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Impacts of forest protection in the Czech Republic on the Central European wood market: A scenario analysis

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Abstract: Expanding forest protection may create a conflict between biodiversity conservation objectives and the availability of wood raw material for downstream industries. This study aimed to assess the potential impacts of this conflict on the Czech wood-processing sector and to identify mechanisms that could mitigate emerging raw-material shortages. A systematic synthesis of 311 unique studies was combined with an evidence-constrained scenario model incorporating supply restrictions, trade adjustment, production leakage, domestic adaptation, and sector-specific exposure. For the Czech reference industrial wood supply of 14.558 million m^3, three scenarios were assessed: LOW (5%), CENTRAL (12.5%), and HIGH (37%). Under the CENTRAL scenario, reference trade adjustment reduced the deficit to 559.9 thousand m^3, corresponding to 3.85% of baseline supply; with full implementation of the identified technical adaptation potential, the deficit could decline to 1.28%. Under the HIGH scenario, however, a deficit of 13.53% remained even after trade adjustment and maximum identified adaptation. The results show that the compatibility of stronger forest protection with the functioning of the wood-processing industry depends on the magnitude of the initial supply shock, trade response, implementation of adaptation measures, and maintenance of critical raw-material flows.

Keywords: market displacement; material efficiency; processing capacity; resource allocation; secondary fibre; supply-chain adaptation

European forests simultaneously provide productive, environmental, climatic, and social functions, whose importance is increasingly reflected in European environmental and economic policy. The EU Biodiversity Strategy for 2030 established a target of legally protecting at least 30% of the EU's land area, with approximately one third of protected areas subject to strict protection; particular emphasis is also placed on safeguarding the remaining primary and old-growth forests. The New EU Forest Strategy for 2030 further stresses the need to strengthen the protection, restoration, and resilience of forest ecosystems while maintaining their socio-economic functions and the competitiveness of the forest bioeconomy (European Commission 2020, 2021). This dual ambition raises a fundamental question as to the extent to which expanding area-based protection and restricting

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management intensity can be reconciled with the stable availability of wood for European processing industries.

The potential conflict between biodiversity conservation and the productive function of forests is not merely a consequence of the recent European policy agenda. It reflects the broader challenge of allocating limited forest resources among wood production, carbon sequestration, biodiversity conservation, and the provision of other ecosystem services. European research indicates that the relationships between wood production, biodiversity, and climate objectives are among the most important trade-offs discussed within the forest bioeconomy (Winkel et al. 2022; Hetemäki et al. 2024; Laimer et al. 2026). Spatial analyses further indicate that areas with high forest productivity may overlap with areas of high biodiversity value, meaning that conservation measures may affect locations with substantial production potential (Khamila et al. 2023). The optimal balance between conservation and production is therefore not universal but depends on the spatial configuration of protection, management regime, required production level, and prioritised ecosystem services (Banaś et al. 2021; Vergarechea et al. 2023).

Quantitative studies confirm that management restrictions can substantially affect the volume of wood available, although the magnitude of this effect depends strongly on the specific protection regime and regional conditions. Kärkkäinen et al. (2020) estimated that existing land-use restrictions in Finland reduced annual roundwood removals by approximately 17% compared with a scenario without such restrictions, with substantially larger effects at the regional level. Similarly, Pikkarainen et al. (2024) found that expanding protected areas increased carbon stocks, deadwood, and habitat suitability but substantially reduced timber yield during the initial periods; under certain conditions, part of this production decline could be mitigated through more intensive management in the productive parts of the landscape. A German analysis of alternative implementation pathways for the EU Biodiversity Strategy likewise demonstrated that different protection regimes can have markedly different production and economic consequences (Regelmann et al. 2023). These findings confirm that the relationship between the proportion of protected area and changes in wood supply cannot be represented by a single universal coefficient.

Broader European evidence further supports this conclusion. Räty et al. (2023) showed that the compatibility of biodiversity targets with wood production depends substantially on the spatial configuration and management design of conservation measures. Similarly, Mazziotta et al. (2023) demonstrated that the resulting biodiversity–production frontier depends on spatial configuration and the selected conservation target, while Schorn et al. (2025), in a Central European beech forest, explicitly linked biodiversity conservation value to the opportunity costs of timber harvesting. Together, these studies further support the use of a scenario-based approach rather than a single general protection–supply elasticity.

The impacts of reduced domestic harvesting also extend beyond forest and national boundaries. Wood and wood products are internationally traded commodities, and raw-material shortages in one region may be partly offset by reduced exports, increased imports, or displacement of production to other countries. Integrated forest-sector models therefore require forest resources, industrial demand, production, and international trade to be assessed jointly (Jonsson et al. 2018). More recent modelling studies of the EU Biodiversity Strategy confirm this interdependence. Di Fulvio et al. (2025) showed that conservation measures may substantially affect not only harvesting but also net exports and the external dependence of the European wood-based bioeconomy. Their model further identified leakage ranging from 22% to 79%, depending on the scenario. Similarly, Kallio and Rannestad (2025) showed that part of the reduction in European harvesting may be offset through market responses that increase production outside the regulated region. Päivinen et al. (2022) further demonstrated that constraints on harvest volumes must be interpreted jointly with subsequent developments in forest-sector markets. Recent evidence also indicates that the magnitude of leakage may vary substantially across timber assortments and time horizons (Lundmark 2025).

Production or harvest leakage is also crucial to the environmental interpretation of conservation policies. If reduced harvesting in a protected region is replaced by increased production elsewhere, a local reduction in pressure on forest ecosystems may not result in an equivalent global environmental benefit. Fischer et al. (2024) showed that potential supply regions outside the EU exhibited greater

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vulnerability than EU countries for most of the biodiversity and governance indicators assessed. Similarly, Kallio and Rannestad (2025) warned that leakage may shift harvesting pressure towards regions with greater environmental risks. Assessing conservation solely on the basis of changes in domestic harvesting may therefore overlook an important part of its actual global consequences.

For the processing industry, however, not only the total volume of available wood matters, but also its assortment, species, and spatial composition. Different parts of the forest-based value chain use different inputs and have different substitution possibilities. Sawmills depend primarily on suitable sawlog-quality raw material, panel production also uses industrial by-products and recovered wood, while the pulp and paper sector relies heavily on fibre assortments. By linking European forest resources with processing capacities, Bozzolan et al. (2024) identified, among other issues, constraints in the availability of softwood raw material in the Czech Republic and showed that procurement basins for pulp and paper and bioenergy facilities can be considerably larger than the more localised supply areas of sawmills. An aggregate reduction in wood supply may therefore not be transmitted proportionally across individual industries.

