FGMs and, where possible, derived from model simulations calibrated against empirical observations.

Flexibility and adaptability of indicators were also prioritized to accommodate frequent updates in data availability, shifts in environmental conditions, and advances in scientific understanding (Pearce-Higgins et al. 2022; Lindner et al. 2010). Finally, transparency and thorough documentation of indicator definitions, data sources, and computational methods were regarded as essential to enhance credibility, reproducibility, and stakeholder confidence in monitoring outcomes.

Identification and evaluation of Forest Growth Models

To operationalize indicator-based BE monitoring for German forests, we systematically reviewed FGMs for their suitability to generate relevant ecological indicators at the national scale. The evaluation focused on identifying models that offer robust, policy-relevant simulations aligned with the indicator framework described in previous sections.

Eligibility criteria

Candidate FGMs were screened based on their demonstrated applicability for Germany-wide projections, either through direct national-scale simulations or disaggregation of larger-scale model domains. Models were only considered if they permitted time series analyses extending through at least 2050 and could output results at a temporal resolution of 10 years or finer—requirements essential for evaluating long-term forest dynamics and management interventions under changing environmental conditions.

Further, eligible models were required to incorporate key aspects of forest management (e.g., thinning, salvage logging, replanting) and to represent central ecological processes, including natural regeneration and mortality. The ability to track growing stock and its changes at the unit-area level was set as a minimum technical prerequisite. Both empirical and process-based models were included if they fulfilled these core requirements.

Model-indicator mapping and assessment

For each FGM, we documented available output variables and assessed their correspondence to the prioritized indicator groups (see the "Development of a conceptual monitoring framework and selection of indicator groups" and "Criteria for selecting suitable indicators for forest-based bioeconomy monitoring" sections). An iterative process, involving cross-referencing model documentation and testing output availability against indicator requirements, ensured both policy relevance and practical feasibility. Models and indicators were subsequently classified according to their degree of compatibility (fully, partially/potentially, or not suitable).

This mapping informed a final synthesis of model-supported indicators available for BE monitoring in Germany, while also revealing coverage gaps and areas in need of future model development or supplementary data sources. Historical datasets used for benchmarking and calibration were compiled for each compatible model and indicator.

Expert review and framework/indicator refinement

Following the preliminary identification of suitable FGMs and the mapping of potential indicators within the conceptual monitoring framework, we engaged an expert panel to validate and refine both indicator selection and framework structure. This participatory phase was conducted to ensure robustness, policy relevance, and operational feasibility of the proposed monitoring system.

Experts with domain-specific experience in forest modeling participated via an online exchange platform across five structured meetings between February and July 2023 lasting 1.5 to 2 h each. Participant number varied between 8 and 18 participants per meeting, with an average of 12 participants. Discussions focused on assessing the suitability of each indicator group for quantifying environmental impacts of the forest-based BE, evaluating how well FGMs capture these indicators, and identifying existing gaps or priorities for model development.

To guide deliberations, we posed targeted questions addressing indicator completeness, clarity of definitions, appropriate units of measurement, and differentiation levels, as well as temporal and spatial resolution requirements. This iterative consultation integrated diverse expertise to balance scientific rigor with practical applicability.

Consistent with academic standards, experts who contributed substantively beyond feedback—such as to data analysis, interpretation, or manuscript preparation—were invited to co-author the resulting publication. All expert inputs were systematically incorporated, resulting in a refined and validated set of indicators and an enhanced evaluation of FGM suitability for forest bioeconomy monitoring.

Results

Conceptual framework and indicator groups

Conceptual framework

Our literature review identified several established frameworks linking ecosystem goods and services to societal needs, sustainable resource use, and environmental protection. Among these, the DPSIR (Drivers, Pressures, State, Impact, Response) framework is particularly suited for analyzing causal chains between society and the environment and supporting adaptive management (Maxim et al. 2009; Kristensen 2004; Smeets and Weterings 1999), making it particularly interesting for integrating forest-based BE monitoring into policy planning (Table 1).

Life-cycle assessment (LCA), as defined in ISO 14040/44 (ISO 2006a; 2006b), evaluates environmental impacts of products over their life cycle. Its results inform industry, policymakers, and consumers, and highlight opportunities to reduce impacts. For example, net greenhouse gas balance assessment provides evidence of the climate benefits or drawbacks of bioenergy production (RED III, EU 2023; Table 1).

Environmental footprint (FP) analysis methods extend this to carbon emissions, land use, biodiversity, and water impacts, applicable from product to national scales (e.g., ISO 14067, ISO 14046, see Bringezu et al. 2021; Table 1). The HANPP (Human Appropriation of Net Primary Production) concept was reviewed but deemed too theoretical and vague in its determination, calculation, and interpretation and therefore ill-suited for forest BE monitoring.

Certification systems, often informed by LCA and FP, verify sustainability compliance of biomass production and use to social, economic, and environmental standards through third party audits, with varying depth and scope. The ISO 13065 standard offers an internationally recognized meta standard for bioenergy assessments (ISO 2015; Table 1), while schemes such as FSC and PEFC also integrate social and governance criteria (Schleicher et al. 2019).

