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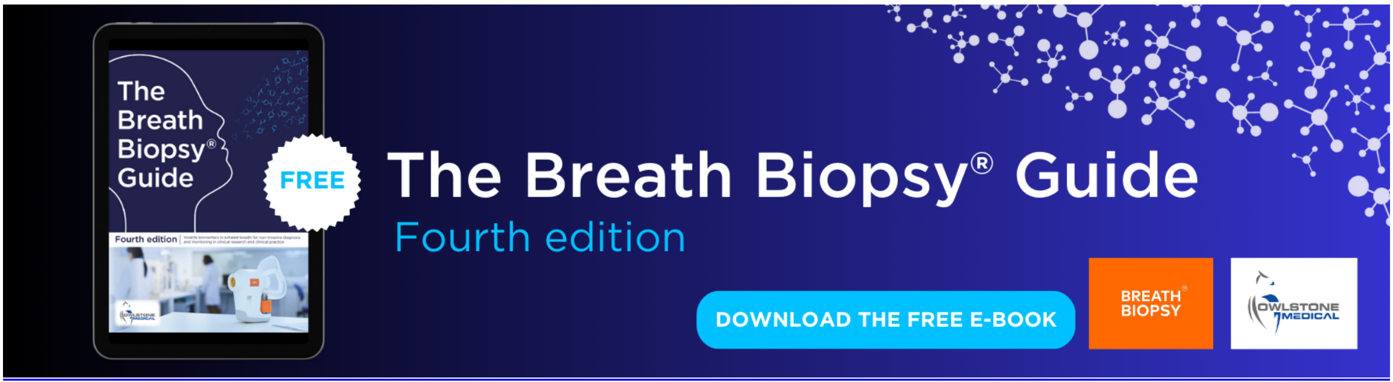

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TOPICAL REVIEW

Scoping review of carbon pricing systems in forest sector models

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Abstract

Forest-based measures to mitigate climate change are increasingly being acknowledged as options for meeting the global targets of the Paris Agreement. In this context, carbon pricing systems may foster carbon sequestration in forests and harvested wood products. Forest sector models (FSMs) are established simulation instruments for assessing the possible impacts of carbon pricing systems on forest-based mitigation potentials, forestry, and forest product markets. However, the characteristics of the implemented carbon pricing systems differ among these assessment tools. To map and evaluate this variability, we conducted a scoping review of carbon pricing systems in FSMs, following the RepOrting standards for Systematic Evidence Syntheses (ROSES). Drawing on 49 modeling studies, including 351 scenarios, we provide an overview of the state-of-the-art methods for implementing carbon pricing systems in FSMs, discuss technical aspects and uncertainties, and identify possible future research trends. Our results reveal similarities in the types of carbon pricing systems and differences regarding the system boundaries and carbon price-related characteristics of the implemented systems. Geographically, since most studies target either the Northern Hemisphere or the world, we found a lack of in-depth assessments in tropical and boreal countries. Further, additionality, permanence, and leakage of forest-related mitigation measures are addressed using different approaches with varying practicability. Mostly, the observed heterogeneity in the implemented carbon pricing systems can be related to the attributes of pre-existing modeling frameworks. We systematically collect and highlight tools to analyze the role of forest-based mitigation measures in the context of climate commitments and outline carbon pricing policies that could support their implementation. For future studies, the assessment of policy mixes involving carbon pricing and the inclusion of climate change effects on forest growth appear to be crucial for delivering more robust projections of forest-based mitigation potentials and, hence, for increasing the reliability of the forest-based contribution to climate mitigation actions.

1. Introduction

Human-induced climate change is increasingly shaping global climate conditions. Weather and climate extremes are causing widespread damage to nature and people, which is likely to intensify in the future (IPCC 2023).

Through carbon uptake by photosynthesis, forests are primary elements in the global carbon cycle, significantly influencing the removal of CO_2 on land. About 25% of net anthropogenic greenhouse gas (GHG) emissions are attributed to the land sector, with half of this ascribed to land use, land-use change activities, and forestry (LULUCF) (Canadell *et al* 2023). While deforestation is a main driver of the CO_2 emissions from LULUCF, net removals from forest land counterbalance these effects on a global scale (Friedlingstein *et al* 2020, Tubiello *et al* 2021). Since sound forest management can reduce GHG emissions and enhance carbon removals, the forest sector is decisive in generating negative emissions (Nabuurs *et al* 2023).

Consequently, forest-based mitigation measures as part of LULUCF mitigation options are increasingly acknowledged as crucial for meeting the Paris Agreement targets and, thus, for limiting global warming to well below 2 °C above pre-industrial levels (Rogelj *et al* 2018, Roe *et al* 2019).

Forest-based measures for climate change mitigation include afforestation, reforestation, improved forest management, avoided deforestation, and forest conservation, as well as product storage and substitution. Particularly in the first half of the 21st century, these forest-based mitigation strategies might be critical components of global abatement portfolios (Nabuurs *et al* 2023) due to their low abatement costs compared to other abatement options (Richards and Stokes 2004, van Kooten *et al* 2004, Griscom *et al* 2017). Climate policies that incentivize cost-efficient mitigation options are likely to encourage forest-based mitigation strategies. Grassi *et al* (2017) estimate that LULUCF-related measures primarily avoided deforestation and forest management could represent approximately 25% of the global emission reductions required by the Nationally Determined Contributions (NDCs). However, there is still uncertainty in the NDCs regarding the specific LULUCF measures necessary for unlocking the described climate commitments (Griscom *et al* 2017, Roe *et al* 2019). Inadequate mitigation investments, especially regarding forest-based measures, could further compromise achieving the NDCs (Roe *et al* 2019, Kreibiehl *et al* 2023).

Here, economic incentives in the form of carbon pricing systems setting an explicit monetary value on GHG emissions and removals (World Bank 2020) might help close the investment gap (Kreibiehl *et al* 2023). Thus far, such economic incentives targeting forest-based climate change mitigation measures are either implemented through independent or governmental carbon crediting mechanisms (e.g. the Verified Carbon Standard, Climate Action Reserve, and California's Compliance Offset Program, to mention a few) or in carbon pricing initiatives (e.g. the New Zealand Emission Trading System). For a comprehensive overview of the economic incentives for forest-based carbon sequestration, see World Bank (2020).

Two main approaches for pricing carbon emissions exist: On a mandatory basis, governments can enact carbon pricing systems by either defining a limit on carbon emissions and allowing the trade of carbon credits to comply with the limit (e.g. an emission trading system (ETS)) or setting a price for carbon emissions (e.g. a carbon tax). In an ETS, prices for carbon emissions are determined through the demand and supply of carbon credits. For voluntarily implemented emissions reduction or removal activities, tradable credits can be issued through carbon crediting mechanisms. Emitters can purchase these credits to comply with their mandatory emission requirements under single carbon pricing systems or to offset emissions from unregulated activities on a voluntary basis (World Bank 2021).

Incorporating LULUCF mitigation in the United Nations Framework Convention on Climate Change (UNFCCC) has been challenging (Schlamadinger *et al* 2007). Despite their low abatement costs, forest-based mitigation measures play a minor role under the Kyoto Protocol (UNFCCC 2002). Concerns relating to additionality, permanence, and leakage are the main barriers to recognizing forest-based mitigation measures (Gren and Aklilu 2016). In addition, there is a large degree of uncertainty due to the difficulty of tracking forest growth and related carbon removals and emissions, which are shaped by stochastic and environmental factors. These factors are heterogeneous and can differ between regions, making generalized assumptions difficult. The uncertainty surrounding forest growth is further compounded by the growing influence of climate change (Gren and Aklilu 2016, Baker *et al* 2019). Similar uncertainty issues hold for monitoring carbon flows in harvested wood products (HWPs) (Bates *et al* 2017). Because of these concerns, forest-based climate mitigation measures are mainly valued through voluntary crediting mechanisms (World Bank 2020). Within voluntary carbon markets, they accounted for 40% of the offset volume sold between 2019 and 2021 (Forest Trends' Ecosystem Marketplace 2021, 2022) and thus are a decisive source of carbon credits.

With an emphasis on low abatement costs relative to other mitigation options, forest-based mitigation measures and carbon pricing systems have received considerable attention in the forest economic literature. Reviewing this literature in a non-systematic manner, Wong and Alavalapati (2002) differentiate three levels of impact assessment: stand-level, sectoral, and economy-wide.

At the forest stand level, numerous studies have evaluated the impact of carbon pricing systems under a broad range of biological and economic conditions using forest management models. Based on Hartman's seminal work (Hartman 1976), these studies analyze the impact of carbon pricing systems on forest management practices, but omit potential feedback effects on timber prices (e.g. van Kooten *et al* 1995).

To capture potential market-driven feedback effects, sectoral and economy-wide assessments integrate carbon pricing systems in model frameworks with endogenous price calculations.

Economy-wide assessments based on computable general equilibrium (CGE) models capture cross-sectoral impacts and provide an overall picture of the effectiveness of carbon pricing systems. However, representing the forest sector in these CGE models tends to be aggregated and simplified (Hertel *et al* 2008, Sohngen *et al* 2008b).

Combining the projection of market dynamics with a detailed representation of the forest sector, forest sector models (FSMs) cover a group of simulation tools that have been developed since the 1980s to assess the impact of LULUCF-related policies on the development of the forestry and wood products markets (Rivière *et al* 2020). FSMs are models that 'take into account both forestry and forestry industries and the interactions between these two activities' (Solberg 1986, p 420). In line with Rivière and Caurla (2020, p 522), FSMs are defined as 'partial equilibrium, mathematical models enabling the [endogenous] determination of product prices, supply, and demand quantities' by maximizing the economic welfare of the forest sector (Latta *et al* 2013). Given the increasing relevance of multifunctionality in forest-related policy, FSM-based research increasingly addresses non-timber services, including carbon sequestration in forests and HWP (Rivière *et al* 2020). To inform policy about the forest-based mitigation potential, FSMs are used to assess the impact of implemented or planned carbon pricing policies (called hereafter carbon pricing systems) in the forest sector by conducting 'what-if' analyses of possible policy options and strategies.

Differences between the individual FSM frameworks can be seen, e.g. in the formulation of the objective function, the representation of sector components, and the geographical and temporal scope (Latta *et al* 2013, Sjølie *et al* 2015, Rivière *et al* 2020). Following Latta *et al* (2013), FSMs can be categorized into recursive and intertemporal models based on their optimization characteristics.

Intertemporal FSMs simultaneously maximize the economic welfare over all modeled periods, assuming that forest owners have perfect foresight of all upcoming economic changes. They represent forestry activities and timber supply in greater detail by scaling up proven methods of harvest scheduling problems. As a result, intertemporal FSMs can make longer projections relative to recursive models (Sjølie *et al* 2015). Yet, forest data requirements and computational capacities tend to limit either the geographical scope or the number of represented HWP in intertemporal FSMs (Latta *et al* 2013, Sjølie *et al* 2015).

By contrast, recursive FSMs maximize the economic welfare for each modeled period. In this case, forest owners are considered to be myopic concerning future economic development (Latta *et al* 2013). Although less detailed, forestry activities are commonly represented in recursive FSMs via econometric approaches based on historical data, ensuring coherence with trends in official statistics. Moreover, recursive FSMs tend to include more HWP for larger geographical areas compared to intertemporal models. (Sjølie *et al* 2015).

These differences have shaped the applications of both types of FSMs. While recursive models seem to be more suitable for short-to-medium-term market analyses on larger geographical scales, FSMs using intertemporal optimization appear to be better equipped to handle research questions focusing on long-term forestry issues (Latta *et al* 2013, Sjølie *et al* 2015, Rivière *et al* 2020). Due to this heterogeneity across FSM frameworks, approaches to integrating carbon pricing systems into FSMs might be subject to differences that could, in turn, influence the projection of carbon mitigation potentials.