The ability of the processing sector to respond to reduced primary raw-material availability depends, among other factors, on species and feedstock substitution, circularity, and more efficient use of secondary material flows. Lauri et al. (2021) showed that substitution among coniferous, non-coniferous, and recycled biomass can substantially alter the structure of industrial consumption and regional competitiveness, while individual feedstock types cannot be regarded as perfectly interchangeable. Szichta et al. (2022) identified substantial long-term potential for recovered wood in cascading use and demonstrated that the availability of secondary raw material may increase further. The dynamic material-flow analysis by Wang and Haller (2024) additionally showed that changes in recycling, product stocks, and secondary-resource flows can influence long-term demand for primary wood. Circularity therefore represents an important adaptation pathway, although its actual contribution is constrained by technological compatibility, the quality and availability of secondary raw materials, and existing processing capacity.

Another source of competition is the use of woody biomass for energy. Forest-sector models indicate that increasing demand for, or prices of, energy wood may lead not only to greater utilisation of residual streams but also to the diversion of pulpwood and other assortments suitable for material use. Moiseyev et al. (2011) found that panel and pulp industries may be particularly exposed when energy-wood prices are high. For Sweden, Guo and Gong (2019) showed that increasing fuelwood demand intensifies competition particularly for pulpwood, whereas sawlog markets are affected to a lesser extent. A similar mechanism was documented by Hu et al. (2023), who found that the expansion of bioenergy with carbon capture and storage (Bio-CCS) particularly increases the prices of pulpwood and sawdust. Intersectoral dependencies must also be considered: lower sawmill throughput reduces the generation of sawdust, chips, and other by-products used by the panel, pulp, and energy sectors (Schwarzbauer et al. 2015).

These issues are particularly relevant to the Czech Republic. The Czech forest-based sector is characterised by the major role of coniferous wood, the traditional orientation of primary processing towards sawlogs, and substantial cross-border flows of unprocessed roundwood (Kupčák, Šmída 2015; Purwestri et al. 2020). The high share of exports of unprocessed or relatively low-processed wood and the need to increase domestic value added have long been discussed (Kupčák, Pek 2015; Paluš et al. 2017; Purwestri et al. 2020). Analyses of cascading wood use in the Czech Republic also indicate scope for more efficient utilisation of wood raw material and secondary material flows (Babuka et al. 2020). The Czech Raw Materials Policy for Wood identifies wood as a strategic renewable raw material and includes among its main priorities greater domestic processing and value creation, more efficient material utilisation, broader use of different tree species, and the principles of recycling and cascading use (Ministry of Agriculture of the Czech Republic et al. 2024). At the same time, the Czech processing industry forms part of an open Central European market, meaning that the availability of suitable assortments depends not only on domestic harvesting but also on export and import flows, processing capacities in neighbouring countries, and competition among alternative uses. In this context, Bozzolan et al. (2024) indi-

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cate an existing imbalance between the potential availability of coniferous raw material and Czech industrial capacity even before any additional supply restrictions are imposed.

The existing literature thus provides extensive evidence on individual components of the problem, but these are often analysed separately; Auer and Rauch (2021) similarly identified a lack of an integrated perspective across the wood supply chain. One group of studies evaluates biodiversity–production trade-offs, another examines forest-sector market responses and leakage, while others focus on substitution, circularity, bioenergy competition, or supply-chain resilience. Hetemäki et al. (2024) noted that only a limited proportion of the European forest-bioeconomy literature explicitly analyses synergies and trade-offs, and that their policy implications often remain general. Although recent studies have directly assessed the implications of the EU Biodiversity Strategy for European harvesting, trade, and the wood-based bioeconomy (Kallio, Rannestad 2025; Di Fulvio et al. 2025), a transparent framework is still lacking that integrates, at the level of a specific national economy, a protection-induced supply shock, trade buffering, production leakage, domestic adaptation capacity, and the differing exposure of individual processing industries.

The aim of this study is therefore to synthesise quantitative evidence on the impacts of forest protection on wood availability and the subsequent responses of the forest-based sector, and to apply the resulting evidence-constrained scenario framework to the Czech Republic. The study combines a systematic review with a mechanism-based synthesis and a Czech scenario analysis. In contrast to approaches that assess conservation, trade, or industrial adaptation in isolation, the framework sequentially distinguishes the gross supply loss, the trade-buffered domestic deficit, production leakage, technical adaptation potential, and the extent to which this potential can be realised across different parts of the processing chain.

The study addresses four research questions: RQ_1: What quantitative impacts of increased forest protection on harvesting and industrial wood availability are supported by the existing scientific literature? RQ_2: To what extent can trade adjustment and production leakage modify the domestic and global consequences of wood-supply restrictions? RQ_3: What proportion of the residual wood shortage in the Czech Republic could be mitigated by identifiable domestic adaptation mechanisms, particularly greater material use of hardwood and increased circularity of secondary raw materials? RQ_4: How are residual supply constraints transmitted to the main wood-processing industries under alternative protection scenarios?

This approach shifts the assessment beyond a simple relationship between the extent of forest protection and harvesting towards the question of how much of the initial supply shock is ultimately transmitted to the domestic wood-processing industry after trade and adaptation responses, and what broader environmental consequences such adaptation may entail.

MATERIAL AND METHODS

Systematic review and study selection. The systematic review was designed to capture scientific evidence covering the entire causal chain linking forest protection, wood availability, and responses of the forest-based sector. The review process followed the principles of PRISMA 2020 and the recommendations of the Guidelines and Standards for Evidence Synthesis in Environmental Management (Collaboration for Environmental Evidence 2022; Page et al. 2021).

The search was not restricted to studies explicitly using the term 'forest protection', but also included studies examining management restrictions, harvesting and wood-supply effects, trade and market responses, production leakage, raw-material substitution, circularity, bioenergy competition, mobilisation, and adaptation or resilience mechanisms within the wood-processing industry.

The primary bibliographic search was conducted in the Web of Science Core Collection and Scopus databases. The search strategy combined four thematic blocks: (*i*) forest protection and management restrictions, (*ii*) harvesting and wood availability, (*iii*) market, trade, and industrial effects, and (*iv*) substitution and adaptation mechanisms. Combinations of terms related to, among others, forest protection, protected areas, biodiversity conservation, harvest restriction, wood supply, timber availability, roundwood, forest sector, wood-processing industry, trade, leakage, substitution, recycled wood, cascading, and bioenergy were used. The databases, archived search-set identifiers, numbers of records retrieved, and thematic blocks

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used in the modular search strategy are reported in Table S1 in the Electronic Supplementary Material (ESM).

The results from both databases were combined and deduplicated using DOI, normalised title, and bibliographic metadata. After deduplication, the dataset comprised 3 042 unique records. Screening was conducted in two stages. Following title and abstract screening, 1 942 records were excluded, leaving 1 100 publications for full-text assessment.

Studies were included in the full-text stage if they provided evidence for at least one component of the causal chain:

forest protection or management restriction → → change in harvesting or wood availability → → market and trade response → industrial exposure → adaptation and resilience

Eligible studies assessed changes in harvesting or wood availability, trade and price responses, production displacement or leakage, raw-material substitution, circularity, cascading use, mobilisation and logistics, bioenergy competition, or implementation and resilience mechanisms. Studies focusing exclusively on ecological outcomes without an identifiable link to wood supply, markets, or industrial adaptation were excluded. European evidence was prioritised for parameterisation; studies from other regions were included only when they provided a transferable mechanism and could not independently determine the central Czech parameters.