At the European level, the EU Bioeconomy Monitoring Framework compiles indicators aligned with EU Bioeconomy Objectives, SDGs, and the Green Deal (Wydra and Kroll 2024; Robert et al. 2020; EC 2024; Table 1). For example, a "forest growing stock" indicator contributes simultaneously to the Green Deal's goal of "Preserving and Restoring Ecosystems and Biodiversity," the SDGs' "Life on Land," and the bioeconomy objective of "Managing Natural Resources Sustainably." Forest-related indicators include

Table 1 Overview of existing conceptional frameworks and applied environmental indicator groups

Title, reference	Concept/topic	Aim	Approach	Environmental indicators and indicator groups
DPSIR-framework (Kristensen 2004; Smeets and Weterings 1999)	Causal framework to describe the interactions between society and environment	Provide a systematic approach to assess environmental issues; develop effective policies for sustainable development	Causal chain approach based on sequential links between driving forces (human activities), pressures (stress on environment), states (environmental conditions), impacts (on ecosystems, human well-being), and responses (mitigation/adaptation measures)	Depends on application purpose, defined by user of the framework; examples: environmental quality parameters (air, water), biodiversity, habitat quality, ecosystem services indicators
ISO 13065:2015 (ISO 2015)	Sustainability criteria for bioenergy supply chains	Establish a meta standard for the development of certification systems in the field of bioenergy; facilitate comparability of bioenergy vs. other energy options	Description of principles, criteria and indicators that should be covered by certification systems	Biodiversity, soil, water, air, GHG emissions, energy efficiency, waste
Environmental footprint analysis (FP, Bringezu et al. 2021)	Environmental and socio-economic footprints of the German BE	Analysis of footprints in relation to the domestic use of biomass in Germany; differentiated by impacts in Germany and in other countries of origin	Combining economic modelling (including trade flows) and land-use modelling; deriving information needed for single footprints	Land-use change due to agriculture (including biodiversity impacts), water withdrawals, GHG emissions, agricultural and forest biomass flows
EU BE monitoring framework (European Commission 2024a)	Comprehensive overview of European trends in indicators related to the EU bioeconomy	Assess the EU's progress towards BE objectives, and to inform about the progress of goals specified under the SDG-framework and the Green Deal	Query masks covering existing BE-related indicators	Sustainable natural resource management: roundwood removals; felling/net increment; growing stock; bird & butterfly indices | Not yet active: deadwood; primary residue fraction; certified forests Climate change adaptation/mitigation: net GHG (LULUCF) | Not yet active: soil moisture; soil erosion
RED III (RED III 2023)	Minimize the risk of using forest biomass derived from unsustainable production	Definition of legally binding criteria operators must fulfill	Proof that criteria are met requires a certificate	Bioenergy criteria (forest biomass): respect protection areas; soil quality and biodiversity (see also RED III 2023 EC 2018, Art. 29.6), accordance with sustainable forest management; GHG-emission reduction vs. fossil fuels (substitution potential of forest biomass)

growing stock, roundwood removals, felling to increment ratio, bird and butterfly indices, Natura 2000 area, and LULUCF GHG emissions (European Commission 2024a).

Further considered inputs included the Renewable Energy Directive (RED III, EU 2023) that outlines mandatory targets for renewable energy sources within the EU, and the pilot report of the "Systemic Monitoring and Modelling of the Bioeconomy (Symobio)" project (Bringezu et al. 2020, 2021) with exploratory approaches specifically tailored to BE-related challenges.

Aligning with DPSIR principles, our conceptual forest BE monitoring framework (see illustration in Fig. 2) defines societal needs as the main drivers of policy. Provisioning services such as wood for material and energy use are balanced with regulating, supporting, and cultural services, including LULUCF GHG targets, biodiversity, water protection, recreation, income, and employment. These needs are translated into measurable targets that guide forest management strategies, mediating between policy objectives and actual forest states, generating trade-offs or synergies depending on chosen strategies.