Generating crucial amounts of negative emissions, the development of LULUCF activities, and, in particular, trends in the forest sector will have far-reaching implications for achieving global climate mitigation goals (Rogelj *et al* 2018, Roe *et al* 2019). Beyond GHG emission aspects, forests provide other important ecosystem services, including water and nutrient regulation, biodiversity protection, provision of renewable resources, and local climate regulation (Nabuurs *et al* 2023). Having a sound knowledge of forest-based mitigation potential and how it might be influenced by carbon pricing policies would thus appear to be crucial to the success of climate change mitigation.

Previous review articles analyzing FSM-based studies (e.g Latta *et al* 2013, Rivière *et al* 2020) commonly provide a general overview of research applications and trends rather than a deep insight into a specific topic or modeling approach. Unlike past reviews, this systematic scoping review focuses on different applications of carbon pricing systems in FSMs. The objective of this study is to map state-of-the-art approaches for integrating carbon pricing systems into FSM frameworks. To fulfill this objective, we address the following research questions:

(1) How are carbon pricing systems integrated into FSM frameworks to analyze their impact on forestry and forest product markets?
(2) Which spatial and temporal scopes are covered by the reviewed studies?
(3) What technical differences and similarities can be detected between these approaches?
(4) How do the reviewed FSMs address issues regarding additionality, permanence, and leakage effects when implementing carbon pricing systems?

This review aims to systematically capture the current state of research on the analysis of carbon pricing policies in the forest sector. For this, we compare the technical aspects and scopes of implementing carbon pricing policies into FSMs and document how methods have changed over time. In addition, we identify research gaps, outline related uncertainties, and pinpoint possible research trends. We also delve into the potential development of carbon pricing systems in the future. In this way, this scoping review provides a solid basis for assessing the impact of carbon pricing policies on the forestry and wood products markets and their contribution to the LULUCF mitigation potential. The paper highlights methodological tools for analyzing the role of forest-based mitigation options in the context of the NDCs and outlines carbon pricing policies that could support their implementation.

2. Method

Systematic scoping reviews refer to a research synthesis method that involves collecting, describing, and mapping the available evidence base of a particular research topic. Thereby, scoping reviews provide a comprehensive overview of the targeted research topic and act as a preliminary step in determining whether further analyses (e.g. systematic literature reviews or meta-analyses) should be conducted (Munn *et al* 2018). This scoping review was formalized following the RepOrting standards for Systematic Evidence Syntheses (ROSES) (Haddaway *et al* 2018). Based on ROSES, we used a specific protocol that predefines the objectives of the scoping review and provides a detailed description of the research strategy, including the different steps of the analysis. This enhances transparency, ensures reproducibility, and prevents systematic omissions and biases in literature selection (Munn *et al* 2018).

In line with ROSES, we structured the review process into three parts: (1) the definition of database-specific search strings; (2) the screening process in which the eligibility of selected studies was individually verified according to predefined criteria; and, finally, (3) the extraction and compilation of qualitative and quantitative data. These steps are described below.

2.1. Definition of search strings, scoping boundaries, and data collection

We collected data from two complementary literature databases: Scopus and Web of Science. These databases are freely accessible and cover the most relevant journals in forest economics and its connected research fields. A key element of the research strategy for any literature review is the search string used to exploit the content of the databases. To develop the search string for the present scoping review, we carried out a non-systematic literature research on ResearchGate and Google Scholar and used two literature reviews conducted by Latta *et al* (2013) and Rivière *et al* (2020) to compile the benchmark list of relevant articles on our research subject[3]. Based on the benchmark list, we then gathered search terms and drafted a search string for each literature database (table 1). Encouraged by Bramer *et al* (2018), we applied the thesaurus tool of the literature database GEOBASE[4] to identify related search terms. Through a stepwise inclusion of possible synonyms, we iteratively developed the search string, considering the balance between its specificity and sensitivity. The final search string was able to find 90% of the articles recorded on the benchmark list. Some relevant articles on the benchmark list were not captured by the final search string because the implemented carbon pricing systems were not sufficiently specified in the titles and abstracts of the respective articles. The best balanced search strings considering specificity and sensitivity are listed in table 1.

Since a critical appraisal of the selected articles was not part of this study, we only included peer-reviewed articles in English to ensure scientific quality. Furthermore, we restricted our search to articles published after 1990 since significant political actions to decrease global GHG emissions were initiated during that period, including the Rio Earth Summit in 1992 and the resulting Kyoto Protocol in 1997. An additional argument for this temporal restriction is that after the emergence of the first FSM in the 1980s, numerous extensions of these models to non-timber commodities and carbon sequestration occurred after 1990 (Rivière and Caurla 2020, Rivière *et al* 2020). As defined by the research protocol, the automatic search for articles was complemented by screening the reference lists of identified articles for additional relevant literature. Any articles omitted during the initial search were manually included in the scoping review and annotated accordingly.

2.2. Screening process (scoping boundaries and eligibility criteria)

The objective of the screening process was to identify relevant articles for the analysis. Following ROSES, the screening process was structured into two steps.

In the first step, after removing duplicates among the extracted articles from both databases, we screened the titles, abstracts, and keywords of the retrieved articles for eligibility. We evaluated the relevance of the retrieved articles based on eligibility criteria, targeting both the study metadata (e.g. only peer-reviewed and English articles published after 1990) and study content (e.g. relevance to the research questions). The content-related criteria were twofold. First, the study had to use an FSM in its analysis. Second, carbon pricing systems, defined as 'initiatives that set an explicit price on GHG emissions expressed in a monetary unit per ton of carbon dioxide equivalent (tCO_2e)' (World Bank 2020, p 16),

[3] A complete overview of the benchmark list is provided in the supplementary materials (table S1).

[4] The GEOBASE database is integrated into the search platform Engineering Village which covers multiple research areas, including forest economics. The database was accessed on 15 March 2021 (www.elsevier.com/solutions/engineering-village).

Table 1. Database-specific search strings used for Scopus and Web of Science[5].

Literature database	Search string
Scopus	TITLE-ABS-KEY (wood* OR lumber* OR timber* OR forest*) AND TITLE-ABS-KEY (‘carbon pric*’ OR ‘carbon market*’ OR ‘carbon tax*’ OR ‘*emission* trad*’ OR ‘*emission* market*’ OR ‘*emission* tax*’ OR ‘*emission* permit*’ OR ‘carbon trad*’ OR ‘carbon rent*’ OR ‘*offset pay*’ OR ‘pay* for carbon’ OR ‘carbon revenue*’ OR ‘carbon* credit*’ OR ‘ETS’ OR ‘cap and trade*’ OR ‘CO2* pric*’ OR ‘CO2* tax*’ OR ‘CO2* trad*’ OR ‘CO2* credit*’ OR ‘carbon* incentive*’ OR ‘carbon sequestration incentive*’ OR ‘carbon subsid*’ OR ‘carbon reward*’) AND (PUBYEAR > 1989)
Web of Science	TS = (wood* OR lumber* OR timber* OR forest*) AND TS = (‘carbon pric*’ OR ‘carbon market*’ OR ‘carbon tax*’ OR ‘*emission* trad*’ OR ‘*emission* market*’ OR ‘*emission* tax*’ OR ‘*emission* permit*’ OR ‘carbon trad*’ OR ‘carbon rent*’ OR ‘*offset pay*’ OR ‘pay* for carbon’ OR ‘carbon revenue*’ OR ‘carbon* credit*’ OR ‘ETS’ OR ‘cap and trade*’ OR ‘CO2* pric*’ OR ‘CO2* tax*’ OR ‘CO2* trad*’ OR ‘CO2* credit*’ OR “carbon* incentive*“ OR “carbon sequestration incentive*“ OR ‘carbon subsid*’ OR ‘carbon reward*’) AND PY = (1989–2021)

had to be included in the objective function of the FSM.

We excluded articles that did not deal with the implementation of carbon pricing systems in FSMs. We further excluded articles without a transparent description of the technical implementation of a carbon pricing system. Moreover, we did not include studies that exogenously mimicked the assumed effects of implementing a carbon pricing system, such as timber harvest reductions. Studies estimating the carbon prices necessary to achieve predefined carbon sequestration targets in the forest sector through the implementation of optimization boundaries were also excluded as they do not comply with the chosen definition of carbon pricing systems.

In the second step, we reviewed the full texts of articles selected during the first screening and assessed their final eligibility status. Articles with an unclear eligibility status during the first screening were included in the full-text screening. At both stages of the screening process, the retrieved articles were randomly distributed among the reviewers. After each screening step, the reviewers cross-checked the eligibility status of the retrieved articles to handle possible inconsistencies and errors. To ensure transparency, we saved article-specific information about the reasons for inclusion or exclusion. We utilized Citavi to manage the literature during the screening process.

The standardized literature research in both databases yielded 2582 records. We added 20 records from the reference lists of included records. After removing duplicates, 1755 records were screened based on titles, abstracts, and keywords. Of these, we included 253 records for a full-text screening. After applying the predefined eligibility criteria, we excluded 81% of these records. Of these excluded articles, 81% applied forest management models rather than FSMs, 9% involved techno-economic analyses, 5% did not use a model-based approach, and 4% provided incomplete information regarding the implemented carbon pricing system. In the end, we included 49 eligible records in our in-depth analysis. In these 49 articles, we identified 351 distinct scenarios and compiled them in sets with homogenous characteristics. These include carbon pools considered, carbon price pathways used, and the type of carbon price system applied. Figure 1 provides an overview of the results of the searching and screening process.

2.3. Data extraction, coding and transformation

After identifying the eligible articles, we extracted and coded relevant data using a predefined extraction matrix. We iteratively adapted the extraction matrix with a random subset of the articles until we agreed upon each variable in the matrix. We discussed the different entries until a unanimous formulation was obtained. In this way, we targeted an increased reproducibility and reliability of the extraction and encoding processes.

We grouped the extracted data into six categories (table 2). In addition to article metadata encompassing bibliographic information, we extracted data regarding the temporal and spatial scope. Data related to the study design, the modeling framework, the implemented carbon pricing system, valued emission sinks and sources, and carbon price pathways were separately collected. We also gathered information on approaches used to address issues related to additionality, permanence, and carbon leakage of forest-based mitigation measures. Moreover, we mapped acknowledged research gaps to highlight potential future research trends. Since most reviewed articles build upon previous modeling efforts, the technical features of the applied models are commonly not described in detail in the reviewed articles. To provide a technical overview of the carbon pricing