Following verification of publication data, including DOI and source identity, full-text eligibility assessment, consolidation of study families, and final deduplication, the final evidence base comprised 311 unique studies (Figure 1). The complete list of included studies and the eligibility and exclusion framework are provided in Tables S2 and S3 in the ESM, respectively.

Evidence extraction, critical appraisal and synthesis. A structured extraction template was applied to all included studies. The information recorded included geographical area, forest type, study design, model or analytical method applied, time horizon, type of protection or management restriction, comparator, outcome variable, original unit of measurement, any harmonised effect, and key assumptions. For downstream evidence, price, trade, and industrial responses were additionally recorded, while adaptation studies were assessed for species and feedstock substitution, recovered wood, cascading use, mobilisation, logistics, and competition between material and energy uses.

Numerical results were harmonised only where the transformation was unambiguous and auditable. Relative changes in harvest volume were calculated only where the baseline was known, and leakage was expressed as the additional production outside the regulated region per unit of production decline in the region subject to the original restriction. Where an exact value could not be verified in the original source, it was recorded as not reported/not reliably retrieved and was not imputed.

Critical appraisal was adapted to the study design. For non-randomised empirical studies, the assessment drew on relevant conceptual domains of ROBINS-I (Sterne et al. 2016); however, ROBINS-I was not mechanically applied to forest-sector models, technical experiments, or scenario studies. For modelling studies, the assessment focused particularly on the transparency of model structure, definition of the comparator, explicitness of assumptions, reproducibility of parameters, and structural or scenario uncertainty. In addition to internal validity, directness, quantitative completeness, and geographical transferability were assessed separately. The complete appraisal framework and study-level assessments are provided in Table S4 in the ESM.

Studies were not reduced to a single mechanical quality score. A numerical parameter was eligible for inclusion in the main scenario architecture only if it was auditable, sufficiently direct in its relevance, and geographically transferable on a defensible basis. Technical maxima were distinguished from realised flows, and calibration assumptions from empirically identified effects.

Given the substantial heterogeneity in interventions, outcome definitions, geographical scales, and modelling designs, a pooled meta-analysis based on a common effect size was not performed. Instead, a mechanism-based structured synthesis was applied, reflecting the heterogeneous nature of the environmental evidence (Collaboration for Environmental Evidence 2022).

The resulting analytical structure was:

forest protection → gross wood-supply shock → trade buffering → residual domestic supply gap → domestic adaptation → sector-specific exposure

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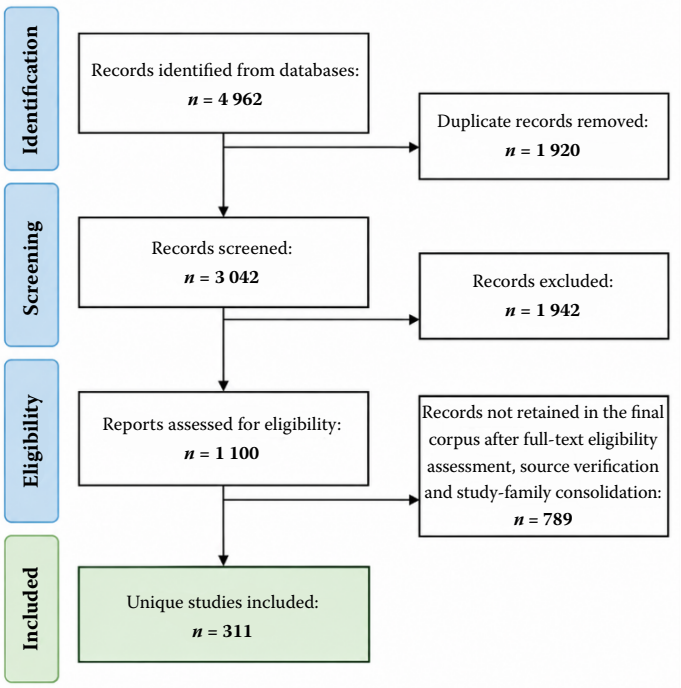

Figure 1. PRISMA 2020 flow diagram of the study selection process

Production leakage was assessed in parallel as the global consequence of the spatial displacement of production (i.e. the geographical redistribution of harvesting). The evidence-to-parameter matrix is provided in Table S5 in the ESM.

Czech baseline and feedstock structure. The Czech application was anchored to 2024, which represented the most recent complete reference year available when the model was constructed. The primary source for the assortment structure was the official statistics of the Czech Statistical Office, particularly the Deliveries of roundwood table in Forestry – data for 2024 (Czech Statistical Office 2025).

The primary physical baseline was defined as shown in Equation (1):

$$H_0 = 14.558 \text{ million m}^3 \quad (1)$$

where:

H_0 – reference industrial wood supply volume.

Given the differences between national administrative categories and fully harmonised forest-product balances, H_0 was interpreted as an industrial wood delivery proxy, rather than as a complete production–consumption balance.

The baseline was divided into four assortment groups: 8.822 million m^3 of coniferous sawlogs, 0.680 million m^3 of non-coniferous sawlogs, 4.321 million m^3 of coniferous pulpwood and other industrial wood, and 0.735 million m^3 of the corresponding non-coniferous category. Fuelwood production was not included in the reference industrial wood supply volume (H_0). For sectoral mapping, the two sawlog categories were aggregated into a sawmill feedstock pool, as defined in Equation (2):

$$F_{SAW,0} = 9.502 \text{ million m}^3 \quad (2)$$

where:

$F_{SAW,0}$ – baseline volume of the sawmill feedstock pool, comprising coniferous and non-coniferous sawlogs.

For the two fibre/other industrial wood categories, see Equation (3):

$$F_{FIBRE,0} = 5.056 \text{ million m}^3 \quad (3)$$

where:

$F_{FIBRE,0}$ – baseline volume of the fibre and other industrial wood feedstock pool, comprising coniferous and non-coniferous pulpwood and other industrial wood.

These values represent analytical feedstock pools and should not be interpreted as implying

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the exclusive end use of individual material flows. Wood-based panels were assessed separately because they use a mixture of primary wood, sawmill residues, and recovered wood. Bioenergy was modelled as a competing feedstock use rather than as an additional mutually exclusive component of H_0.

The structural plausibility of the Czech baseline was assessed against the spatial analysis by Bozzolan et al. (2024), which links European forest resources with processing capacities and identifies, among other findings, an existing shortage of coniferous raw material relative to installed processing capacity in the Czech Republic. However, these modelled values were not used as a substitute for the Czech administrative baseline.

For the trade module, indicative Czech industrial-roundwood anchors derived from harmonised forest-product statistics were used (UNECE 2024/2025; FAO 2025), see Equation (4):

$$X_0 = 1.400 \text{ million m}^3,\ M_0 = 2.100 \text{ million m}^3 \quad (4)$$

where:

X_0 – baseline volume of Czech industrial roundwood exports;

M_0 – the corresponding baseline import volume.