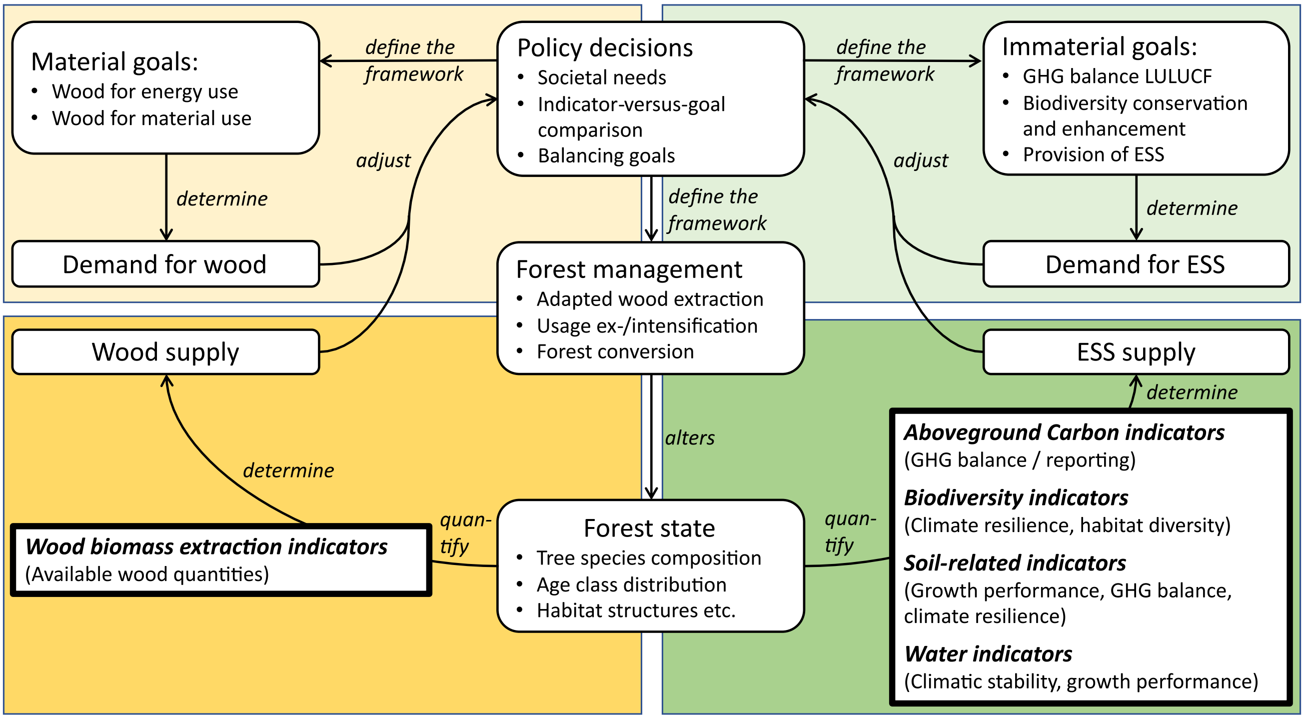

Fig. 2 Conceptual framework for indicator-based monitoring of the forest-based bioeconomy in Germany. Societal needs for provisioning services (e.g., harvested wood, energy use) vs. supporting services (e.g., GHG balance, biodiversity, water retention, recreation) drive forest sector policy, implemented via forest management strategies. Monitoring based on quantitative indicators—wood supply, carbon, biodiversity, soil, and water—derived from empirical data and forest growth models (FGMs) supports adaptive management by benchmarking indicators against policy targets and informing regulatory adjustments. ESS, ecosystem services; LULUCF, land use, land use change, and forestry

Indicator-based monitoring includes carbon stocks, biodiversity, soil, water, and wood supply. Quantitative ecological indicators for these groups derive both from empirical data (forest inventories, remote sensing, field surveys, harvest statistics) and FGMs simulating forest dynamics, which complement and extend data by filling spatiotemporal gaps and project future developments under alternative management and climate scenarios. Continuous integration of empirical and modeled data supports feedback loops, using monitoring outcomes for adaptive policy updates and management adjustments through decisions of forest owners and managers.

The framework thus operationalizes monitoring of the German forest–based BE as a structured, evidence-based, and adaptive system. By combining empirical data with dynamic FGM outputs across key ecological indicators, it provides a robust basis for evaluating sustainability trade-offs and guiding policy under changing environmental and societal conditions.

Definition of indicator groups

Building on the review of existing frameworks (the "Conceptual framework" section) and the socio-ecological context outlined above, we refined the indicator system leaning on the indicator groups defined in ISO 13065 (ISO 2015)—covering greenhouse gas emissions, water, soil, air, biodiversity, energy efficiency, and waste—to four ecological domains that are policy relevant and representable in FGMs. The four groups were selected based on:

1. **International acceptance**: Ensuring comparability and broad recognition.
2. **Relevance to biomass**: Direct applicability to sustainable biomass production systems.
3. **Comprehensive coverage**: Spanning key environmental aspects reflected in frameworks such as DPSIR or RED III.
4. **Applicability in certification**: Demonstrated practical relevance.
5. **Alignment with other frameworks**: Substantial overlap with DPSIR and others (see Table 1).

The four environmentally relevant groups that were chosen to inform on ecosystem service status in forests are (see Fig. 2):

1. **Carbon indicators, including wood extraction indicators**: Quantify forest's contributions to greenhouse gas

balances under the LULUCF sector (including national inventory reporting) and wood supply potentials.
2. **Biodiversity indicators**: Capture structural and compositional dimensions of forests that underpin species diversity and resilience. Suitable proxies include tree species composition, volume of habitat trees, and deadwood availability, which can be derived from inventories and model simulations.
3. **Soil indicators**: Track long-term stability of carbon and nutrient stocks, which strongly influence growth potential, carbon fluxes, and ecosystem resilience.
4. **Water indicators**: Capture water availability constraints and address forest vulnerability to changing climatic conditions, especially drought.

By focusing on these domains, the indicator set balances the ability of FGMs to generate robust, quantitative outputs with the ecological dimensions most critical for sustainable BE monitoring. Unlike broader sustainability frameworks (ISO 13065, RED III), our approach prioritizes those indicator groups that can be directly represented in forest simulation models and evaluated against national datasets (e.g., National Forest Inventory, soil surveys, meteorological records).

This focus ensures that the monitoring framework adds value beyond descriptive statistics: it allows continuous dynamic projection of forest states and services under alternative management and climate scenarios. The chosen groups therefore operationalize an ecologically centered but model-based perspective on monitoring, directly linking empirical and simulated information with adaptive forest-BE governance.

Summary of selected indicators

The literature review of FGMs suitable for BE monitoring in Germany identified commonly represented indicators that we aligned with the indicator groups highlighted in the "Definition of indicator groups" section. In sum, the chosen indicators provide a comprehensive set spanning biomass supply, carbon, biodiversity, soil, and water and form the operational backbone of the monitoring framework. The indicator set was chosen with the aim to balance forest productivity with ecosystem health, supporting evidence-based policy and sustainable forest management in Germany.

Table 2 summarizes these groups and specific indicators, including their relevance, recommended differentiation based on FGM outputs, suggested units, available German datasets for calibration and benchmarking, and the number of FGMs representing each indicator. The following sections provide summaries of selected indicators by group. Details from expert workshop discussions on indicator selection are available in Supplementary Material S1.

Economy-related indicators

Economy-related indicators quantifying wood extraction are well established in German forestry statistics and inventories, providing direct measures of wood supply and forest management activity. They include wood quantities from harvest, thinning, and salvage logging, as well as growing stock and net stock change and help assess sustainable harvest levels to identify risks of overexploitation under the BE transition.

FGMs consistently represent these indicators, surpassing static yield tables by dynamically incorporating site- and climate-specific growth responses and allowing adjustments for climate and disturbance impacts. For monitoring, differentiation by species groups, or at least by broadleaf vs. needleleaf wood, and diameter classes should be provided, with the latter providing usage-independent perspectives. Quantities are ideally tracked in cubic meters under bark (m^3 u.b.) alongside wood density data where available. Statistical data from the German "Einschlagsrückrechnung" (Jochem et al. 2023) and "Holzeinschlagsstatistik" (Destatis Code 41,261) facilitate model calibration and validation, enabling fine-scale and long-term monitoring, but may exclude unregistered extractions, e.g., private use. In alignment with historical harvest statistics and surveys, FGM-derived wood extraction indicators should be tracked with annual resolution. Complementing harvest data, the National Forest Inventory (NFI) can provide estimates of forest growing stock, stock changes, tree growth increment, mortality, and wood extraction at lower temporal resolution based on a 4 × 4 km resolution and partially at 2.83 × 2.83 km or 2 × 2 km. More details are provided in supplementary material S1.2.