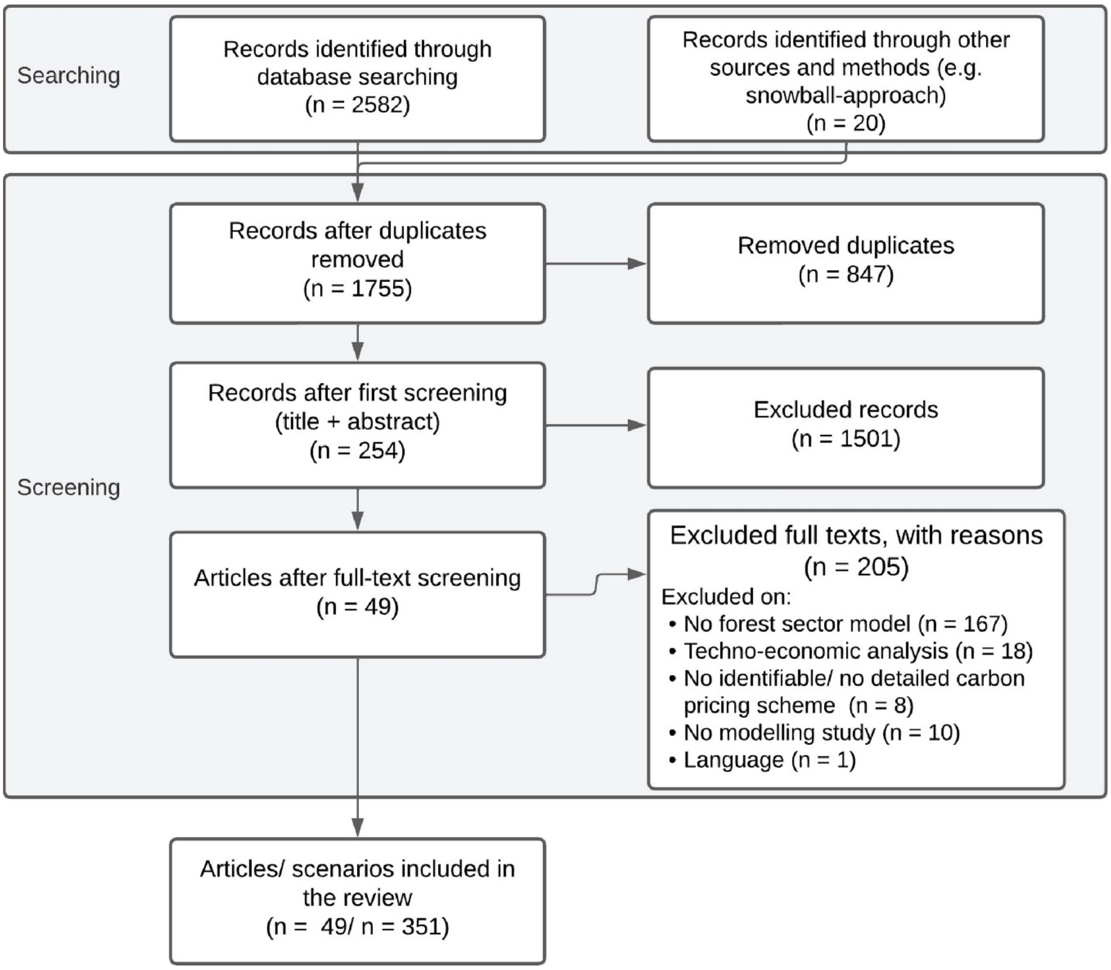

Figure 1. Flow diagram of the searching and screening procedure, specifying the number of excluded and included records for each stage. Adapted from Haddaway *et al* (2018). CC BY 4.0.

systems implemented, backtracking of earlier model descriptions was necessary (table S2). For some FSMs, we observed variations between different technical descriptions of specific aspects of carbon pricing systems. In this case, we referred to the description of the most recent technical publication. Sometimes, the characteristics of the carbon pricing systems analyzed varied between the scenarios assessed in one article. Therefore, we formed scenario sets with homogenous characteristics to cluster methodological differences and similarities across the reviewed articles. Depending on the model features analyzed, a variable number of scenario sets were constituted for each article. Thus, the number of occurrences may differ from the number of reviewed articles in the following analyses.

After data extraction and encoding, the main author cross-checked the data collection for errors and inconsistencies and subsequently discussed the results with the co-author. Missing information or entries that remained unclear were coded as 'not reported' or 'unclear'.

To facilitate comparisons among all eligible articles, we harmonized the different units used for carbon prices across the articles. A metric ton of carbon dioxide equivalent (tCO_2e) was set as the reference unit. The conversion from tons of carbon (tC) to tCO_2e was calculated using the following formula based on the atomic weights of C and CO_2 (Pingoud *et al* 2006).

$$\mathrm{tC} = \left(\frac{44}{12}\right)\mathrm{tCO_2e}.$$

The US dollar (USD) was used as the monetary reference unit. If a conversion was not provided in the original article, the different monetary units were converted to USD without adjustments for inflation (Richards and Stokes 2004) using exchange rates corresponding to each article's publication year (Statista 2022). When carbon prices changed over the projection period, we calculated final carbon prices using the indications provided by the original article on starting prices and growth rates. We calculated the

Table 2. Categories of extracted data (based on CEE 2018).

Categories	Type of data
1. Bibliographic information	(a) Year of publication (b) Journal
2. Research scope	(a) Temporal scope (b) Geographical scope
3. Study design	(a) Level of analysis (b) Model framework (model type and further characteristics) (c) Number of scenario sets and scenario characteristics
4. Information related to the carbon pricing system	(a) Type of carbon pricing systems (b) System boundaries of the carbon pricing systems (carbon sinks and sources considered) (c) Carbon pricing pathways–discount rates used
5. Information related to the implementation barriers of carbon pricing policies	(a) Additionality (b) Permanence (c) Carbon leakage
6. Additional information	(a) Research gaps and research recommendations

annual average carbon prices (USD tCO_2e^{-1} yr^{-1}) to account for differences in the length of the projection periods when the information provided by the reviewed article allowed a conversion. The original data, the converted data, and the conversion assumptions are provided in the supplementary materials (table S4).

3. Results

3.1. Study scopes

According to the findings of the present study, the first inclusion of a carbon pricing system in an FSM framework was in 2003 (Sohngen and Mendelsohn 2003; figure 2(b)). In total, and until 2021[6], we found 49 scientific articles that implement a carbon pricing system in FSMs[7]. Figure 2(a) provides information on the geographical coverage of the FSMs employed in the reviewed articles ($n = 50$)[8]. We were unable to detect a distinct geographical trend in the coverage of the studies' countries or regions between 2003 and 2021 (figure 2(b)).

3.2. FSMs used in research

In total, we identified 17 different FSMs across the reviewed articles (figure 3(b))[9]. Three of these FSMs are used in 56% of the reviewed articles. Regarding the frequency of use, we found that 28% of the articles (14 articles) alone relied on one global model (GTM). For the assessment of national carbon pricing policies, two models (FASOM-GHG and NorFor) prevailed in the reviewed articles with nine and five applications, respectively. Of the 17 models, six FSMs depict the forest sector from a global perspective, 10 FSMs represent the forest sector at the national or subnational level, and one model covers a region of multiple countries (the European Union). Of the national FSMs, 27% are models for European countries (e.g. Norway, Sweden, Finland, and France), and another 23% cover the US (figure 2(a)). Most of the models listed are used as standalone models. However, at the global level, two models (GTM and GLOBIOM) are respectively linked in five and three studies with other models. On the national scale, one model (FFSM) is subject to linkage approaches (figure 3(b), table S3).

3.3. Representation and characteristics of carbon pricing systems in FSMs

3.3.1. FSMs and types of carbon pricing systems

We found four major types of carbon pricing systems implemented in the reviewed FSMs: (a) carbon tax and subsidy schemes, (b) carbon rental schemes, (c) carbon offset payments, and (d) carbon taxes. Thereby, two main categories of carbon pricing systems are identified (figure 4): symmetric and asymmetric systems (Adams *et al* 2011), where either net or gross emission reductions are valued. Net emission reductions can be determined based on carbon flows or carbon stocks. Flow-based carbon pricing systems subsidize and tax carbon inflows and outflows relative to a baseline level over one period (figure 4(a); van Kooten *et al* 1995). Stock-based carbon pricing systems monetize each additional ton of carbon relative to the baseline stored over one year by applying a carbon rent equal to the discounted carbon price (figure 4(b); Sohngen and Mendelsohn 2003). When gross emission reductions are valued,

[6] End year of the scoping review.

[7] The complete list of reviewed articles is provided in table S3.

[8] The number of articles does not correspond to the number of FSMs used, as Kindermann *et al* (2008) used two distinct FSMs for their analysis.

[9] The acronyms and further descriptions of all the FSMs identified are provided in tables S2 and S3.

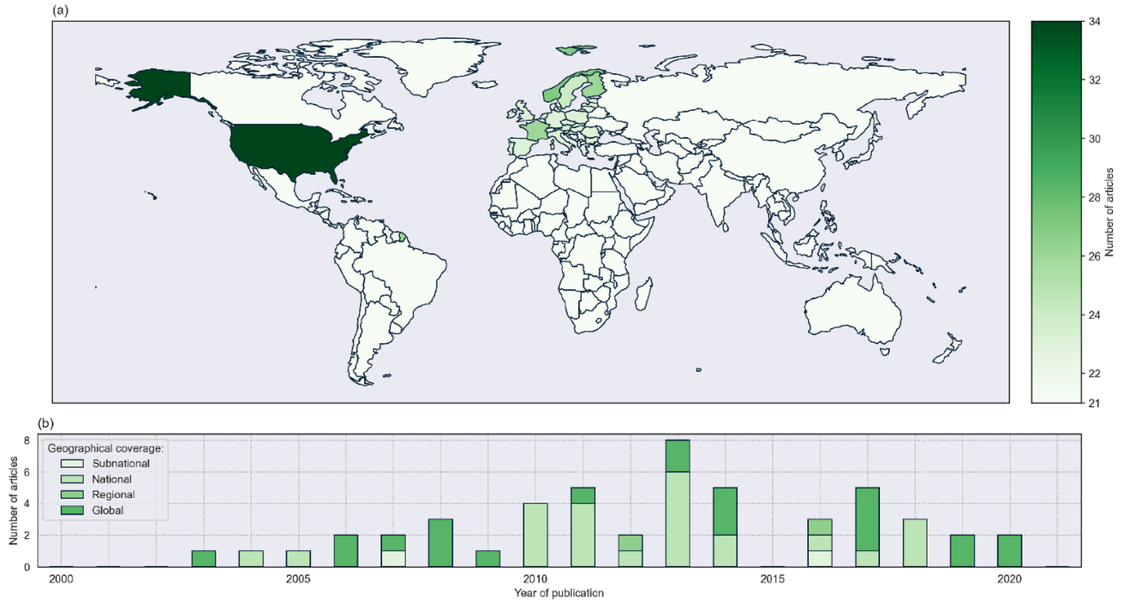

Figure 2. (a) World map displaying the distribution of countries covered by FSMs in the reviewed studies ($n = 50$); (b) distribution of reviewed studies per date of publication and geographical coverage.

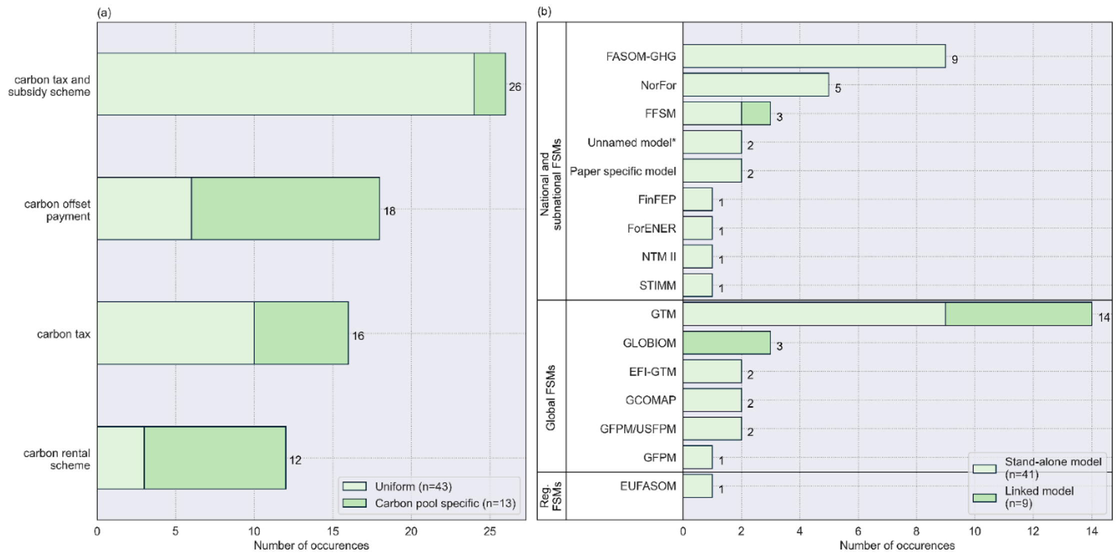

Figure 3. Characteristics of the carbon pricing systems represented across scenario sets ($n = 56$) and employed FSMs; (a) represents the distribution of the type of carbon pricing system used in the scenario sets (uniform and carbon pool specific); (b) shows the distribution of the FSMs identified in the scenario sets, detailing whether the FSMs are used as a stand-alone model or linked to other models, and national, global, and regional FSMs are also grouped. *The unnamed model is based on a publication of Adams and Latta (2005)[10].

all additional increases in carbon stocks relative to a baseline level are incentivized with an offset payment, without accounting for future decreases (figure 4(c)). In addition, carbon taxes put an explicit price on GHG emissions (figure 4(d)).