While X_0 entered directly into the export-buffer constraint, M_0 served as a contextual trade anchor and plausibility check rather than as an explicit upper bound on import replacement.

Protection, trade and leakage scenarios. The impact of forest protection was not modelled as a direct function of the percentage of protected area. The systematic evidence indicates that the harvest response depends on the intensity of management restrictions, the spatial configuration of protection, baseline management intensity, and the scope for compensatory management outside protected areas (Kärkkäinen et al. 2020; Räty et al. 2023; Regelmann et al. 2023; Pikkarainen et al. 2024).

Based on triangulation of the quantitative evidence, three evidence-constrained supply-shock scenarios were defined, representing LOW, CENTRAL, and HIGH levels of supply restriction. Their quantitative parameterisation is reported in the Results and Discussion (Table 1). These values were not interpreted as probabilities or as universal causal effects of protected-area expansion. The LOW, CENTRAL, and HIGH scenarios represent alternative magnitudes of protection-induced wood-supply restrictions relative to the 2024 Czech baseline, rather than successive stages of a time-dependent projection. No fixed future year was assigned to individual scenarios, as the timing of supply responses depends on the implementation and intensity of forest protection measures. The results should therefore be interpreted as comparative, conditional supply outcomes rather than forecasts for specific calendar years. The gross supply shock was calculated according to Equation (5):

$$\Delta H_s^{gross} = h_s H_0 \quad (5)$$

where:

ΔH_s^{gross} – gross reduction in industrial wood supply under scenario s, before trade adjustment and domestic adaptation;

h_s – relative supply shock under scenario s.

Domestic trade buffering refers to the mitigation of a domestic industrial wood-supply shortage through adjustments in international trade flows. In the model, this mechanism was applied sequentially: first, part of the wood originally intended for export was redirected to the domestic market (export redirection), and second, part of the remaining shortage was compensated for by additional imports (import replacement), see Equations (6) and (7):

$$B_{X,s} = \min\left(\Delta H_s^{gross}, EBR \times X_0\right) \quad (6)$$

$$D_s^{trade} = \left(1 - IRR_{CZ}\right)\max\left(0, \Delta H_s^{gross} - B_{X,s}\right) \quad (7)$$

where:

$B_{X,s}$ – volume of the gross supply reduction offset by redirecting exports to the domestic market under scenario s;

EBR – export-buffering ratio, representing the maximum proportion of baseline exports available for redirection;

D_s^{trade} – remaining domestic industrial wood-supply deficit after export redirection and import replacement under scenario s;

IRR_{CZ} – import-replacement ratio, representing the assumed proportion of the remaining supply deficit offset by additional imports in the Czech Republic.

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Table 1. Evidence-constrained protection-induced wood-supply scenarios

Scenario	Supply shock (%)	Interpretation
LOW	5.0	limited supply effect and/or effective compensation outside protected areas
CENTRAL	12.5	main reference scenario
HIGH	37.0	upper evidence-based stress scenario

LOW, CENTRAL and HIGH are evidence-constrained scenario values derived from the structured synthesis; they are not empirical elasticities of protected-area expansion

The post-trade gap (D_s^{trade}) represents the remaining domestic industrial wood-supply deficit after export redirection and import replacement, but before the implementation of domestic adaptation measures. The reference values represent calibrated working assumptions, rather than empirically estimated Czech trade elasticities: $EBR = 0.50$, $IRR_{CZ} = 0.50$.

Production leakage refers to the displacement of harvesting or wood production to regions outside the area subject to forest protection restrictions, where additional production may partially compensate for the reduction in the regulated region. In the model, production leakage was quantified as the proportion of the initial supply reduction offset by additional production elsewhere and was assessed separately from the domestic trade response, see Equation (8):

$$L_s^{phys} = \lambda_s \Delta H_s^{gross} \quad (8)$$

where $\lambda_{LOW} = 0.22$; $\lambda_{CENTRAL} = 0.60$; $\lambda_{HIGH} = 0.79$

where:

L_s^{phys} – volume of additional wood production outside the regulated region attributable to production leakage under scenario s;

λ_s – production leakage coefficient under scenario s, representing the proportion of the gross supply reduction offset by additional production outside the regulated region.

The range was derived from European forest-sector evidence, particularly Di Fulvio et al. (2025) and Kallio and Rannestad (2025). Leakage was not deducted from the Czech residual supply gap because domestic scarcity and international production displacement represent two distinct analytical quantities.

Domestic adaptation and implementation. Following trade buffering, three potential domestic adaptation mechanisms were considered: increased material use of hardwood, circularity/recovered wood, and additional mobilisation of domestic resources.

For hardwood adaptation, no defensible universal softwood–hardwood substitution coefficient was identified. The Czech diagnostic cap $A_{HW} = 83 \times 10^3$ m^3 was therefore derived solely as the difference between broadleaf sawlog availability reported by Bozzolan et al. (2024) and the Czech administrative baseline. This value represents a diagnostic cap, rather than guaranteed 1 : 1 substitution of softwood by hardwood.

For circularity, an explicitly identified Czech technological development project focused on oriented strand board (OSB) production was used. The project 'OSB with Increased Amount of Recycled Wood' aims to increase the proportion of recycled wood in the production mix from the current 5–10% to 25–35%, with an estimated saving of approximately 290 thousand m^3 of virgin wood raw material per year (Technology Agency of the Czech Republic 2025). However, the publicly available project description does not specify whether this estimate refers to a particular production facility or a broader application of the technology. Therefore, the value cannot be interpreted as a verified industry-wide substitution potential. In the scenario model, the technical circularity adaptation cap ($A_{CIRC} = 290 \times 10^3$ m^3·yr^{-1})was retained as a conditional, project-derived forward technical cap, rather than an observed material flow or an established national adaptation capacity.

For general additional mobilisation in the Czech Republic, sufficiently robust short- to medium-term evidence was not identified. The core model therefore assumed zero additional domestic wood mobilisation in the Czech Republic ($A_{MOB, CZ} = 0$). This decision does not imply the absence of local or resource-specific mobilisation potential. It reflects only the distinction between theoretical resource availability and additional supply that can actually be realised, as highlighted by the broader European evidence (Olschewski et al. 2019; Alberdi et al. 2020; Eriksson et al. 2024).

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Technical potential was not equated with realised adaptation. For mechanism *j*, see Equation (9):

$$A_j^{real} = g_j A_j^{technical}, \quad 0 \le g_j \le 1 \tag{9}$$

where:

A_j^{real} – realised adaptation volume for mechanism *j*;

g_j – implementation coefficient for adaptation mechanism *j*, ranging from 0 to 1;

$A_j^{technical}$ – maximum identified technical adaptation potential for mechanism *j*.

