https://doi.org/10.17221/43/2026-JFS

Evaluation of selected forest ecosystem services in forest management planning using multi-criteria decision analysis: A pilot study in the Czech Republic

Jan Kašpar, Zohreh Mohammadi, Meryem Tahri*

Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic

**Corresponding author: kasparj@fld.czu.cz*

Citation: Kašpar J., Mohammadi Z., Tahri M. (2026): Evaluation of selected forest ecosystem services in forest management planning using multi-criteria decision analysis: A pilot study in the Czech Republic. J. For. Sci., 72: 308–321.

Abstract: Forest ecosystems provide multiple ecosystem services (ES), including timber production, carbon sequestration, biodiversity conservation, soil protection, and cultural functions. Integrating these often conflicting objectives into forest management planning represents a complex multi-criteria decision-making (MCDA) problem. This study proposes a practical MCDA framework for evaluating selected ecosystem services within the Czech forest management planning system (LHP/LHO). The framework integrates forest growth simulation, ecosystem service indicators, GIS data, and MCDA methods. Five indicators were evaluated: wood production, carbon stock, erosion risk, biodiversity, and cultural ecosystem value. Criteria weights were derived using the analytical hierarchy process (AHP), while management scenarios were ranked using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and PROMETHEE methods. A pilot simulation over a 100-year horizon compared four forest management scenarios: clear-cutting, shelterwood, selective, and non-intervention management. Selective management achieved the highest multifunctional sustainability [composite sustainability index (*CSI*) = 0.855], combining relatively high production with strong ecological and cultural performance. Clear-cutting management maximised short-term production but showed higher erosion risk and lower biodiversity. The study demonstrates the potential of MCDA to support transparent multifunctional forest management under Central European conditions.

Keywords: Czech Republic forests; non-productive forest functions; strategic planning; sustainability assessment

Forest ecosystems provide a wide spectrum of ecosystem services (ES), including timber production, carbon sequestration, soil and water protection, biodiversity conservation, and cultural and recreational functions. These services form the ecological and socio-economic foundation of sustainable forest management and are increasingly recognised as essential components of climate change adaptation and regional resilience strategies. At the same time, many of these ecosystem

Supported by the Ministry of Agriculture of the Czech Republic for the period 2021–2025 within the project 'Adaptation of forestry for sustainable use of natural resources' (Grant No. QK21010198).

https://doi.org/10.17221/43/2026-JFS

services are mutually conflicting. Management approaches maximising timber production may reduce biodiversity, increase erosion risk, or lower long-term ecosystem stability, whereas non-intervention management may support ecological integrity but significantly reduce provisioning services. Forest management planning therefore represents a complex multi-objective decision-making problem requiring transparent evaluation of trade-offs among competing ecosystem functions.

The growing intensity of climate change, increasing disturbance regimes, and rising societal demands for non-production forest functions further amplify this complexity. Forest managers are increasingly required to integrate ecological, economic, and social objectives simultaneously while operating under substantial uncertainty. Traditional forest management planning systems, historically focused primarily on timber production and sustained yield, are often insufficient for evaluating broader multifunctional forest objectives. As a result, there is a growing need for decision-support approaches capable of integrating multiple ecosystem services into transparent and reproducible planning frameworks.

Multi-criteria decision analysis (MCDA) has become one of the principal methodological approaches for addressing these challenges in forestry. MCDA enables the integration of heterogeneous criteria, supports transparent prioritisation of management objectives, and facilitates the evaluation of trade-offs between provisioning, regulating, supporting, and cultural ecosystem services. Kangas and Kangas (2005) describe MCDA as a particularly suitable framework for structured forest decision-making under uncertainty, while Mendoza and Martins (2006) emphasise its importance in natural resource management where both quantitative and qualitative criteria must be considered simultaneously. Ananda and Herath (2009) further highlight the importance of data quality, weighting procedures, and stakeholder participation in MCDA applications for forest planning.

In recent years, MCDA has been increasingly applied to multifunctional forest management and ecosystem service evaluation. Başkent (2018, 2020) developed dynamic approaches integrating forest growth simulation, ecosystem service modelling, and multi-purpose planning principles. Marques et al. (2021) demonstrated the applicability of participatory and spatial MCDA for ecosystem service prioritisation, while Paletto et al. (2021) applied MCDA to the assessment of forest restoration strategies in Mediterranean ecosystems. Systematic reviews (Uhde et al. 2015; Kpadé et al. 2024) confirm the growing importance of hybrid MCDA approaches combining analytical hierarchy process (AHP), TOPSIS, PROMETHEE, and GIS-based analyses for sustainable forest ecosystem management.

Despite extensive international development, the practical implementation of MCDA within Czech forest management planning remains limited. The Czech forest management planning system, based on Forest Management Plans and Forest Management Programmes (LHP/LHO), provides extensive stand-level information including species composition, age structure, stocking, site classification, and harvest regulation parameters. Additional data sources, including the National Forest Inventory (NFI), digital terrain models (DEM), and GIS datasets, provide further opportunities for ecosystem service assessment. However, these data sources are not currently integrated into a unified and transparent MCDA framework capable of evaluating multiple ecosystem services simultaneously.

Current Czech forest planning methodologies primarily emphasise production indicators, while regulatory, ecological, and cultural ecosystem services are frequently evaluated only qualitatively or inconsistently. Furthermore, many ecosystem service indicators remain methodologically heterogeneous and are calculated differently across studies, particularly biodiversity and cultural service indicators. This creates difficulties for practical implementation, comparison of management scenarios, and transparent stakeholder communication. A standardised and reproducible MCDA framework adapted to Czech forestry conditions could therefore substantially improve multifunctional forest planning and support ecosystem-based decision-making under climate uncertainty.