Carbon indicators

Carbon-related indicators are central both for tracking forest carbon stocks and national GHG reporting under UNFCCC/EU frameworks and for evaluating forest's role in the BE transition, supporting compliance with national targets. All assessed FGMs simulate C-storage and dynamics in biomass pools (stems, branches, leaves, roots, dead wood), supporting monitoring of stock dynamics influenced by harvests, climate-related diebacks and disturbances (storms, droughts, beetle outbreaks, fire), growth, and regeneration. Differentiation by stand development phase, species group, and biomass pool refines analysis for management and trend evaluation.

Annual indicator resolution allows capturing climate impacts across seasonal cycles. Volume-based units are easier to derive but can be converted to carbon units via representative wood densities. Although carbon stored in harvested wood products is relevant for GHG reporting, it falls outside typical forest management influence and FGM scope and is excluded from our framework. Further details are provided in Supplementary Material S1.1.

Table 2 List of proposed indicators for BE monitoring of forests

Proposed groups and indicators	Main reason for choice of indicators	Level of further differentiation	Units of indicators	Available historical data base for Germany	Implemented in models for Germany (11 models)*
1. Economy-related indicators					
1.1 Wood extraction	Quantification of wood supply; indication of forest management activities	- Harvest, thinning, salvage logging - Species groups (e.g., needle-leaf vs. broadleaf) - Diameter classes (favorable) or assortments (stemwood, indusrial wood)	[m^3 o.b. > 7 cm dbh] or [m^3 o.b. > 7 cm dbh ha^{-1}] values can also be expressed u.b.	Einschlagrückrechnung (Jochem et al. 2023); NFI, Destatis Holzeinschlagsstatistik (Code 41261)	Harvest: 10/1/0 Thinning: 10/1/0 Salvage logging: 4/2/5
1.2 Growing stock	Volume of living trees	- Species groups (e.g., needle-leaf vs. broadleaf) - Diameter classes (favorable) or assortments (stemwood, industrial wood)	[m^3 o.b. > 7 cm dbh] or [m^3 o.b. > 7 cm dbh ha^{-1}]	National forest inventories (https://bwi.info)	6/5/0
1.4 Gross increment	Growth increment of living trees	- Species groups - Diameter classes	[m^3 o.b. > 7 cm dbh] or [m^3 o.b. > 7 cm dbh ha^{-1}]	National forest inventories (https://bwi.info)	6/5/0
1.3 Net stock change	Quantification of annual net stock change (increment and establishment minus losses due to harvest, thinning and natural mortality); indicator for forest management intensity	- Species groups - Diameter classes	[m^3 o.b. > 7 cm dbh] or [m^3 o.b. > 7 cm dbh ha^{-1}]	National forest inventories (https://bwi.info)	6/5/0
2. Carbon indicators					
2.1 Carbon stocks in different biomass pools	Quantification for GHG inventory reporting; indicator of forest state	- Stems, branches, coarse roots, leaves, fine roots, dead wood - Species groups	[t C] or [t C ha^{-1}]	National GHG Reporting (UBA 2024), National forest inventories (https://bwi.info)	11/0/0
2.2 Change of biomass carbon stocks	Quantification of annual changes for GHG inventory reporting; Indicator of forest state	- Stems, branches, coarse roots, leaves, fine roots, dead wood - Species groups	[t C $year^{-1}$] or [t C ha^{-1} $year^{-1}$]	National GHG Reporting (UBA 2024), National forest inventories (https://bwi.info)	11/0/0
3. Biodiversity indicators					
3.1 Volume of broadleaf habitat trees	Quantification of potential rare habitat structures; Indicator needed for threatened and endangered species	Broadleaf trees > 60 cm dbh	[m^3 o.b. > 60 cm dbh] or [m^3 o.b. > 60 cm dbh ha^{-1}]	National forest inventories (https://bwi.info)	5/2/4
3.2 Deadwood volume	Quantification of deadwood habitats; Indicator of forest development stage	Deadwood class and orientation (standing, lying)	[m^3 o.b.] or [m^3 o.b. ha^{-1}]		7/1/3
3.3 Simpson diversity index for tree species diversity	Quantification of α-diversity of tree species	Calculation based on basal area of species at plot-level; mean value, 10%-quantiles etc. per year; multi-panel histograms	Index	Potentially by the analysis of national forest inventory data (https://bwi.info)	1/5/5
3.4 Gini coefficient for structural diversity of stands	Quantification of structural diversity of stands	Calculation based on basal area of size classes at plot-level; mean value, 10%-quantiles etc. per year; multi-panel histograms	Index	Potentially by the analysis of national forest inventory data (https://bwi.info)	3/3/5
4. Soil-related indicators					
4.1 Soil carbon stocks	Quantification for GHG inventory reporting;	–	[t C] or [t C ha^{-1}]	National forest soil survey (Bodenzustandserhebung; FAO; IIASA; ISRIC; ISSCAS; JRC 2009); ISRIC-WISE; HWSD (Harmonized World Soil Database)	8/1/2

Table 2 (continued)