Given the lack of evidence supporting a single universal implementation coefficient g_j was not assigned a single central value. Instead, three ordinal implementation states were distinguished: I-LOW, I-CENTRAL, and I-HIGH. I-CENTRAL was not mechanically represented by a value of 0.5. The implementation states describe alternative degrees of adaptation realisation rather than predefined implementation periods. In practice, export redirection and import adjustments may respond more rapidly to supply restrictions, whereas increased hardwood utilisation and the expansion of recycled-wood processing depend on technological, organisational, and investment conditions and may require longer implementation periods. As the available evidence did not support robust Czech-specific implementation timelines, no fixed number of years was assigned to the adaptation states. Consequently, the maximum adaptation case represents a conditional technical potential, not an estimate of adaptation achievable within a specified period.

The integrated residual deficit was expressed as Equation (10):

$$D^{INT} = \max\left(0, D^{\text{trade}} - g_{HW} A_{HW} - g_{CIRC} A_{CIRC} - g_{MOB} A_{MOB}\right) \tag{10}$$

where:

D^{INT} – integrated residual domestic industrial wood-supply deficit after trade adjustment and domestic adaptation;

D^{trade} – domestic industrial wood-supply deficit remaining after trade adjustment;

g_{HW} – implementation coefficient for hardwood adaptation;

A_{HW} – diagnostic technical cap for additional hardwood utilisation;

g_{CIRC} – implementation coefficient for circularity adaptation;

A_{CIRC} – conditional technical cap for primary wood savings through increased use of recovered wood;

g_{MOB} – implementation coefficient for additional domestic wood mobilisation;

A_{MOB} – technical potential for additional domestic wood mobilisation.

For all mechanisms, the model applied the rule that one physical m^3 could offset the deficit only once.

Sectoral transmission and uncertainty analysis. In the final step, the residual deficit was allocated to the main segments of the wood-processing industry according to their dominant feedstock dependence. Sawmilling was linked primarily to the baseline sawmill feedstock pool ($F_{SAW,0}$), and pulp/fibre processing to the baseline fibre and other industrial wood feedstock pool ($F_{FIBRE,0}$), whereas wood-based panels were assessed on the basis of a combination of primary fibre, industrial residues, and recovered wood.

The availability of industrial residues was considered partly endogenous to sawmill output, as lower sawmill throughput simultaneously reduces the available volume of sawdust, wood chips and other by-products for the panel, pulp and bioenergy sectors, see Equation (11):

$$Residues_t = f\left(Y_{SAW,t}\right) \tag{11}$$

where:

$Residues_t$ – volume of industrial wood residues available at time *t*;

f – functional relationship between sawmill output and the availability of industrial wood residues;

$Y_{SAW,t}$ – sawmill output at time *t*.

Only sensitivity multipliers were used to provide an indicative conversion of feedstock scarcity into industrial output response, see Equation (12):

$$\frac{\Delta Y_k}{Y_{k,0}} = -\beta_k d_k \tag{12}$$

where:

$Y_{k,0}$ – baseline output of wood-processing sector *k*;

ΔY_k – change in output of sector k relative to the baseline;

β_k – sensitivity multiplier translating relative feedstock scarcity into a conditional output response for sector *k*;

d_k – relative feedstock exposure of the sector *k* and $\beta_{SAW} = 0.8$, $\beta_{PANEL} = 1.0$, $\beta_{PULP} = 0.8$.

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These values are not empirically estimated Czech production elasticities, and the results derived from them were interpreted exclusively as conditional sensitivity outcomes.

Bioenergy competition was analysed as a separate source of structural uncertainty. Under the reference E-NORMAL setting, no universal negative volume was added to the Czech supply gap. Under the E-STRESS variant, stronger competition for pulpwood, industrial residues, and recovered wood was considered, but only at the sectoral level rather than through a single national coefficient. This approach is consistent with evidence showing differing exposure across individual feedstocks and industries (Guo, Gong 2019; Moiseyev et al. 2011; Jåstad et al. 2020; Hu et al. 2023).

Uncertainty was assessed through structured scenario sensitivity rather than Monte Carlo simulation, because probability distributions could not be empirically identified for several parameters. Changes in the protection shock, trade calibration, adaptation configuration, implementation state, bioenergy regime, and sectoral transmission assumptions were systematically compared.

Quality assurance included checks of mass balance, units and direction of effect, monotonicity (LOW ≤ CENTRAL ≤ HIGH), the constraint $0 \leq \lambda \leq 1$, the condition that realised adaptation does not exceed the corresponding technical potential ($A^{real} \leq A^{technical}$), the prohibition of double counting, and the provenance of every active parameter.

The complete parameter, sensitivity, scenario, and QA register is provided in Table S6 in the ESM.

Employment and gross value added were not converted into point forecasts because no sufficiently robust Czech causal coefficient was identified to derive them from the output shock. The main results of the study are therefore presented hierarchically as:

physical wood supply → residual feedstock exposure → conditional industrial sensitivity

RESULTS AND DISCUSSION

Systematic-review evidence and protection–wood-supply effects. The final evidence base comprised 311 unique studies covering both the direct relationship between forest protection and wood availability and the associated trade, adaptation, institutional, and industrial mechanisms. For quantification of the initial supply shock, the most relevant studies were those directly addressing harvest, removals, or timber availability and providing sufficient quantitative completeness and geographical transferability. The overall direction of the evidence was consistent: stricter forest protection or management restrictions generally reduce the productive use of forests, whereas the magnitude of the effect depends strongly on the specific protection regime, its spatial configuration, and the scope for compensatory management.

Kärkkäinen et al. (2020) estimated an approximately 17% reduction in national roundwood removals in Finland compared with a scenario without land-use restrictions, with substantially larger impacts at the regional level. Pikkarainen et al. (2024) found that increasing the conservation area by 10–20% resulted in an approximately 17–38% decline in timber yield during the first 30-year period, while also showing that part of the production loss could be mitigated over the longer term through changes in management outside protected areas. Similarly, Regelmann et al. (2023) demonstrated for Germany that alternative implementation pathways for the EU Biodiversity Strategy can result in markedly different harvest effects.

The results further indicate that the spatial and management design of forest protection plays an important role. Eggers et al. (2022) showed that management diversification can, under some configurations, improve biodiversity indicators while maintaining or increasing harvest levels in the production-oriented parts of the landscape. Räty et al. (2023) likewise confirmed that the compatibility of biodiversity objectives with wood production depends on the specific spatial and management configuration. Mazziotta et al. (2023) identified different ecological–economic frontiers under alternative spatial strategies, while Schorn et al. (2025) directly quantified the opportunity costs associated with maintaining biodiversity value in Central European beech forests. This evidence supports a scenario-based interpretation and does not support the assumption that a given percentage increase in forest protection necessarily results in an equivalent percentage reduction in harvesting.

Based on triangulation of the studies with the highest directness and quantitative completeness, the LOW (5%), CENTRAL (12.5%), and HIGH (37%) scenarios were therefore defined (Table 1).