To deal with the diversity of carbon pricing systems used in the identified 351 scenarios, we formed 56 scenario sets in which the scenarios of the same type of carbon pricing system or combination of systems were grouped (table S3). In order of their frequency of application, 36% of the scenario sets applied carbon tax and subsidy schemes (mainly used as uniform carbon pricing system), 25% applied carbon offset payments (mainly used to monetize specific carbon pools), 22% implemented carbon taxes (mainly used as uniform carbon pricing system), and 17% of the scenario sets applied

[10] Since some scenario sets employ multiple carbon pricing systems, the number of scenario sets does not correspond to the sum of occurrences in panel (a). Similarly, the sum of occurrences in panel (b) ($n = 50$) does not match the number of reviewed articles ($n = 49$) as Kindermann *et al* (2008) integrate two different FSMs in their article.

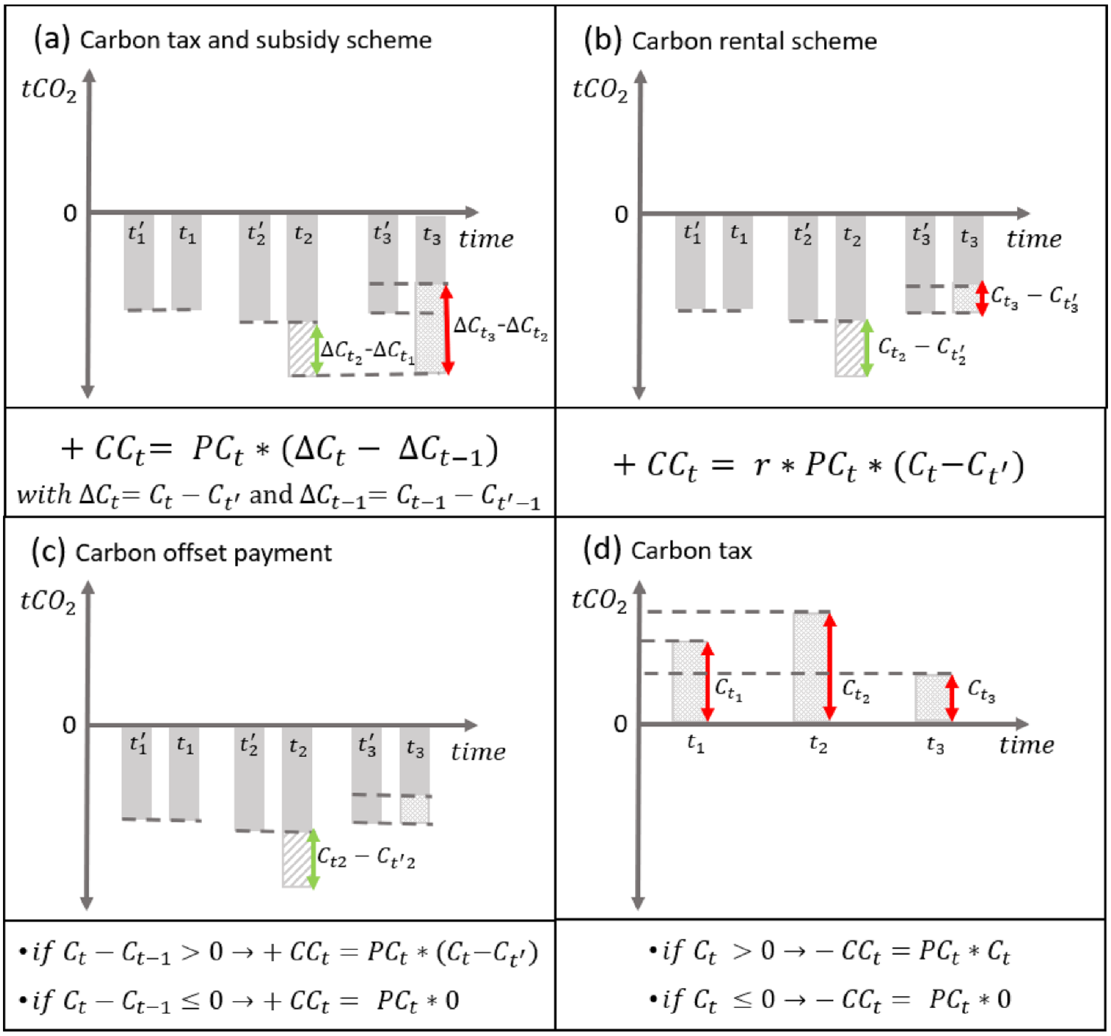

Figure 4. Different carbon pricing systems identified in the reviewed articles and schematic terms in the objective function of an FSM ($\boldsymbol{CC_t}$). (Over the three periods (t_1, t_2, t_3), the gray bars represent the carbon stock ($\boldsymbol{C_t}$) in [$\boldsymbol{tCO_2}$]. For each period, carbon stocks are given for a reference scenario without carbon pricing ($\boldsymbol{C_t'}$) and for a scenario with carbon pricing ($\boldsymbol{C_t}$). Except for (d), the additionality of carbon sequestration under the carbon pricing policy is secured by subtracting carbon stocks in the reference and the policy scenario. The green and red arrows, respectively, indicate increases or reductions in carbon stocks valued at a constant carbon price ($\boldsymbol{PC_t}$). In (a), carbon flows during each period, calculated as the difference of stocks between two consecutive periods ($\boldsymbol{\Delta C_t} - \boldsymbol{\Delta C_{t-1}}$), are valued by the carbon tax and subsidy scheme ($\boldsymbol{CC_t}$) at the carbon price ($\boldsymbol{PC_t}$). Net inflows ($\boldsymbol{\Delta Ct_2} - \boldsymbol{\Delta Ct_1}$) to and outflows ($\boldsymbol{\Delta Ct_3} - \boldsymbol{\Delta Ct_2}$) from carbon pools are respectively subsidized and taxed at the level of the carbon price. Changes in carbon stocks relative to the reference level in period $\boldsymbol{t}$ are denoted $\boldsymbol{\Delta C_t}$. In (b), changes in carbon stocks relative to the reference level ($\boldsymbol{C_t} - \boldsymbol{C_t'}$) are rented annually at the carbon price ($\boldsymbol{PC_t}$) and interest rate ($\boldsymbol{r}$) in each period. Increases in carbon stocks ($\boldsymbol{C_{t2}} - \boldsymbol{C_{t2}'}$) are incentivized through positive carbon rents, while decreases in carbon stocks ($\boldsymbol{C_{t2}} - \boldsymbol{C_{t2}'}$) are penalized via reduced carbon rents. In (c), additional increases in carbon stocks relative to the reference level are valued by an offset payment ($\boldsymbol{CC_t}$) at each point in time at the carbon price ($\boldsymbol{PC_t}$). For each period in time, $\boldsymbol{CC_t} \geq 0$. In contrast to the other types of carbon pricing, the total carbon emissions are valued by a carbon tax ($\boldsymbol{CC_t}$) in (d). For each period in time, $\boldsymbol{CC_t} \leq 0$. Indicated formulas can be subject to changes depending on the characteristics of the model or the carbon pricing system and the definition of additionality (table S3).

a rental scheme (mainly used to monetize for specific carbon pools) (figure 3(a)). Different carbon pools considered in one scenario are valued either with a uniform pricing system (77% of the scenario sets) or with different, pool-specific carbon pricing systems (23% of the scenario sets) (figure 3(a)). Most scenario sets applying pool-specific carbon pricing systems rely on a combination of carbon rental schemes and offset payments (75%) (table S3).

3.3.2. System boundaries of carbon pricing systems

We found that carbon pricing systems vary in regard to their system boundaries. First, policies valuing forest-based carbon sequestration can be unilateral (e.g. regional or national) or multilateral (e.g. global). We observed that most carbon pricing systems are introduced as global (43%) or national (49%) policies.

Second, the participation of forest owners or forest industries in a carbon pricing system can be

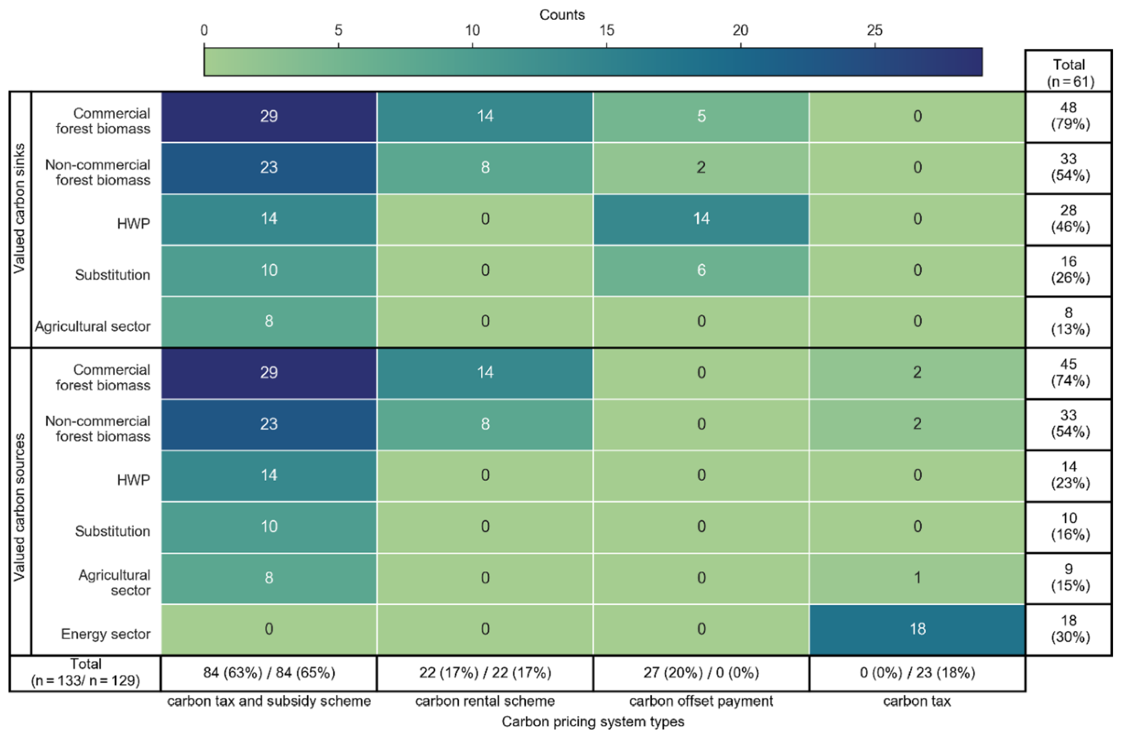

Figure 5. Carbon sink and source categories valued by each carbon pricing system type across identified scenario sets ($n = 61$). The categories used follow the terminology of the Intergovernmental Panel on Climate Change (Domke *et al* 2019, Rüter *et al* 2019). Row totals represent the number of scenario sets that value each category of carbon sinks and sources. Column totals represent the sums of carbon sinks ($n = 133$) and carbon sources ($n = 129$) valued by each carbon pricing system type, given in absolute terms, with relative terms in parentheses. In each article, scenario sets can simultaneously value multiple carbon sinks and sources.

mandatory or voluntary. In a mandatory carbon pricing system, the system boundaries include all forests in the implementation area. In contrast, only a subset of forests is subject to carbon valuation in a voluntary policy (e.g. Latta *et al* 2011, 2016, Nepal *et al* 2013a, 2013b). According to our findings, participation is assumed to be mandatory in 93% of the implemented carbon pricing systems (table S3).