Proposed groups and indicators	Main reason for choice of indicators	Level of further differentiation	Units of indicators	Available historical data base for Germany	Implemented in models for Germany (11 models)*
4.2 Changes in soil carbon stock	Quantification of annual changes for GHG inventory reporting;	–	[t C year^{-1}] or [t C ha^{-1} year^{-1}]	National forest soil survey (Bodenzustandserhebung), National GHG Reporting (UBA 2024)	8/1/2
4.3 Soil nitrogen	Quantification of site productivity; nitrogen loads/deposition; N_2O emission	–	[t N] or [t N ha^{-1}]	Ballabio et al. 2019; emep 2018; Schaap et al. 2018; ISRIC 2017	4/0/7
4.4 Changes in soil nitrogen	Quantification of changes in site productivity; nutrient loads/nitrogen deposition; N_2O emission, nitrate leaching	–	[t N yr^{-1}] or [t N ha^{-1} year^{-1}]	Ballabio et al. 2019; emep 2018; Schaap et al. 2018; ISRIC 2017	4/0/7
5. Water indicators					
Annual water deficit (aET/pET), combined with stand basal area and usable field capacity	Quantification of annual drought stress	Calculation at plot-level; mean value, 10%-quantile etc. per year; multi-panel histograms	[mm/mm]	Can be derived from data provided by German Weather Service (DWD)	3/2/6

*Explanation of model counts: Out of 11 models (4C, EFISCEN-space, EFISCEN 4.1, FABio-Forest, FORMIND, FORMIT-M, Landscape-DNDC, LPJmL-FIT, LPJ-GUESS, Thünen Matrixmodel, WEHAM; see Supplemental Material S 2.1), x models have available output/possible but no output yet/not possible, e.g., 8/1/2; *o.b.*, over bark; *u.b.*, under bark; *aET/pET*, actual to potential evapotranspiration

Biodiversity indicators

Biodiversity is not a key focus of FGMs. Nonetheless, they can capture partial but informative proxies. Structural and compositional indicators such as tree species diversity, size distribution, habitat trees, and deadwood volume are recognized as meaningful for assessing habitat quality and resilience. Among the eleven assessed models, five provide outputs on habitat tree potential, seven on deadwood, and several allow derivation of diversity metrics such as Simpson's index (one model with available output, five with potential to calculate it but no output yet) or Gini coefficients (three models with available output, three with potential but no output yet; see Table 2). Suggested quantitative units for monitoring indicators include wood volume per species or species group (m^3), or basal area (m^2), with a differentiation by species, size, and, for deadwood, decay class and orientation where possible.

Suitable temporal resolutions for biodiversity indicators are annual or longer, reflecting the typically slow changes in forest composition and biodiversity, except under disturbance events. The proposed model-based proxies align with national and EU biodiversity policy needs (e.g., Nature Restoration Law) and complement empirical data from the NFI. While not comprehensive, they provide operational entry points for linking forest management and biodiversity outcomes. More details from expert discussions are provided in Supplementary Material S1.3.

Soil-related indicators

Forest soils provide vital ecosystem services by regulating carbon, water, and nutrient cycles. Soil carbon stocks often represent a significant portion of total forest carbon (Grüneberg et al. 2019). Currently available national soil inventories provide snapshots of soil-related indicators, albeit at low temporal resolution, highlighting the value of continuous model-based projections. Most process-based and some empirical FGMs can simulate soil carbon stocks and their dynamics with varying degrees of process simplification. These indicators have policy relevance for GHG reporting and ecosystem resilience assessments. Suggested indicator units for monitoring are t C, tons C ha^{-1}, tons C year^{-1}, and tons C ha^{-1} year^{-1}.

Compared to soil carbon aspects, the representation of soil nutrient cycles in FGMs is less consistent but could provide indicators to quantify nutrient constraints on productivity, site-specific N-loads, and the risk of N_2O emissions and nitrate leaching. C/N ratios can derive insights on decomposition, organic matter quality, and microbial activity. Currently, nitrogen dynamics is only included in a minority of the assessed FGMs, while phosphorus and biological processes are even less commonly represented. Analogous to carbon, monitoring of nutrient stocks and fluxes should use mass-based units (e.g., t ha^{-1}, t ha^{-1} year^{-1}), enabling aggregation at regional or national scales. Standardized reference soil depths are necessary for comparability. Challenges related to soil indicators discussed during expert evaluation are provided in detail in Supplementary Material S1.4.

Water indicators

Water availability and drought stress influence forest growth, productivity, mortality, C-sequestration, and species composition and are increasingly important for assessing forest resilience under climate change. Water availability depends on climatic conditions, stand properties, and soil characteristics including rooting depth, soil texture, organic matter content, and compaction. Suggested monitoring indices include the Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al. 2010) and the ratio of actual to potential evapotranspiration (annual water deficit, aET/pET), which additionally accounts for plant water processes.

Using meteorological input data from weather stations or climate models external to FGMs in combination with input on soil characteristics, a subset of process-based FGMs can simulate water balances and evapotranspiration dynamics, while the assessed empirical models currently lack this capacity. Indicators such as annual water deficit (aET/pET) or standardized drought indices can therefore be derived in some cases. Indirect proxies hinting on water stress potential include stand basal area or stand density and structure, combined with information on species composition and site-specific environmental conditions. Suggested temporal resolutions for water indicators range from growing season to annual. Further background information from the expert exchange on water-related indicators is provided in Supplementary Material S1.5.

Suitability of Forest Growth Models, indicator representation by models, and historical data availability

We identified eleven FGMs suitable for forest BE monitoring in Germany (see Supplementary Material S2.1), including eight process-based models (4C, EFISCEN-space, EFISCEN 4.1, FORMIND, FORMIT-M, LPJmL-FIT, LPJ-GUESS, LandscapeDNDC) and three empirical ones (FABio-Forest, WEHAM, Thuenen matrix model). Most models simulate forests at high spatial resolution (stand or tree level), except the Thuenen matrix model, which aggregates National Forest Inventory (NFI) data. The degree of indicator representation and approaches how models cover the selected indicators vary considerably.