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CENTRAL represents the reference value within the central range of the strongest evidence rather than the mean of all published estimates; HIGH represents the upper stress range rather than an expected development in the Czech Republic.

The systematic synthesis therefore provides strong evidence for the direction of the protection–supply effect, but substantially weaker support for any single universal numerical magnitude. In the subsequent analysis, the protection shock is therefore interpreted as an initial physical supply constraint whose actual impact on the Czech wood-processing industry is subsequently modified by trade, adaptation, and the structure of individual feedstock markets.

Czech wood-supply impacts, trade buffering and leakage. Applying the scenarios from Table 1 to the Czech reference industrial wood supply of H_0 = 14.558 million m^3 resulted in a gross supply loss of 727.90 thousand m^3 under the LOW scenario, 1 819.75 thousand m^3 under CENTRAL, and 5 386.46 thousand m^3 under HIGH. These values represent the initial physical supply constraint before international trade responses and domestic adaptation.

Reference trade buffering substantially reduced these deficits. With EBR = 0.50 and IRR_{CZ} = 0.50, the residual gaps after trade adjustment were 13.95 thousand m^3 under LOW, 559.88 thousand m^3 under CENTRAL, and 2 343.23 thousand m^3 under HIGH, corresponding to 0.10%, 3.85%, and 16.10% of the Czech baseline, respectively (Table 2).

The results reveal a marked difference between the gross supply shock and domestic scarcity. Under the LOW scenario, existing trade flexibility can absorb almost the entire shock. Under CENTRAL, trade reduces the initial deficit from 12.5% to 3.85%, whereas under HIGH, more than 2.3 million m^3 remains unavailable even after the reference trade response. Thus, as the magnitude of the shock increases, the relative stabilising capacity of trade declines.

This mechanism is consistent with the broader forest-sector literature. Di Fulvio et al. (2025) show that protection-induced changes in the EU affect not only harvesting but also the trade position and external sourcing. Similarly, Kallio and Rannestad (2025) model a substantial response of global production to reduced European supply. Päivinen et al. (2022) further confirm that harvest constraints need to be interpreted in the context of subsequent market adjustment. Lenglet et al. (2017) demonstrate a comparable mechanism in the context of log-export policy: export restrictions can increase domestic availability for processors while simultaneously redistributing material flows across markets and industries.

Trade buffering, however, is not equivalent to global environmental compensation. Di Fulvio et al. (2025) identified production leakage of approximately 22–79%, depending on the protection scenario. In their main EU Biodiversity Strategy (EUBDS) scenario, Kallio and Rannestad (2025) found that approximately two-thirds of the reduction in European harvesting was replaced by production in other regions. Comparable estimates were reported by Lundmark (2025), who found that approximately 24–77% of a regional timber-supply restriction may be offset by increased harvesting elsewhere, with the magnitude depending on the product group and time horizon.

From an environmental perspective, the destination of this displacement is also important. Fischer et al. (2024) found that almost 80% of the assessed biodiversity/governance indicators indicated greater vulnerability in potential non-EU leakage destinations. Maintaining domestic processing capacity through imports may therefore

Table 2. Protection-induced supply loss, trade buffering and production leakage in the Czech scenarios

Scenario	Gross loss (ths m^3)	Post-trade gap (ths m^3)	Gap/H_0 (%)	Leakage λ	Physical leakage (ths m^3)
LOW	727.90	13.95	0.10	0.22	160.14
CENTRAL	1 819.75	559.88	3.85	0.60	1 091.85
HIGH	5 386.46	2 343.23	16.10	0.79	4 255.30

Trade-buffering results use the reference Czech calibration EBR = 0.50 and IRR_{CZ} = 0.50; these are calibrated working assumptions rather than empirical Czech trade elasticities; the post-trade gap represents the remaining domestic industrial wood-supply deficit after trade adjustment and before domestic adaptation; leakage coefficients constitute a separate scenario layer and are not deducted from the Czech residual gap

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not result in an equivalent improvement in global biodiversity outcomes.

The CENTRAL scenario can therefore be summarised as:

12.5% gross supply shock → 3.85% post-trade domestic gap

This residual deficit provides the starting point for assessing domestic adaptation.

Domestic adaptation potential. Following trade adjustment, the main numerically defensible domestic adaptation pathways identified were increased material use of hardwood and greater circularity through recovered wood. By contrast, sufficiently strong evidence for a general short- to medium-term Czech mobilisation offset was not identified, and the core model therefore retains: $A_{MOB,\ CZ} = 0$.

This conservative approach is consistent with the broader European literature. Alberdi et al. (2020) show that total forest resources differ substantially from actual forest availability for wood supply once environmental and technical constraints are taken into account. Eriksson et al. (2024) further show that potential supply may be overestimated if the actual harvesting behaviour of forest owners is not considered. Olschewski et al. (2019) confirm that mobilisation is not solely a biological issue but also depends on decision-making and market incentives. Logistics optimisation can improve the use of existing resources, but cannot create a new biological resource pool. Trzciński and Tymendorf (2020), for example, demonstrate substantial scope for reducing transport work through more efficient organisation of deliveries.

For hardwood adaptation, no evidence supporting a universal softwood–hardwood substitution coefficient was identified. Lauri et al. (2021) demonstrate substantial substitution potential among coniferous, non-coniferous, and recycled biomass, but also show that this potential depends strongly on end-use requirements. Auer and Rauch (2025) document considerable scope in Germany for shifting hardwood from energy to material use, but this cannot be translated into a 1 : 1 Czech substitution coefficient. For the Czech Republic, only a diagnostic headroom of 83 thousand m^3 was therefore used, derived from the difference between modelled broadleaf sawlog availability reported by Bozzolan et al. (2024) and the Czech administrative baseline.

Greater potential was identified for circularity. Szichta et al. (2022) show increasing recovered-timber potential in Germany, while the dynamic material-flow analysis by Wang and Haller (2024) confirms that the long-term development of product stocks, recycling, and secondary material flows can substantially affect primary wood requirements. Goldaraz-Salamero et al. (2024) document opportunities for cascading pathways within specific European product chains, and Zhang et al. (2026) show that greater circularity can simultaneously reduce dependency on primary wood imports. The broader technological and institutional conditions of a wood-based circular bioeconomy are reviewed by Ali and Russell (2025).

For the Czech application, however, only an explicitly identified technological forward case was used. The project 'OSB with Increased Amount of Recycled Wood' assumes an increase in recycled content from approximately 5–10% to 25–35% and estimates a potential saving of approximately 290 thousand m^3 of primary wood raw material per year (Technology Agency of the Czech Republic 2025). The maximum identified technical pool therefore amounts to: 83 + 290 = 373 thousand m^3. Its effect is summarised in Table 3.