Third, carbon pricing systems can value different carbon sinks and sources (figure 5). The majority of the scenario sets (79%) account for carbon sequestration in commercial forest biomass, also referred to as aboveground biomass. Carbon in non-commercial forest biomass, including below-ground biomass, dead wood, and forest soils is accounted for by carbon pricing systems in 54% of the scenario sets. In 46% of the scenario sets, carbon pricing systems value carbon sequestered in HWP. The related substitution effects induced by replacing GHG emission-intensive goods with HWP are accounted for in 26% of the scenario sets. In addition to the forest sector, 13% of the scenario sets integrate carbon sinks from the agricultural sector into carbon pricing systems.

On the other hand, carbon sources of commercial and non-commercial forest biomass are taxed in 74% and 54% of the scenario sets, respectively. In the agricultural and energy sectors, carbon emissions are taxed in 15% and 30% of the scenario sets, respectively (figure 5).

We are unable to detect a chronological trend regarding the number of carbon sinks and sources valued in the reviewed articles. However, national FSMs tend to integrate more carbon pools than global FSMs. The latter focus on forest sector-related carbon pools, whereas carbon pricing systems in national FSMs are often extended to other sectors (e.g. agricultural and energy sectors) (table S5).

The carbon sinks and sources identified are valued by different carbon pricing systems. Combined carbon tax and subsidy schemes and carbon rental schemes are used in 90% and 96% of the scenario sets, respectively, to value carbon in commercial forest biomass. To value carbon in non-commercial forest biomass, both carbon tax and subsidy schemes and carbon rental schemes are used in 94% of the scenario sets. While carbon rental schemes are exclusively employed to value carbon in forest biomass, carbon tax and subsidy schemes are used more diversely. Carbon removals by HWP and the related substitution effects are either valued by carbon tax and subsidy schemes (50% and 63% of the scenario sets, respectively) or by carbon offset payments (50% and 38% of the scenario sets, respectively). However, carbon emissions from the decay of HWP and the related substitution effects are only considered in carbon tax and subsidy schemes. Carbon fluxes from the agricultural sector are incentivized only by carbon tax and subsidy schemes. In turn, carbon taxes are mainly

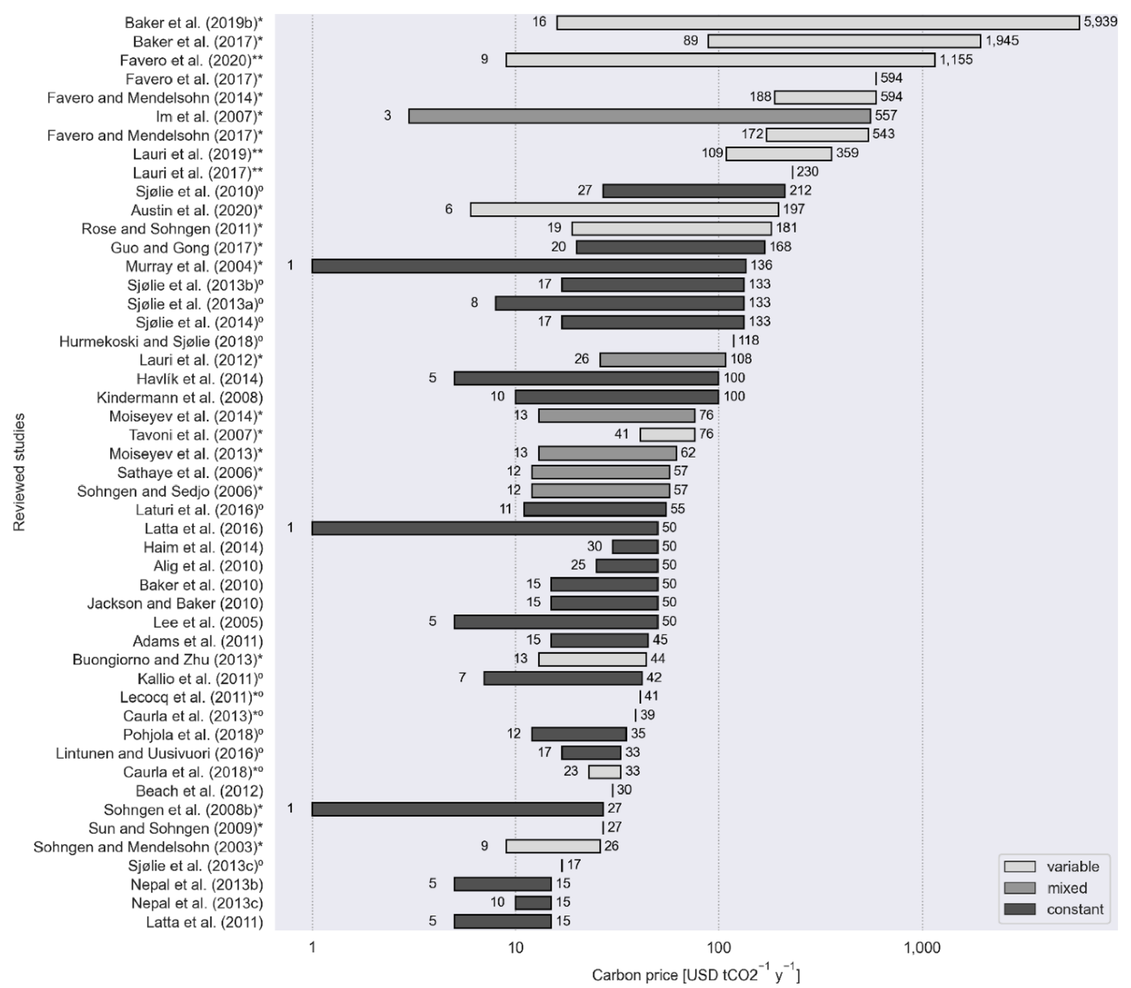

Figure 6. Range of mean annual carbon prices [USD tCO_2^{-1} yr^{-1}] calculated over the projection period for each reviewed study in ascending order, categorized by their development characteristics (variable, mixed, or constant). Articles assuming different types of carbon price development across their scenarios are labeled as mixed. Reference scenarios without a carbon pricing policy are excluded. (*Original carbon prices converted according to information provided in the original studies and the method described. **Carbon prices retrieved from the IIASA SSP database (Riahi *et al* 2017). [0]Carbon prices converted from € to USD. Details of original and transformed data are provided in table S4).

applied to carbon emissions from the energy sector (figure 5).

3.3.3. Carbon prices and discount rates

The carbon price adopted to value carbon sinks and sources is a central element of carbon pricing systems. In the reviewed literature, applied carbon prices differ in multiple ways.

First, carbon price pathways are either constant or variable over the projection period. Constant and variable carbon prices are implemented in 53% and 35% of the reviewed articles, respectively. By combining constant and variable carbon prices across different scenarios, 12% of the reviewed articles rely on mixed carbon price pathways (figure 6, table S4).

Second, the mean annual carbon price is subject to significant variations, ranging from 1 to 5939 USD tCO_2e^{-1} yr^{-1} over the projected period across the identified scenario sets. The majority of scenario sets (68%) adopt mean annual carbon prices of between 10 and 100 USD tCO_2e^{-1} yr^{-1}. Mean annual carbon prices over 100 USD tCO_2^{-1} yr^{-1} are applied in 21% of the scenario sets, which, for most, assume variable carbon price pathways (14%) (figure 6). While no evident chronological trend in the level of carbon prices can be observed in the data, more recent publications seem to favor larger ranges of carbon prices, reaching higher levels at the end of the projection period (figure 6).

Finally, the carbon price can be an endogenous or exogenous variable in the model framework. In 90% of the reviewed articles, carbon prices are implemented as an exogenous variable determined by the authors, due to the partial nature of FSMs. Exogenous carbon prices applied in the reviewed studies are retrieved from scientific literature (31%), policy documents (10%), carbon market statistics (2%), or a combination of these sources (4%).

However, for most articles (43%), carbon prices are selected without specifying their source (table S4). Through a linkage with additional models, 10% of the reviewed articles integrate carbon prices as an endogenous variable.

In addition to carbon price levels, discount factors are involved in the valuation of carbon sequestration. Applied discount rates vary between 3% and 7% for non-carbon values and zero and 8% for carbon values. However, 30% of reviewed articles do not provide information on discount rates. Except for Sjølie *et al* (2013a), all articles assumed homogenous discount rates for revenues related to timber sales (e.g. non-carbon values) and carbon credits (e.g. carbon values).

3.4. Targeting implementation barriers of forest-based carbon pricing policies

Concerns about the additionality, permanence, and leakage of forest-based mitigation measures shape the implementation of carbon pricing systems in FSMs and are addressed in different ways.

To ensure the additionality of forest-based carbon sequestration, most reviewed articles establish reference levels of sequestration against which relative changes in carbon sequestration are quantified. However, several types of reference levels are identified (figure 7(a)). In the reviewed articles, additionality is secured by restricting the valuation to increases in carbon sequestration either relative to the level of sequestration without a carbon pricing policy (48%), relative to the level of sequestration in the previous modeling period (14%), or relative to the averaged regional carbon stocks (6%). The total carbon sequestration of at least one carbon pool is valued by carbon pricing systems in 25% of the reviewed articles, of which 18% are ascribed to articles valuing carbon sequestration in HWP using GTM.

Diverse methods are applied in the reviewed articles to account for the potential reversion of carbon sequestration (figure 7(b)). In 57% of the reviewed articles, authors address issues about permanence by using symmetric carbon pricing systems, valuing both carbon removals and emissions simultaneously (e.g. carbon tax and subsidy or carbon rental schemes). In certain cases (23%), permanence is addressed via carbon pool-specific assumptions. Depending on the carbon pool, either the total (e.g. for forest soils and wood-based bioenergy in combination with carbon capture and storage) or a percentage (e.g. for HWP) of the carbon is assumed to be permanently sequestered. To ensure permanence, 12% of the reviewed articles integrate binding contract lengths or harvest bans as additional optimization constraints, inspired by existing standards for the valuation of forest-based carbon credits (e.g. the Verified Carbon Standard, Climate Action Reserve).

To address concerns about leakage issues, an important subset of the reviewed articles conducts post-optimization analyses of the model results. Such analyses focus on shifts in production between areas implementing a carbon pricing system and other areas remaining outside, using either increases of imports relative to exports (21%) or changes in harvest volumes (15%) as an indicator of leakage. In 4% of the reviewed articles, leakage is addressed by comparing the mitigation effects of unilateral and multilateral carbon pricing systems. The difference in mitigation between the two systems is interpreted as the leakage effect of the unilateral carbon pricing system (e.g. Buongiorno and Zhu 2013, Baker *et al* 2017). As leakage effects result from the partial coverage of carbon pricing systems, 34% of the reviewed articles overcome this issue by valuing carbon sequestration in all forests worldwide. Some articles address concerns about leakage effects by reducing the number of saleable credits for specific carbon pools (e.g. the HWP pool). A quarter of the reviewed articles omit quantitative and qualitative assessments of leakage effects (figure 7(c)).

By either complementing or replacing quantitative methods to address these three main barriers, a large subset of the reviewed articles qualitatively emphasizes their importance and interprets the modeling results considering additionality, permanence, and leakage.

3.5. Mapping research gaps and future research trends

In total, 84% of the 49 reviewed articles indicate research gaps or provide recommendations for future research. In 23 articles, the authors listed multiple research gaps and recommendations. We grouped the research gaps and recommendations into four thematic categories (figure 8).