All FGMs provide robust representation of wood extraction and forest growth, supporting indicators such as wood harvesting, net stock change, and biomass carbon pools (see Table 2). Most models simulate detailed biomass compartments (stems, branches, bark, leaves), with deadwood outputs varying among models. Salvage logging is explicitly modeled by five FGMs. Historical data for these indicators are available from established databases (Jochem et al. 2023), Holzeinschlagsstatistik (Code 41,261), the NFI (https://bwi.info), and the German National GHG Inventory (UBA 2025; Table 2).

Carbon indicators, central to GHG accounting, are well covered and scalable to national levels. Temporal resolution differs across models, affecting comparability for long-term projections or detailed analyses. Where possible, models with sub-annual or lower-than-annual temporal resolution should aggregate or interpolate their results to annual values, as required for integrated BE monitoring.

In contrast, biodiversity indicators are less comprehensively represented. Only five FGMs provide output for the volume of broadleaf habitat trees (DBH > 60 cm), and seven cover deadwood volume, while advanced metrics (e.g., Simpson's diversity index, Gini coefficient) are seldom directly available. Historical data exist through the NFI but lack annual resolution.

All process-based FGMs simulate soil C-stocks, while empirical models provide limited coverage. Only four process-based FGMs simulate soil nitrogen dynamics, with varying detail. National soil carbon inventories occur approximately every 15 years (National forest soil survey, Thünen-Institut 2024), compensated partly by models such as Yasso15 (Viskari et al. 2020) used for the German National GHG Inventory (UBA 2023).

Process-based FGMs simulating carbon assimilation and water balance based on climatic and soil inputs can provide water-related indicators. Three process-based FGMs directly supply seasonal or annual evaporative index (i.e., aET/pET), two more can potentially derive it. The empirical FGMs lack soil water dynamics simulation and cannot provide this indicator. Accurate modeling of soil water dynamics—including infiltration, percolation, plant water uptake, and evaporation—ideally requires sub-daily or at least daily time steps. For monitoring, appropriate aggregation periods—annual, growing season, or critical months (e.g., June–August for drought/mortality analysis)—depend on specific objectives.

Overall, FGMs effectively represent wood supply and carbon pools, yet significant gaps remain for comprehensive biodiversity, soil nutrient, and water indicators.

Discussion and conclusions

Applicability and scope of the conceptual framework

The opportunities and challenges of the transition to a circular BE require a robust monitoring framework to ensure sustainable development (Hagemann et al. 2016; Thrän

2022; Zeug et al. 2021). Our study addresses this need by proposing a model-based monitoring framework for the German forest sector that aims for a quantitative assessment of ecosystem conditions with ecological indicators aligned to national and international bioeconomy strategies. In addition, the proposed conceptual framework should be applicable to other countries with available FGMs capable of providing relevant BE monitoring indicators. However, specific indicators may require adjustment to reflect the unique policy objectives, ecological contexts, data availability, and capabilities of FGMs in each country.

The framework is deliberately focused on forest ecosystem states, emphasizing indicators related to wood production, carbon, biodiversity, soil, and water. While this ecological orientation ensures strong compatibility with forest growth models (FGMs) and allows projection of climate adaptation and mitigation impacts through model scenarios, corresponding socio-economic aspects such as trade flows, employment, and market dynamics cannot be represented within the current system boundaries. Similarly, allocation of harvested wood products to material or energy use lies largely outside the scope of FGMs. However, model outputs generated by FGMs can serve as valuable input for downstream assessments, including lifecycle analysis (LCA) and linkage to the broader BE value chain (e.g., D'Amato et al. 2020).

Given this scope, the framework is most suited to informing policy and strategic forestry decisions that address broad objectives—such as sustainable harvesting regulations, climate mitigation targets under the LULUCF sector, or biodiversity conservation—but less useful for detailed operational management. Moreover, evaluating policies shaped primarily by socio-economic mechanisms requires integration with additional models and datasets beyond the ecological focus of FGMs.

This limitation opens possibilities for complementing our approach with broader monitoring instruments that capture economic and governance dimensions. Previous work highlights the utility of LCA, monetary valuation of ecosystem services, and governance indicators in assessing the wider sustainability of the bioeconomy (Bouma and van Beukering 2015; Koetse et al. 2015; Whitehead et al. 2008). Incorporating these perspectives would enrich the assessment of trade-offs and synergies between ecological sustainability, economic performance, and societal well-being.

In sum, while the proposed framework does not comprehensively cover the entire bioeconomy, it provides a structured and model-based foundation for monitoring ecological dimensions. Strengthening interdisciplinary linkages and integrating complementary approaches will be key to addressing socio-economic gaps and ensuring the long-term policy relevance of forest-based BE-monitoring.

Representation of indicator groups in Forest Growth Models, evaluation against selection criteria, and potential applications

We designed our monitoring framework to provide a model-based assessment of the forest-based bioeconomy (BE) in Germany. Indicator selection was guided by their policy relevance, data availability, measurability, and compatibility with forest growth models (FGMs), as outlined in the "Criteria for selecting suitable indicators for forest-based bioeconomy monitoring" section. FGMs necessarily simplify complex ecosystem processes. Their outputs should therefore be interpreted with an understanding of underlying assumptions and uncertainties, supported by model comparisons, ensemble simulations, and rigorous uncertainty analyses. Robust application also depends on high-quality empirical data for model initialization, calibration, and validation. Below, we discuss how well FGMs represent indicator groups, evaluate indicators against selection criteria, and outline potential applications of each indicator group.

Economy-related indicators

As highlighted in previous sections, all analyzed FGMs are principally oriented towards wood production indicators, providing robust simulations for sustainable yield management, trend detection, and policy support. These indicators, including harvest volume and standing stock stratified by species and dimensions, align with international reporting standards and the ecological focus of the presented monitoring framework (see also (Barreiro et al. 2016; Blujdea et al. 2021). Importantly, FGMs advance beyond traditional yield tables by capturing the dynamic effects of mixed and uneven-aged stands and climate variability, enhancing the accuracy of projections in scenarios such as those underpinning Germany's "Climate-adapted Forest Management" compensation schemes.