Table 3. Domestic adaptation and residual Czech wood-supply gap

Scenario/technical adaptation case	Adaptation (ths m^3)	Residual gap (ths m^3)	Gap/H_0 (%)
CENTRAL – no additional adaptation	0	559.88	3.85
CENTRAL – full hardwood diagnostic cap	83	476.88	3.28
CENTRAL – full hardwood + circularity caps	373	186.88	1.28
HIGH – no additional adaptation	0	2 343.23	16.10
HIGH – full hardwood + circularity caps	373	1 970.23	13.53

The 83 ths m^3 hardwood value is a diagnostic headroom, whereas 290 ths $m^3 \cdot yr^{-1}$ is a forward technical circularity cap; full-cap cases assume high implementation and should not be interpreted as forecasts

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The difference between CENTRAL and HIGH is substantial. Under CENTRAL, the maximum identified technical adaptation can absorb approximately 66.6% of the post-trade gap, whereas under HIGH, it can absorb only 15.9%. These values are consistent with the calculations reported in the study.

To reduce the CENTRAL gap below 2% of H_0 at least 268.7 thousand m^3 of adaptation must be realised. Assuming full use of the 83 thousand m^3 hardwood headroom, this requires realisation of approximately 64% of the identified circularity cap.

The results therefore highlight the distinction between technical availability and implementation. A moderate supply shock can be substantially mitigated by the available adaptation mechanisms, whereas the HIGH shock remains structurally significant even with full utilisation of all domestic adaptation caps identified to date.

Sector-specific implications for the wood-processing industry. The residual national deficit is not transmitted uniformly across all wood-processing industries. Feedstock quality, substitution possibilities, and linkages between primary and secondary material flows are critical. Sawmills depend predominantly on sawlogs, panel production on a combination of primary wood, industrial residues, and recovered wood, and pulp production primarily on pulpwood/fibre.

Sawmilling has limited scope to substitute secondary raw materials for high-quality coniferous sawlogs. At the same time, however, it represents an upstream segment for other industries because it generates chips, sawdust, and other industrial residues. Schwarzbauer et al. (2015) showed that constraints on sawmill capacity can reduce the availability of these secondary flows and transmit the supply constraint to other forest-based industries.

For the Czech context, experience with a disturbance-induced shock operating in the opposite direction is also relevant. Maitah et al. (2022) demonstrated that salvage harvesting affected the price development of spruce fuel biomass and spruce pulpwood in the Czech Republic. This study does not provide a direct coefficient for protection-induced scarcity, but it confirms the sensitivity of these assortment markets to substantial changes in supply.

Wood-based panels have the highest identified circularity potential, which at the same time creates a specific source of vulnerability. Recovered wood and industrial residues can reduce primary feedstock requirements, but the same material flows can also be used for bioenergy. Under stronger energy demand, the mechanism that enhances the adaptive capacity of the panel sector may therefore itself be constrained by competing use.

Pulp and paper are particularly exposed to competition for fibre. Guo and Gong (2019) show that higher fuelwood demand increases pressure particularly on pulpwood markets, while Hu et al. (2023) found that Bio-CCS expansion had a stronger impact on pulpwood and sawdust than on sawlogs. Similarly, Moiseyev et al. (2011) show that at high energy-wood prices, the pulp and panel industries may be more strongly affected than sawmilling. Policies supporting forest-based liquid biofuels may further intensify competing demand (Jåstad et al. 2020).

Competition for fibre does not arise solely from energy use. Kallio (2021) shows the growing importance of wood-based textile fibres as an additional market using pulp-quality feedstock. More generally, Buongiorno (2021) confirms that changes in supply and demand propagate through prices, trade, and substitution across interconnected forest-product markets. This supports the interpretation of sectoral exposure as a network phenomenon rather than an isolated one. The resulting profile is summarised in Table 4.

The working coefficients $\beta_{SAW} = 0.8$, $\beta_{PANEL} = 1.0$ and $\beta_{PULP} = 0.8$ remain sensitivity parameters only. The main result therefore does not consist of a point forecast of industrial output, but rather in identifying the feedstock constraints and inter-industry linkages that are critical for individual sectors. The results thus show that assortment-specific and secondary material flows, rather than the aggregate national gap alone, determine sectoral vulnerability.

From manageable scarcity to structural stress: integrated interpretation and policy implications. The integrated results distinguish three qualitatively different states. Under the reference trade response, LOW is almost fully absorbed. CENTRAL represents manageable but materially significant scarcity, whose final magnitude depends on the actual implementation of adaptation measures. HIGH represents structural stress because neither trade nor the maximum identified adaptation pool is sufficient to eliminate most of the deficit.

Under the CENTRAL scenario, the post-trade gap amounts to 3.85% of H_0. With full realisation of the

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Table 4. Qualitative evidence-based sectoral exposure and adaptation profile

Sector	Primary feedstock risk	Adaptation capacity	Bioenergy-stress exposure	Main systemic linkage
Sawmills	sawlog scarcity	low–medium	medium	lower throughput reduces residue supply
Panels	residues/ recovered wood	high	very high	circularity competes with energy use
Pulp/paper	pulpwood/ fibre scarcity	medium	very high	direct competition for fibre
Bioenergy	secondary and low-quality wood allocation	high flexibility	driver	can crowd out material uses

Categories represent qualitative evidence-synthesis rankings and should not be interpreted as estimated sector-specific elasticities

identified hardwood and circularity caps, it can decline to 1.28%. This value, however, represents the best identified conditional adaptation case, assuming full realisation of the specified technical potentials, rather than a forecast of what can be achieved within a particular time horizon. The critical factor is the implementation gap between technical and realised potential. The circularity component requires particular caution because the assumed saving of 290 thousand m^3 per year originates from a specific OSB technology development project. The available project information does not establish its applicability across the Czech wood-processing industry. Consequently, the modelled contribution of recycled wood should be interpreted as a conditional sensitivity assumption, not as an empirically verified national substitution capacity.

García-Jácome et al. (2025) show that the operational resilience of timber-supply systems depends, among other factors, on processing capacity, harvesting systems, and value-chain organisation. Paluš et al. (2017) confirm the importance of market pull in the implementation of standards in the Czech and Slovak wood-processing sector. Creutzburg and Lieberherr (2021) further show that willingness to mobilise wood depends on actor preferences and policy networks, meaning that theoretical resource potential cannot automatically be translated into realised supply.

At the supply-chain level, part of the implementation risk can be reduced through better coordination. Kogler and Rauch (2020) demonstrate the importance of contingency planning in addressing bottlenecks, while Mensah et al. (2025) identify sourcing diversification, logistics coordination, and risk management as key elements of resilience in wood-product supply chains. These mechanisms increase the system's capacity to absorb a shock; however, they do not create additional biological volumes of wood.

The HIGH scenario is qualitatively different. Without adaptation, the remaining availability corresponds to approximately 83.9% of the baseline, whereas with the maximum identified adaptation, it reaches approximately 86.5%. García-Jácome et al. (2025) used a lower resilience threshold of around 86% of the reference supply for the Czech Kostelec case. This benchmark has only case-specific diagnostic status and should not be interpreted as a universal critical threshold for the Czech Republic.