First, research gaps and recommendations relating to the applied model framework form the largest thematic cluster, covering 51% of all mapped gaps and recommendations. In this context, several authors emphasize the implementation of intersectoral dynamics between the forest and competing sectors as a crucial topic (13 articles). In addition, seven articles suggest that future research should revise model parameters, such as macroeconomic variables (e.g. elasticities), and incorporate more regionalized parameters. Furthermore, the extension of the product structure (five articles) and the revision of the representation of forest dynamics (five articles) are highlighted for further development.

Second, 29% of all research recommendations and gaps are linked to carbon pricing policies. To increase the robustness of the modeling results, some

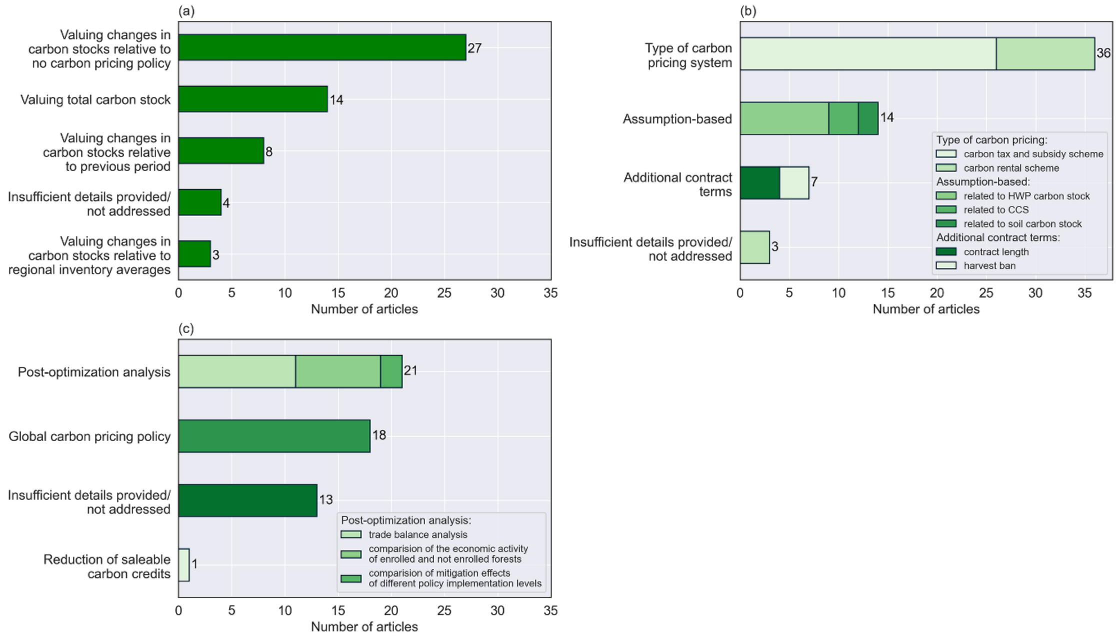

Figure 7. Methods implemented to address issues of forest-based carbon credits related to additionality (a), permanence (b), and leakage (c), and the number of applications across reviewed articles ($n = 49$). For some articles, a mix of the different approaches listed here is applied.

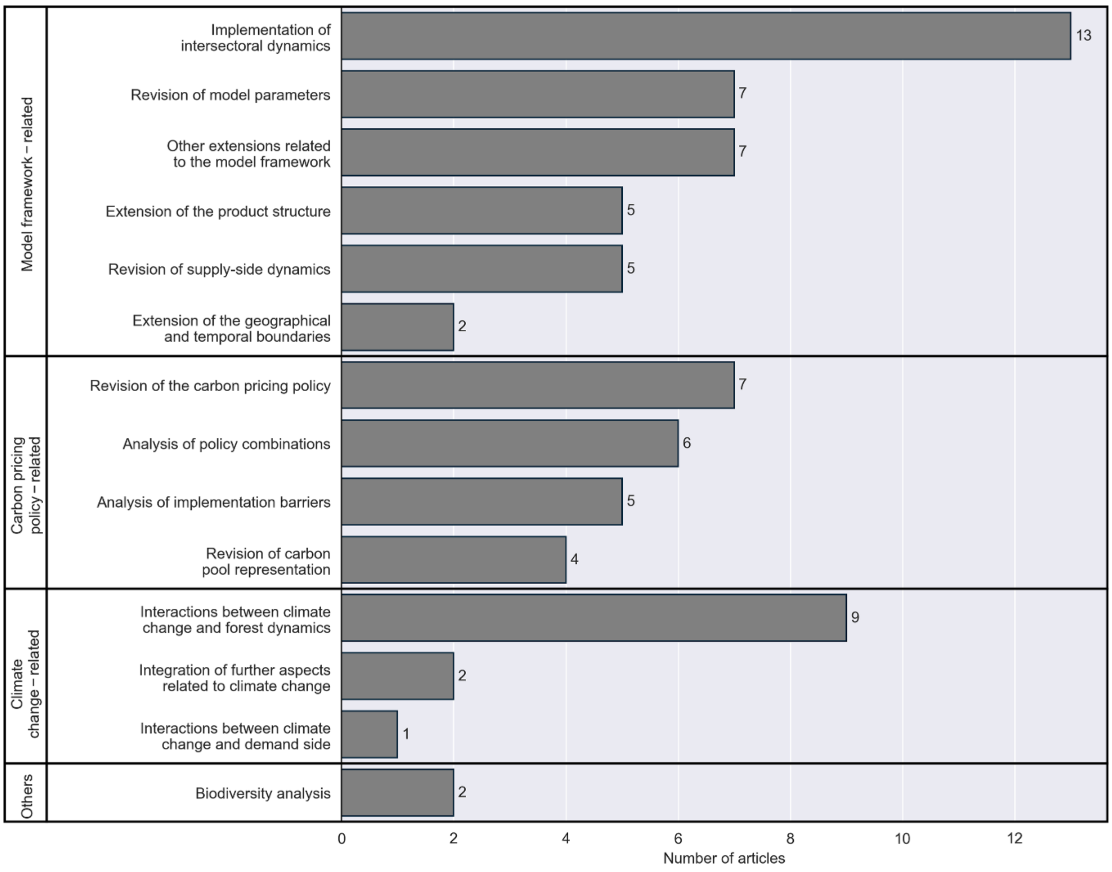

Figure 8. Research gaps and recommendations ($n = 75$) specified in the reviewed articles ($n = 49$) and thematically categorized. Some articles list multiple research gaps and recommendations. Thus, the total number of identified research gaps and recommendations exceeds the number of reviewed articles.

authors claim that future research on carbon pricing systems should entail a greater diversity of system characteristics (seven articles), including different types of carbon pricing systems, carbon price pathways, and system boundaries. Additionally, carbon pricing policies are commonly implemented as elements of a policy mix. The analysis of synergies and trade-offs between carbon pricing and other policies is seen as an important topic for future research (six articles). Five articles call for more research on the main implementation barriers (additionality, permanence, and leakage). In four articles, the authors express the need to enhance the representation of carbon pools in the employed model framework. This could be achieved by revising the implemented carbon pools or including new ones.

Finally, 16% of the identified research gaps and recommendations in the reviewed articles refer to issues relating to climate change. In particular, the impact of climate change on forest dynamics is addressed as a major research gap, since these interactions are rarely represented in most of the reviewed FSMs (nine articles).

4. Discussion

LULUCF mitigation options, in particular forest-based measures, are expected to be key elements in 2 °C-compatible pathways (Rogelj *et al* 2018, Roe *et al* 2019). Yet, political actions and financial investments are required to unlock this mitigation potential (Kreibiehl *et al* 2023, Nabuurs *et al* 2023). To support the contribution of forest-based mitigation policies to global climate commitments, a sound knowledge of the possible impacts of carbon pricing policies in the forest sector appears to be crucial. In this context, the present scoping review captures the current state of research on carbon pricing policies in the FSM literature by systematically mapping approaches to modeling carbon pricing systems. We highlight the technical characteristics and scopes covered by carbon pricing policy analyses conducted using FSMs, identify methodological differences and similarities, and document research gaps. In this way, this study provides an in-depth overview of the approaches available in the FSM context for specifying the role of forest-based mitigation options in global climate commitments.

4.1. Geographical and temporal scope of research

In light of the second research question, it is striking that, besides global studies, most articles provide national analyses for the USA and EU countries. This coincides with the historical clusters of FSM research (Latta *et al* 2013, Rivière *et al* 2020). Thus, the potential implications of carbon pricing for many important wood-processing countries have been solely analyzed at an aggregated level by global FSMs. These models might deliver less detailed impact assessments of carbon pricing systems for individual countries (Wong and Alavalapati 2002, Buongiorno and Zhu 2013), especially when it comes to mitigation measures related to afforestation, reforestation, and forest management (Sjølie *et al* 2013b). Therefore, the potential capacity of carbon pricing systems to mobilize forest-based mitigation potentials is still not well studied for a large subset of highly relevant countries (e.g. Russia, Brazil, Canada, and China) and also, e.g. for tropical and boreal areas. Refining the analysis to include tropical and boreal regions appears to be key as afforestation and reforestation in these areas entail significant mitigation potentials, especially at lower carbon prices (Griscom *et al* 2017, Roe *et al* 2019, Nabuurs *et al* 2023). For this, national impact assessments can complement and specify global LULUCF mitigation estimations.

It is further remarkable that some forest-rich countries or regions that have adopted carbon pricing policies for the forest sector have not been the subject of national FSM studies but are solely addressed in global analyses (e.g. Australia, Canada, China, New Zealand) (World Bank 2020). Such analyses might have been hampered by the requirements of resources and expertise needed to establish a national FSM. Both resources and expertise have been traditionally available in the USA and Europe (Rivière *et al* 2020). Moreover, reliable forest sector data are still scarce in many countries (Romijn *et al* 2015, Kallio and Solberg 2018, FAO 2021). However, other methods are used to assess the potential impact of carbon pricing policies in the forest sector for these countries (e.g. CGE models by Liu and Wu (2017) in China, scaled-up stand-level models by Comerford *et al* (2015) in Australia, or carbon budget models by Smyth *et al* (2020) in British Columbia).

From a temporal perspective, although long-term evaluations are crucial for climate change mitigation, policymakers rely on medium-term assessments to implement tangible measures and track progress toward defined commitments, meaning both of these planning periods are important. Recursive and intertemporal FSMs are limited in delivering short-term projections of mitigation potentials because they do not usually simulate annual market fluctuations. However, by providing intermediate modeling results, most articles simultaneously allow for medium- to long-term analyses of mitigation potentials.

4.2. Technical overview of carbon pricing systems in FSMs

We found that pre-existing FSM frameworks have been extended in two ways for integrating and analyzing carbon pricing systems. In light of research questions (1) and (3), their technical differences, similarities, and methodological patterns are discussed below.

4.2.1. Projecting carbon sequestration

First, FSMs have been extended to track and quantify the dynamics of carbon stocks or fluxes. On the supply side, all the reviewed FSMs include carbon as a function of forest biomass by applying conversion factors. National and subnational FSMs tend to specify carbon projections by accounting for various stand characteristics, such as the age-class distribution and tree species composition (e.g. NorFor, FinFEP, FASOM-GHG, FFSM, and Western Oregon FSM). At the global level, only two FSMs (GTM and GLOBIOM) provide carbon projections on the supply side at stand level based on the data availability for each region (Sohngen and Sedjo 2000, Lauri *et al* 2019). Driven by data constraints, other global FSMs aggregate forest biomass as total forest stock and omit additional stand characteristics (e.g. GFPM Buongiorno 2015, EFI-GTM, Kallio *et al* 2004). While allowing for the quantification of carbon sequestration without substantial changes to the model, the application of average conversion factors might result in biased carbon projections when the influence of forest stand characteristics (Wear and Coulston 2019) and regional differences in carbon sequestration (Pan *et al* 2011, Harris *et al* 2021) are disregarded. Another source of uncertainty is the influence of climate change on mitigation potentials, which is not considered in any of the FSMs reviewed. However, the antagonistic effects of climate change on forest growth (McDowell *et al* 2020) are likely to have sizeable impacts on carbon sequestration (Nabuurs *et al* 2023). A significant subset of the reviewed articles acknowledges this omission as a decisive field for future research (Lauri *et al* 2017, Pohjola *et al* 2018, Austin *et al* 2020, Favero *et al* 2020). More recent FSM applications specify projections of carbon by integrating climate change dynamics into their framework (Lobianco *et al* 2016) or by linking FSMs to additional models (Favero *et al* 2021), but do not integrate carbon pricing systems.