The strong compatibility with empirical forest inventory data underpins their value for long-term policy evaluation, but also delineates the boundaries of this approach, which currently excludes broader economic indicators like value-added generation, employment effects, and market mechanisms—a limitation that becomes evident by comparison to the studies of Jose et al. (2023) and Kalogiannidis et al. (2022). Closing this gap requires integration with economic and social datasets and modeling approaches outside the scope of ecological FGMs. Thus, the effective application of economy-related indicators represents both a strength and a constraint of FGM-based bioeconomy monitoring.

Overall, while the current scope provides actionable, measurable indicators crucial for national and EU sustainability strategies, existing FGMs should be complemented by economic models and interdisciplinary tools to capture the full spectrum of the forest-based bioeconomy (Bouma and van Beukering 2015; Koetse et al. 2015).

Carbon indicators

Carbon and biomass indicators are core variables in FGMs, essential for modeling forest growth and ecosystem dynamics (Barreiro et al. 2016; Blujdea et al. 2021; Zald et al. 2016). They are consistently represented, though models vary in spatial and temporal resolution, species coverage, and biomass compartment detail. This broad representation enables inter-model comparison, supports uncertainty assessment, and builds confidence where results converge.

Carbon indicators are central to national and EU greenhouse gas (GHG) accounting and reporting. In Germany, reporting under the UNFCCC relies on the National Forest Inventory (NFI), yet its decadal cycle leaves gaps after the most recent 2022 survey. FGMs can bridge these gaps by projecting annual forest growth and carbon stock changes based on emerging climate data series, supporting timely and more accurate forest GHG reporting aligned with the EU LULUCF Regulation (EU 2018) and national climate protection targets.

Model-derived carbon indicators also meet SMART criteria: they are specific (biomass pools), measurable (e.g., t C ha^{-1} $year^{-1}$), and directly linked to inventories and reporting systems. Data availability is strong, models capture key pools such as stems, branches, and deadwood, and outputs are well suited for scenario analysis. Their policy relevance is high, as they feed directly into LULUCF and UNFCCC instruments. A notable limitation is the omission of harvested wood products (HWP) and downstream life-cycle impacts, which remain outside the scope of most FGMs and require complementary approaches for a full carbon balance.

Biodiversity indicators

Biodiversity spans multiple spatial scales (alpha, beta, gamma diversity) and taxonomic, genetic, and functional dimensions, which interact with geodiversity (Read et al. 2020; Scholes et al. 2008). Identifying robust and policy-relevant indicators at national scales therefore remains challenging (Geijzendorffer et al. 2016; Navarro et al. 2017). Rare forest structures support threatened species and unique functions (Leitão et al. 2016; Mouillot et al. 2013), while higher structural and functional diversity strengthens ecosystem resilience under stress through complementarity and facilitation (Niklaus et al. 2017; Trogisch et al. 2021). Germany's shift from Norway spruce monocultures to mixed-species forests exemplifies synergies between climate adaptation, carbon storage, and biodiversity protection (Pörtner et al. 2021).

FGMs face limitations in representing complex functional diversity, fungal, faunal, and understory communities, and landscape connectivity due to simplified ecological processes and model resolutions (Blanco and Lo 2023; Lexer et al. 2000; Leidinger et al. 2021; Puumalainen 2001). However, measurable proxy indicators compatible with FGMs, such as deadwood volume, vertical heterogeneity, tree species composition, and management intensity, are recognized practical biodiversity indicators in European forestry, provide actionable stand-level insights, are available from inventories, and are already established in monitoring frameworks (Feld et al. 2010; Oettel and Lapin 2021; Read et al. 2020; Scholes et al. 2008; Ćosović et al. 2020). Large broadleaf tree abundance (e.g., diameter > 60 cm) can serve as a proxy indicator for rare microhabitats in German forests (Paillet et al. 2019; Spînu et al. 2022), and associations between tree species composition and non-woody taxa allow for indirect assessment of broader ecosystem diversity (Schneider et al. 2021).

The chosen biodiversity indicators can support goals of the EU Biodiversity Strategy and EU Green Deal targets (EC 2024), which require systematic reporting on ecosystem condition and restoration progress. They meet SMART principles insofar as they are specific, measurable, and operational for monitoring and modeling, providing quantifiable information relevant for restoration efforts and identification of synergies with climate protection and adaptation policy decisions. Yet, current proxies only partially cover the ambitions of advanced biodiversity strategies. Future frameworks will need integration of complementary datasets, cross-scale monitoring, and novel methods to close existing gaps.

Soil indicators

Soil modules in FGMs can consistently represent indicators for carbon pools and fluxes. Model-based indicators are measurable, reported in national inventories, and directly relevant for GHG accounting. In Germany, the Yasso model is already applied to estimate carbon emissions and removals from mineral forest soils (Viskari et al. 2020; UBA 2025), but soil carbon indicators are also central to emerging policy frameworks, including the proposed EU Soil Monitoring Law and the revised LULUCF Regulation from 2023, which mandate higher-tier reporting. By providing annual projections of soil carbon, FGMs can move beyond default emission factors.

However, FGMs simplify soil process representation for feasibility, which can cause major sources of uncertainty, for example in flux assessments (Vereecken et al. 2016). Moreover, pronounced spatial heterogeneity and uncertainties in underlying databases used for model initializations, which often require interpolation for continuous coverage, can further obscure climate impact signals (Lark and Bolam 1997; Nachtergaele et al. 2012; Folberth et al. 2016).

Nutrient dynamics, particularly nitrogen, influence tree growth, decomposition, nitrate leaching, and N_2O emissions. Rising deposition since the nineteenth century and synthetic fertilizer use since 1913 have intensified N-related risks (Lamarque et al. 2013; Pretzsch et al. 2014). Monitoring soil

N status thus is central to the critical loads concept (Aazem et al. 2022), and N-cycling is linked to key ecosystem services (Costanza et al. 1997; Kooch et al. 2022). Yet, nutrient cycling is only partially represented in FGMs, with limited estimates of productivity effects or leaching risk.