For policy interpretation, the states shown in Table 5 were therefore distinguished.

Following trade adjustment, the CENTRAL reference case falls within the YELLOW state. The main priority is therefore not a generic increase in harvesting, but more efficient use of existing resources: greater circularity, particularly in the panel sector; protection of industrial-residue flows; sourcing diversification; increased material use of suitable hardwood; and coordination of material–energy allocation.

Without adaptation, HIGH enters the RED state. At this level, individual firm-level adaptations are no longer sufficient, and a combination of protection design, trade strategy, feedstock allocation, maintenance of processing capacity, and the design of biomass incentives becomes relevant. Over the longer term, the adaptation portfolio could be complemented by productivity improvements, planted-forest pathways, or ad-

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Table 5. Operational residual-scarcity states used for policy interpretation

State	Residual gap (%)	Interpretation	Policy orientation
GREEN	$D < 2$	low residual scarcity	monitoring, efficiency, gradual adaptation
YELLOW	$2 \leq D < 5$	manageable material scarcity	circularity, sourcing diversification
ORANGE	$5 \leq D < 14$	emerging structural stress	feedstock and processing-capacity protection
RED	$D \geq 14$	case-specific resilience warning	resilience-first system response

D – residual deficit expressed as percentage of the baseline; the 2% and 5% boundaries are operational decision thresholds; the 14% boundary is a case-specific diagnostic benchmark derived from the Czech resilience case reported by García-Jácome et al. (2025) and is not a universal national tipping point

ditional wood resources outside close-to-nature forests (Candelier et al. 2026). These measures, however, represent long-run structural adaptation rather than a short-term offset to the Czech deficits modelled here.

Under scarcity, the hierarchy of wood use also becomes increasingly important. Energy use of genuine residual flows may involve a relatively low opportunity cost, whereas diverting material-suitable pulpwood, industrial residues, or recovered wood to energy production may increase pressure on the pulp and panel industries. The results therefore support the following principle:

Highest suitable material use → cascading use → → energy use

This hierarchy does not imply the exclusion of bioenergy, but rather recognition of the alternative material value of individual feedstocks.

Production leakage remains an important constraint on domestic adaptation. Trade responses may help preserve Czech processing capacity while simultaneously shifting part of the harvesting pressure outside the EU. Domestic economic resilience and global biodiversity effectiveness therefore cannot be regarded as equivalent objectives.

The main integrated result can be summarised as:

CENTRAL: 12.5% → 3.85% → 1.28%

where the final value represents the best identified forward adaptation case, whereas:

HIGH: 37.0% → 16.10% → 13.53%

remains a structural-stress scenario even with full realisation of all currently identified domestic adaptation caps.

The results therefore do not support a simple dichotomy in which stronger forest protection is either economically compatible or incompatible with the Czech wood-processing sector. Rather, this compatibility is state-dependent: it depends on the magnitude of the supply shock actually induced, trade flexibility, the realisation of circularity and other adaptation mechanisms, the maintenance of critical feedstock flows, and whether domestic economic adaptation generates disproportionate environmental displacement in other regions.

CONCLUSION

This study combined a systematic evidence synthesis with an evidence-constrained scenario model to assess how stronger forest protection could affect wood availability and the wood-processing industry in the Czech Republic. The review covered 311 unique studies and showed that forest protection generally reduces harvest or timber availability, but that the magnitude of this effect varies substantially according to management restrictions, spatial configuration, and the possibility of compensatory management outside protected areas. For this reason, the analysis used LOW, CENTRAL, and HIGH supply-shock scenarios rather than a single universal protection elasticity.

Applied to the Czech 2024 industrial wood baseline of 14.558 million m^3, the CENTRAL scenario produced a gross supply reduction of 12.5%. Under the reference trade calibration, this translated into a post-trade domestic gap of 559.9 thousand m^3, or 3.85% of the baseline. The HIGH scenario remained substantially more severe: a 37% gross shock resulted in a post-trade deficit of 2.343 million m^3, or 16.10%. These results show that trade can strongly buffer small and medium domestic

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supply shocks, but its stabilising role becomes insufficient when the initial restriction is large.

Domestic adaptation further changes the outcome, although its potential is clearly bounded. The identified Czech adaptation pool consisted of an 83 thousand m^3 diagnostic hardwood headroom and a 290 thousand $m^3 \cdot yr^{-1}$ forward technical circularity cap. If fully realised, these mechanisms could reduce the CENTRAL residual gap from 3.85% to 1.28% of the baseline, absorbing about two-thirds of the post-trade deficit. The same adaptation pool would reduce the HIGH scenario only from 16.10% to 13.53%, indicating that strong protection-induced supply restrictions would remain a structural challenge even under favourable implementation conditions.

The analysis also demonstrates that aggregate wood scarcity does not translate uniformly across industries. Sawmills are particularly dependent on sawlog availability and play an additional systemic role as producers of industrial residues. Wood-based panels have the highest identified circularity potential but are also highly exposed to competition for recovered wood and residues. Pulp and paper are especially vulnerable to competition for pulpwood and fibre under strong bioenergy demand. Consequently, the industrial implications of forest protection depend not only on the quantity of available wood, but also on assortment structure, secondary-material flows, and competition between material and energy uses.

A further finding is that domestic economic resilience and global biodiversity effectiveness are not equivalent objectives. Trade buffering can reduce the Czech supply deficit while part of the original harvesting pressure is displaced abroad. Where such leakage is directed towards regions with greater biodiversity or governance vulnerability, part of the environmental benefit of domestic protection may be weakened. Forest-protection policy should therefore be assessed simultaneously from the perspectives of domestic raw-material security and external environmental displacement.

The results support a state-dependent policy response. Moderate scarcity can be addressed primarily through circularity, sourcing diversification, maintenance of critical industrial-residue flows, and improved material use of suitable hardwood. Stronger shocks require a broader resilience-oriented response combining protection design, feedstock allocation, trade strategy, maintenance of processing capacity, and coordination of material and energy uses. Under constrained supply, the results support prioritising the highest suitable material use, followed by cascading and only subsequently energy use, where technically and economically appropriate.

Overall, the study shows that the compatibility of stronger forest protection with the Czech wood-processing sector is not determined by protection targets alone. It depends on the size of the initial supply shock, the capacity of trade to buffer domestic scarcity, the realistic implementation of adaptation measures, and the preservation of critical feedstock flows. The CENTRAL scenario indicates that a moderate protection-induced shock may remain manageable if adaptation is effectively implemented, whereas the HIGH scenario remains a structural-stress case that cannot be resolved by the currently identified adaptation options alone.

The main contribution of the study is therefore the integration of forest-protection evidence, trade buffering, leakage, domestic adaptation, and sector-specific vulnerability within a single transparent framework that distinguishes evidence-constrained parameters, calibrated assumptions, technical caps, and sensitivity relationships. This distinction avoids false precision and provides a reproducible basis for evaluating trade-offs between biodiversity protection, wood availability, and industrial resilience in the Czech Republic.

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