A few of the reviewed FSMs (e.g. GTM) present forest soils as a steady-state pool that regenerates over time after disturbances caused by forest management practices if the area remains afforested. Other FSMs integrate forest soils as a constant carbon pool due to the lack of data on the effects of forest management (FASOM-GHG, STIMM, and NorFor). Given the importance of forest soil carbon (Pan *et al* 2011), its inclusion in FSMs is likely to be crucial for refining carbon projections. However, the lack of reliable inventory data and unclear effects of forest management practices (Mayer *et al* 2020) make this undertaking difficult.

On the demand side, HWP and related substitution effects are acknowledged as the two main carbon sinks. The reviewed FSMs commonly rely on decay rates and associated half-life estimates to capture carbon flows from HWP over time. Since the duration of carbon sequestration in HWP is conditioned by product use (Rüter *et al* 2019), FSMs considering different categories of HWP can account for product-specific carbon fluxes by applying distinct decay rates (e.g. FASOM-GHG). However, some FSMs only simulate the provision of roundwood, making decay rates less practicable. Instead, these FSMs rely on 'pickling' factors (van Kooten *et al* 1995), which describe the share of carbon in roundwood that is assumed to be stored permanently in long-lasting products, thus omitting the carbon released from product decay (e.g. GTM or the paper-specific FSM of Laturi *et al* 2016). For certain models, the parameters employed might be outdated because political and technological conditions have changed since their conception (e.g. GTM relies on 'pickling' factors estimated using data from 1990).

Although substitution effects might be significant, including them is a challenging task, because FSMs are partial models that focus on the forest sector. To compensate for the missing representation of competing commodities, the FSMs employ substitution factors. Substitution factors have only been integrated into national FSMs across the reviewed articles as constant parameters, often based on country-specific life cycle assessments (e.g. NorFor, FFSM, and FASOM-GHG). Even so, because semi-finished products represented in FSMs can result in multiple output products through further processing, identifying competing substitutes is subject to uncertainty (Caurla *et al* 2013). Moreover, using constant factors, the substitution effects of HWP might be overestimated as the planned decarbonization of competing sectors could reduce the GHG intensities of substituted products (Brunet-Navarro *et al* 2021). Since the substitutability of wood- and fossil-based energy is less questionable (Kallio *et al* 2011, Lintunen and Uusivuori 2016), related substitution effects have been considered in several of the studies reviewed here, either by extending the model framework (e.g. EUFASOM, EFI-GTM, GTM, FinFEP) or by linking it with other models (e.g. WITCH, GES).

To increase the reliability of the given mitigation potentials, possible uncertainties related to model parameters of the supply (Domke *et al* 2019, Sohngen *et al* 2019) or the demand (Bates *et al* 2017, Rüter *et al* 2019) side could be considered in future research by conducting additional sensitivity analyses or through the revision of outdated parameters. Moreover, using constant parameters to quantify carbon sequestration on the demand side might impact carbon mitigation potentials since the socioeconomic developments required to mitigate climate change, such as rapid decarbonization, are disregarded. To enhance the projection of forest-based mitigation potentials, dynamic parameters could be used to account for these structural changes (e.g. Brunet-Navarro *et al* 2021 for substitution factors).

The reviewed FSMs apply different accounting methods that rely on multiple assumptions and parameters to project carbon sequestration. Among others, defining which forest areas are eligible for carbon credits is decisive as it affects all supply-side carbon pools. Efforts have been made in LULUCF accounting rules to isolate human-induced mitigation from natural processes in carbon fluxes of extant forests. Thus, credits are restricted to intentional mitigation measures, increasing the comparability with other sectors (Grassi *et al* 2018). To factor out natural effects (e.g. fires, wind, insect pests), accounting guidance for LULUCF proposes focusing on carbon fluxes in managed forests (Domke *et al* 2019). However, other accounting guidelines issued by voluntary carbon programs explicitly include these natural effects in the mitigation assessments of projects (e.g. Verified Carbon Standard, Climate Action Reserve). Conditioned by their pre-existing framework, some FSMs quantify and value carbon fluxes for all forests (e.g. GFPM, EFI-GTM, NorFor). Consistent with LULUCF accounting rules, other models restrict the quantification and valuation of carbon fluxes to managed forests (e.g. GTM, FASOM-GHG). Further models value the effects of natural disturbances on carbon fluxes (NorFor, FASOM-GHG). This variability across the accounting approaches regarding the included forest area might explain parts of the differences in the projected mitigation potentials (e.g. between GTM and GFPM).

4.2.2. Monetizing carbon sequestration

In the second step, the projected carbon removals and emissions are valued through their monetization and integration into the optimization function (Rivière *et al* 2020). To monetize carbon pools with multidirectional dynamics (e.g. carbon removals and emissions), carbon tax and subsidy schemes or carbon rental schemes are introduced into the FSMs. For carbon pools represented unidirectionally (e.g. only removals or emissions), FSMs rely either on carbon offset payments to incentivize carbon removals or carbon taxes to disincentivize carbon emissions from competing sectors.

To stay on a 1.5 °C pathway, future climate mitigation policies in the forest sector should target net reductions and removals of GHG emissions (Grassi *et al* 2017, Roe *et al* 2021). Since carbon tax and subsidy schemes and carbon rental schemes value net GHG fluxes or stocks, they appear to be the most suitable carbon pricing options to support climate mitigation measures in the forest sector.

In terms of mitigation outcomes, the participation of the highest possible number of forestry stakeholders in carbon pricing policies is crucial. The willingness to participate is influenced by the characteristics of the implemented carbon pricing system, including carbon revenues and contract conditions such as contract length and management restrictions (Sharma and Kreye 2022).

While carbon tax and subsidy schemes and carbon rental schemes provide identical monetary incentives from a mathematical perspective (Lintunen *et al* 2016), the distribution of monetary flows differs. Carbon tax and subsidy schemes involve making one-time payments when carbon credits are sold or storage ends. Carbon rental schemes, however, temporarily value carbon as long as it is stored without requiring payments when storage ceases (Tavoni *et al* 2007). In this way, carbon stocks are always an asset for the forest owner (Favero *et al* 2017). Moreover, carbon rental schemes do not require a permanent transfer of ownership, but rather a temporary rental arrangement, which might increase participation.

In addition, measures to secure the permanence of sold credits (e.g. 100 year contracts and the creation of carbon credit buffers), which lowers the participation in carbon pricing systems, are not needed in carbon rental schemes (Parisa *et al* 2022).

Participation by forest owners might be hampered in both systems because controlled (e.g. harvest) and uncontrolled (e.g. abiotic and biotic disturbances) decreases in carbon sequestration are treated equally. However, in contrast to carbon rental schemes, forest owners face the risk of paying back sold credits in carbon tax and subsidy schemes when carbon sequestration decreases under the reference level. This risk increases when carbon units are traded at variable prices under ETS (e.g. New Zealand's ETS), thus affecting the ability to plan future costs if carbon sequestration is reverted. In this case, uncertain carbon costs at harvest due to increased carbon prices can inhibit participation, as observed in New Zealand (Manley 2020).

Given these aspects, implementing carbon rental schemes might increase participation in carbon pricing policies compared to carbon tax and subsidy schemes. Further, extending carbon pricing systems solely considering forestry to integrate carbon sequestration in HWP is likely to increase the participation of forest owners (Manley 2020). However, the costs of monitoring, reporting, and verifying activities necessary for both types of carbon pricing might hinder their actual implementation by forest stakeholders (Gren and Aklilu 2016).

Despite similar carbon pricing system types, FSM analyses might lead to various forest-based mitigation potentials. They result from differences between the models, especially regarding optimization forms. Assuming the perfect foresight of forest owners, intertemporal FSMs are likely to lead to higher mitigation potentials than recursive FSMs, *ceteris paribus* (Lecocq *et al* 2011, Sjølie *et al* 2013a).

Further attributes of implemented carbon pricing systems relating to participation (e.g. mandatory or voluntary systems) and available state budgets (e.g. restricted or unlimited) are likely to influence policy outcomes. Here, most studies reviewed adopt mandatory carbon pricing systems with unlimited budgets, which is expected to increase the application area and the resulting mitigation potential. While the applicability of such carbon pricing policies is questionable (Lecocq *et al* 2011), further refinements in carbon pricing policies require additional changes in the FSM framework, such as the comparison of income from carbon credit and timber sales (Latta *et al* 2011, 2016) or the introduction of additional optimization constraints (Nepal *et al* 2013a, 2013b).

The price at which available carbon sequestration is valued constitutes a main feature of carbon pricing systems. At carbon prices between 10 and 100 USD tCO_2^{-1} yr^{-1}, forest-based mitigation measures could substantially contribute to reaching the 2 °C target (Griscom *et al* 2017, Rogelj *et al* 2018). Even though we found significant differences in the level and development of carbon prices, most scenario sets use prices within the above range. In addition, the majority of scenario sets assume constant carbon prices over the projection period due to the technical characteristics of the applied FSM. However, prices in carbon markets are unlikely to follow unidirectional development patterns, as assumed in the reviewed literature. Instead, carbon prices are subject to volatility (Ji *et al* 2018, World Bank 2021), which could inhibit the deployment of mitigation measures (de Coninck *et al* 2018). To a certain extent, the uncertainty regarding future carbon prices is addressed through sensitivity analyses. However, by restricting carbon prices to be either constant or increasing over the projection period, the effects of more complex price development pathways on forest-based mitigation measures remain unaddressed in the reviewed articles.

4.3. Addressing issues of additionality, permanence, and leakage

Regarding research question (4), the majority of the reviewed articles address the issues of additionality, permanence, and leakage as the main barriers to implementing carbon pricing systems, reflecting their importance in post-Kyoto negotiations (UNFCCC 2002). Taking these issues into account is crucial for evaluating the cost-effectiveness of forest-based mitigation measures because it allows the refinement of estimations of carbon effectively sequestered by these measures at a given carbon price (Murray *et al* 2004, Nepal *et al* 2013b). However, these three issues are treated with different levels of intensity.

The additionality of forest-based carbon sequestration is mainly secured by establishing reference scenarios that depict business-as-usual conditions through the absence of carbon pricing policies. As a result, the valuation is restricted to additional carbon sequestration induced by carbon pricing policies. In practice, however, establishing such reference baselines might result from diverging interests between suppliers and buyers of carbon credits, and be hampered by an asymmetric distribution of information among them (Mason and Plantinga 2013). Using such reference scenarios, the reviewed articles further assume that no changes in implemented policies will occur in the future. While this approach isolates the impact of carbon pricing policies, it might ignore possible synergies and trade-offs of policy mixes that could affect forest-based mitigation potential (e.g. Favero *et al* 2017).

Defining reference scenarios to include LULUCF mitigation in the 2nd commitment period of the Kyoto Protocol has been controversial and remains a critical issue in the NDCs (Grassi *et al* 2017). To reach climate commitments, additional emission reductions were introduced as the difference between emissions in the reference scenario and actual emissions. The inclusion of future policies requiring additional harvesting (e.g. increased bioenergy consumption) in the reference scenarios was criticized as it allows inflating expected net emissions. As a result, additional emission reductions could be increased, making climate commitments easier to fulfill (Grassi *et al* 2018). Further analyses of alternative reference scenarios are important because the impact on the cost-effectiveness of forest-related mitigation measures might be significant (Galik *et al* 2012). Such analyses could provide science-based guidance for defining transparent and reliable reference levels to include LULUCF measures in national mitigation efforts (e.g. the 'forest reference levels' in the EU) .