Phosphorus dynamics, soil biological activity, and soil organism diversity receive even less attention and remain largely outside model scope. Consequently, soil indicators only partially fulfill SMART criteria: carbon pools are specific and measurable, whereas nutrient and biological dimensions are incomplete. Data availability and resolution are sufficient for carbon but remain weak for N and P. Thus, while FGMs provide actionable, policy-relevant insights for soil carbon, the integration of nutrient and biological indicators lags behind, constraining their use for monitoring of soils as multifunctional, biodiversity-supporting systems.

Water indicators

Climate change increases the need for water indicators, exemplified by the widespread Norway spruce dieback during the 2018–2022 droughts (Knapp et al. 2024; Anders et al. 2024). Water availability is a key predictor of drought-induced mortality and growth decline, with implications for carbon stocks, harvest potential, and linkages to carbon and nutrient cycling. Accordingly, water indicators are increasingly relevant to inform the development of adaptation and resilience strategies, such as forest conversion to more diverse stands, which is expected to generate co-benefits for water regulation (Obladen et al. 2021). Additional management interventions such as adjusted thinning can mitigate drought stress by reducing stand density while maintaining canopy microclimate (Bradford et al. 2022; Meyer et al. 2022).

Water indicators are challenging, as high temporal variability makes drought frequency and duration often more critical than integrated annual water deficits (Lazoglou et al. 2024). Aggregation to national or annual scales tends to obscure such variability and complicates interpretation. Moreover, soil properties, including depth, porosity, texture, and organic matter content, strongly influence water availability (Minasny et al. 2021; Nemes and Rawls 2004; Saxton and Rawls 2006), and uncertainties in soil datasets directly affect indicator reliability (Bagnall et al. 2022). Process-based models can partially capture soil-plant-atmosphere interactions (Blyth et al. 2011; Fatichi et al. 2012) when explicitly representing transpiration, evaporation, percolation, and runoff (Bonan et al. 2014). Empirical FGMs currently lack water indicator representations. A particular difficulty remains the estimation of actual evapotranspiration (aET), as model outputs often depend on site-specific conditions.

Against SMART and policy criteria, water indicators align well with priorities on drought and adaptation. Specific indices, such as aET/pET ratios, are interpretable where data permit. However, quantifiability is limited due to model representation and data constraints. Actionability is high in targeted applications, such as drought risk assessment or management planning, but diminishes at broader scales due to temporal and spatial variability.

Research and development needs

Advancing forest growth models (FGMs) for bioeconomy monitoring requires interdisciplinary development and modular integration with complementary ecological models. Current FGMs are primarily designed for tree- and stand-level dynamics, with limited coverage of non-woody plants, fungi, fauna, and functional diversity. Coupling FGMs with models such as BERN and ForestDNDC, as demonstrated by Nagel et al. (2010), can broaden biodiversity and biogeochemical representation. Integrating simulations of mycorrhizal contributions to C- and N-cycling (Meyer et al., 2010) and ectomycorrhizal roles in P-cycling (Bortier et al. 2018; Nakhavali et al. 2022; Thum et al. 2019) provides promising modular pathways to improve functional indicator coverage.

Progress in soil indicator representation is contingent on incorporating detailed nutrient process representations, including N-cycling and in particular P-cycling, which remains simplified or absent in many models. Incorporation of soil biological activity indicators, encompassing faunal and microbial interactions (Komarov et al. 2017), will require more frequent, spatially resolved measurements to develop model representations of these aspects.

Water indicators, especially drought-related metrics and actual-to-potential evapotranspiration (aET/pET), are increasingly critical under climate change (Knapp et al. 2024; Anders et al. 2024; Fischer et al. 2025). Empirical FGMs not representing water indicators should be developed towards representation of water aspects, and the provision of high-resolution water indicators in process-based FGMs should be standardized to facilitate inter-model comparability. Priority research should also target indicators of forest resilience and adaptation, integrating climate extremes, legacy effects of past events, or sensitive phenological stages (Zhang et al. 2025).

Technological advances, from UAV/LIDAR remote sensing to big data analytics and AI/machine learning, can improve model calibration, detect new patterns, and integrate large heterogeneous datasets to enhance predictive capabilities of FGMs (Minunno et al. 2025). Incorporation of such approaches will allow FGMs to evolve with ongoing advances in Earth observation and computational capacities. Further cross-cutting needs also include standardization of monitoring indicators across FGMs to enable comparability and synthesis, since no single model can cover all indicators and effort joining will be beneficial. Regular calibration and validation against empirical data should be institutionalized, using forest inventory updates, new soil surveys, and remote sensing to continually refine model initialization and parameterization.

Finally, the societal relevance of indicator-based monitoring rests on stakeholder participation and transparency. Feedback from forest owners, policymakers, scientists, and the public into monitoring and management processes is essential, especially for translating large-scale monitoring results into locally relevant recommendations that address differing site conditions and vulnerabilities. In this context, the recreational value of forests and regulating services such as air quality improvement, currently not represented by FGM-based indicators, are legitimate components of the forest-based BE, broadening its societal legitimacy and relevance (TEEB DE 2016). Establishing a platform for regular updates and transparent communication of FGM-based monitoring indicators will be central to ensuring acceptance and long-term impact.

In sum, advancing research and development for an indicator-based forest BE monitoring framework will benefit from interdisciplinary model coupling, better soil and water process representation, standardized outputs, improved data infrastructures, integration of emerging technologies, and continuous stakeholder participation. Given such efforts, FGMs can underpin a robust, adaptive monitoring system responsive to future policy and climate challenges.

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Declarations

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