The permanence of forest-based carbon credits is mainly addressed through the choice of a carbon pricing system. Thus, most articles consider both carbon removals and emissions simultaneously (e.g. carbon tax and subsidy or carbon rental schemes) so that carbon sequestration in forests is treated as temporary. Rental or subsidy payments are maintained as long as the suppliers of carbon credits secure carbon storage in forest biomass or HWP. Other approaches incorporate additional contract terms (e.g. defined contract duration and harvest restrictions) in their FSM framework as supplementary optimization constraints inspired by existing standards for forest-based carbon credits (e.g. the Verified Carbon Standard, Climate Action Reserve). Some standards apply variable discount factors and implement backup credit buffers to account for reversal risks (World Bank 2020). We found only one article using backup credits (Latta *et al* 2016). While the stability of carbon sequestration in forest biomass could become more uncertain under the impact of climate change (McDowell *et al* 2020), methods to address permanence issues do not consider this aspect, as any of the articles explicitly integrate the effects of climate change.

Issues related to leakage effects are mostly addressed via post-optimization analyses. Here, shifts in trade balance and economic activity between areas with and without carbon pricing systems serve as the principal indicators of leakage. However, trade-based analyses of carbon leakage in national FSMs are limited as leakage cannot be allocated due to the common aggregation of foreign markets. The same holds for the global FSMs with aggregated regions. A more precise allocation requires global FSMs with a more disaggregated country structure (e.g. GFPM or EFI-GTM). In global FSMs, carbon leakage is often encountered by implementing global carbon pricing systems with a universal carbon price, encompassing all existing forest areas. Thus, carbon leakage between areas enrolled and unenrolled in carbon pricing systems is no longer possible (e.g. Austin *et al* 2020). However, potential institutional challenges might restrict the practicability of such global climate mitigation approaches (Mendelsohn *et al* 2012).

Carbon leakage can also occur across different sectors (Murray *et al* 2004, Kallio *et al* 2018). FSMs are restricted to sectoral analyses between forestry and forest industries. However, by including additional economic sectors in FSMs (e.g. in FASOM-GHG, FinFEP, and EFI-GTM) or by linking FSMs with CGE models, cross-sectoral carbon leakage can, to some extent, be analyzed, but this was not addressed in the reviewed literature. A better understanding of sectoral and cross-sectoral effects of carbon pricing policies implemented in the forest sector is stated as an important issue for future research in the reviewed studies. Carbon border tariffs, as recently introduced in the EU or discussed in other countries (e.g. USA), intending to address the risk of leakage of unilateral climate mitigation policies (EU 2023), might be highly relevant for such research.

Reviewed articles typically assume optimal carbon pricing systems that provide incentives and disincentives instantly and across the entire area of interest whenever removals or releases occur. In such an optimal system, common issues of additionality, permanence, and leakage opposed to forest-based mitigation measures can be defused, although their political practicability remains questionable. Some reviewed articles analyze suboptimal carbon pricing systems via delayed or spatially restricted policy implementation. Sub-optimal carbon pricing systems have been found to reduce the potential mitigation effect of forest-based measures across different FSM frameworks (Rose and Sohngen 2011, Buongiorno and Zhu 2013, Baker *et al* 2017). Moreover, integrating necessary monitoring, reporting, and verifying activities to address implementation barriers may significantly increase the transaction costs of forest-based mitigation measures (Antinori and Sathaye 2007, Sohngen *et al* 2008a, Galik *et al* 2012, Phan *et al* 2017). Accounting for these transaction costs would inherently lower the cost-efficiency of forest-based mitigation measures and could reduce projected mitigation potentials in the forest sector (Kindermann *et al* 2008, Sohngen *et al* 2008a, Baker *et al* 2010).

4.4. Methodological limitations of the scoping review

Through a predefined research protocol and specific selection criteria, scoping reviews offer a method for synthesizing the state of knowledge transparently while minimizing bias in the selection of articles. Despite this, some methodological challenges were encountered in this exercise. Due to differences in the application contexts and targets of FSMs (Rivière *et al* 2020), there seems to be no consensus regarding the terminology relating to these models in the relevant literature. Similarly, the terminology relating to carbon pricing systems is also diverse. This can be explained to some extent by the differing characteristics of the policies analyzed and carbon pricing systems implemented. Owing to the lack of terminological consensus, the inclusion of numerous synonyms in the search string was necessary, but this lowered its specificity: 2582 records were retrieved, of which 98% were excluded during the screening stages. Beyond this, the use of FSMs and the carbon pricing policies implemented are not always clearly specified in the article titles and abstracts. Such omissions made the systematic screening of the literature databases more difficult, as relevant articles might remain undetected due to missing keywords. These challenges were handled by additionally screening the reference lists of the articles. The 41% proportion of manually added articles in the overall number of articles reviewed underlines the importance of this additional step. Since FSMs are extensively used to support policymaking, the results of modeling research are often published as working papers addressed to policymakers or even directly integrated into reports commissioned by governments (e.g. Sedjo *et al* 2001, Murray *et al* 2005, The White House 2016). This grey literature falls outside the scope of this scoping review. However, some working papers were integrated into this scoping review by analyzing related peer-reviewed articles (e.g. Sohngen and Sedjo 2006).

4.5. Research and policy implications

Sectoral assessment models like FSMs tend to include larger portfolios of LULUCF mitigation measures compared to other model types (e.g. integrated assessment models or carbon accounting models), thus allowing for more comprehensive projections of forest-based mitigation potentials (Roe *et al* 2021). Moreover, sectoral assessments can deliver mitigation potentials on a narrower geographical scale and support the specification of country-level mitigation policies in the context of NDCs. Therefore, FSM-based analysis can provide critical information for designing, implementing, and scaling up forest-based mitigation policies.

However, the feasibility of these potentials is likely to be constrained by environmental, sociocultural, and institutional barriers (Roe *et al* 2021, Nabuurs *et al* 2023), which tend to be omitted in the reviewed analyses. Some of these omitted barriers (e.g. unlimited financial resources, omission of transaction costs) and underlying modeling assumptions (e.g. forward-looking optimization and mandatory participation of forest owners and wood industries) could lead to overestimating forest-based mitigation potentials. Meanwhile, other missing aspects (e.g. inadequate activation of forest owners and cross-sectoral dynamics) might undermine the mitigation outcome of such policies. Moreover, the complex impact of climate change on the growth and stability of forests could alter the forest-based contribution to climate mitigation.

Besides GHG removals, the relevance of other forest-based ecosystem services, such as water and nutrient regulation or biodiversity protection, might further increase in strategies to achieve global mitigation commitments (Nabuurs *et al* 2023). However, synergies and trade-offs between increased carbon sequestration through carbon pricing policies and other ecosystem services are usually not addressed in FSM-based analyses given the challenges of including them in available model frameworks (e.g. Rivière *et al* 2020).

To inform policy debates more comprehensively, sectoral mitigation potentials should be used in future research embedded in a broader panel of methods, combining qualitative and quantitative approaches to account for these barriers and open questions. In doing so, the reliability of forest-based mitigation potentials could be increased while refining the overall possible role of the forest sector in the future.

5. Conclusion

This scoping review systematically reviewed modeling approaches for integrating carbon pricing systems into FSMs from a technical perspective. In this way, transparency over literature selection and minimization of selection bias were jointly ensured. The results reveal that FSMs have been extensively used in both past and more recent literature to analyze carbon pricing policies at the national and global levels, reflecting the controversial but continuous recognition of forest-based mitigation potentials in climate mitigation policies.

The findings relating to research question (2) indicate that both the temporal and spatial scopes of the analyses are homogenous, with a focus on the Northern Hemisphere. Tropical and boreal regions, holding significant cost-effective mitigation potentials, are solely covered by global analyses in a less detailed way. Guided by research question (1), our analysis reveals that extensions of pre-existing FSMs to integrate carbon pricing systems have been twofold. First, modelers enable FSMs to project carbon dynamics conditioned by the representation characteristics of the upstream forestry and downstream forest industries. Second, the projected carbon dynamics are valued by incorporating them into the objective function through different carbon pricing systems. To some extent, the representation of carbon pricing policies in FSM frameworks is shaped by the diverging characteristics of pre-existing models, which are related to ulterior research interests and data constraints. Maintaining the model framework obliges modelers to rely on specific assumptions and might have, in certain cases, even hindered more sound analyses. In terms of research question (3), although the reviewed FSM frameworks display technical differences, similarities between implemented carbon pricing systems are found, where their types depend on the characteristics of each carbon pool. Notable differences are observed regarding the system boundaries and carbon price pathways of implemented carbon pricing policies, as well as concerning the approaches to address issues of additionality, permanence, and leakage, analyzed in the context of research question (4). These differences may lead to differing estimates of mitigation potential, which could be amplified through variations between other model characteristics (e.g. optimization forms). The activation of forest stakeholders might depend on the characteristics of the implemented carbon pricing system. Of the identified systems, carbon rental schemes offer advantages that could increase the participation and mitigation outcomes.

When specifying forest-based mitigation contributions to the NDCs, policymakers need sound science-based findings to define appropriate targets and assess the potential contribution of supporting policies in tracking the target achievements (Ohrel 2019). For this, FSM applications provide an important knowledge base for policymakers by simulating potential outcomes of carbon pricing policies for a large panel of LULUCF mitigation measures for medium to long timeframes. Given the heterogeneity across studies, varying estimates could inform policy debates as a range of mitigation potentials in conjunction with other quantitative and qualitative inputs, while accounting for underlying modeling assumptions.

Regarding the main research questions, in the present review we have summarized the technical challenges relating to the implementation of carbon pricing systems in FSM frameworks. These challenges include the complexity of extending pre-existing FSMs to new environmental objectives other than timber production, the diversity of carbon pricing policies, and the need to address issues of additionality, permanence, and leakage. The heterogeneous behaviors of FSM frameworks facing similar carbon pricing policies are the subject of individual model inter-comparisons (Kindermann *et al* 2008, Daigneault *et al* 2022). Drawing on this scoping review, impact assessments of changing characteristics in implemented carbon pricing systems—beyond carbon price levels—on mitigation potential estimates using inter-comparisons of FSMs appear to be crucial when accounting for model-related assumptions. Such sensitivity analyses could increase the reliability of projected forest-based mitigation potentials and support their inclusion in climate mitigation policies.

Given the necessity for global and diversified responses to climate change, upcoming FSM-based research would benefit from combining strengths from global and national model frameworks to analyze carbon pricing policies with other climate change mitigation measures. Since the forest sector is interlinked with other sectors (e.g. the agricultural sector), future analyses of carbon pricing systems in the forest sector could be enhanced by accounting for intersectoral dynamics more thoroughly. In this context, cross-sectoral analyses of the leakage effects of carbon pricing policies by linking FSMs with CGE models could help assess the cost-effectiveness of forest-based mitigation measures from an overall perspective. In addition, the simultaneous impact assessment of climate change and carbon pricing policies on forest dynamics and the wood product markets will be crucial for obtaining more robust projections of climate mitigation potentials in the forest sector and, hence, increasing the reliability of forest-based mitigation measures in global climate commitments.

FSMs are shaped by continuous improvements to their frameworks and features. Some of the technical aspects discussed here might have been adapted since the publication of the reviewed articles. While some of these adaptations are addressed in this review, our aim was not to provide an overview of the current state of all reviewed FSMs.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.3220/DATA20231103100729-0 (Honkomp and Schier 2023).

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Conflict of interest

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

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