The present study aims to propose and demonstrate a practical MCDA framework for the evaluation of selected forest ecosystem services within Czech forest management planning. The framework combines AHP for criteria weighting with TOPSIS and PROMETHEE methods for ranking alternative forest management scenarios. The methodology is specifically designed to utilise commonly available Czech forestry data sources (LHP/LHO, NFI, GIS layers) and to support transparent evaluation

https://doi.org/10.17221/43/2026-JFS

of production, regulatory, ecological, and cultural ecosystem services.

A pilot simulation study is further presented to demonstrate the functionality of the proposed framework under four contrasting forest management scenarios: clear-cutting management, shelterwood management, selective management, and non-intervention management. The simulation evaluates the long-term development of wood production, carbon stock, erosion risk, biodiversity, and cultural value over a 100-year planning horizon and illustrates the trade-offs among different management strategies. The study is intended primarily as a methodological and conceptual demonstration of the proposed framework rather than as a fully calibrated operational decision-support model.

MATERIAL AND METHODS

Overall methodological framework

The proposed methodology integrates ecosystem service assessment, forest growth simulation, and MCDA into a unified decision-support framework for forest management planning. The framework is designed primarily for application within the Czech forest management planning system (LHP/LHO) and utilises commonly available forestry, inventory, and spatial datasets.

The analytical workflow consists of six sequential steps:

(*i*) Collection and preparation of input data;
(*ii*) Simulation of forest stand development under alternative management scenarios;
(*iii*) Calculation of ecosystem service indicators;
(*iv*) Normalisation of indicators;
(*v*) Criteria weighting using AHP;
(*vi*) Aggregation and ranking of management alternatives using TOPSIS and PROMETHEE.

The methodology aims to provide a transparent and reproducible procedure for evaluating trade-offs between provisioning, regulating, supporting, and cultural ecosystem services in multifunctional forest management.

Study area and pilot simulation design

The pilot simulation represents a conceptual demonstration of the proposed methodology under Central European forest conditions. The simulation was designed to reflect typical production forests of the Czech Republic located within moderately productive ecological conditions.

The hypothetical model forest stand was defined using the characteristics described in Table 1. The stand composition and environmental conditions were selected to approximate typical Central European managed forests and to ensure consistency with Czech forestry practice. The simulation is illustrative and conceptual in nature and does not represent a calibrated operational management plan for a specific forest management unit.

Forest management scenarios

Four contrasting forest management scenarios were simulated:

(i) Clear-cutting management (HOL). Conventional rotation forestry based on clear-cut harvesting followed by artificial regeneration. The scenario represents intensive production-oriented management with periodic high-intensity interventions.

Characteristics:
– rotation-based harvesting,
– even-aged stand structure,
– artificial regeneration,
– high timber extraction intensity,
– increased temporary exposure of the soil surface.

(ii) Shelterwood/understory management (POR). Management based on gradual regeneration under partial canopy cover.

Characteristics:
– group or strip regeneration,
– gradual canopy opening,
– mixed age structure,
– moderate harvesting intensity,
– partial preservation of stand continuity.

Table 1. Characteristics of the hypothetical model forest stand

Parameter	Value
Region	Czech Republic
Altitude	450–650 m a.s.l.
Forest vegetation zone	4^{th}–5^{th} vegetation zone
Dominant species	*Picea abies*, *Fagus sylvatica*
Admixture species	*Abies alba*, *Pinus sylvestris*
Site productivity	medium (site class 3)
Initial stand age	60 years
Total analysed area	100 ha
Terrain slope	15–25%
Soil type	Cambisol
Planning horizon	100 years
Simulation step	5 years

https://doi.org/10.17221/43/2026-JFS

(iii) Selective management (VYB). Continuous cover forestry based on selective harvesting and permanent forest cover.

Characteristics:
– uneven-aged stand structure,
– continuous natural regeneration,
– small-scale interventions,
– low disturbance intensity,
– permanent canopy continuity.

(iv) Non-intervention management (BEZ). Scenario without planned harvesting interventions.

Characteristics:
– natural stand development,
– absence of timber production,
– accumulation of biomass and deadwood,
– maximum ecological continuity,
– spontaneous disturbance dynamics.

Input data sources

The framework integrates multiple data sources commonly available within Czech forestry practice (Table 2).

The methodology assumes that ecosystem service indicators can be derived through the integration of forest inventory data and external GIS datasets.

Forest growth simulation

Forest development was simulated in five-year time steps over a 100-year planning horizon. The simulation combined empirical growth assumptions with simplified stand transition rules reflecting typical long-term development trends under different management regimes.

Table 2. Data sources commonly available within Czech forestry practice

Data source	Main use
LHP/LHO database	stand structure, species composition, stocking
NFI	calibration and verification
Digital terrain model (DEM)	slope and topographic factors
GIS layers	spatial analysis
Forest typology maps	site productivity and ecological conditions
Road network data	accessibility and recreation
Climate datasets	rainfall erosivity and climatic conditions

LHP/LHO – Czech forest management planning system; NFI – National Forest Inventory

The simulation respects two fundamental forest management constraints commonly applied in Central European forestry:

(*i*) Oldest-first harvesting rule – harvesting priority is assigned to the oldest stands reaching rotation maturity or management thresholds.

(*ii*) Non-declining yield principle – long-term timber harvest volume is maintained at relatively stable levels over time to ensure sustainable production continuity.

The simulation was intentionally simplified to maintain methodological transparency and demonstrate the structure of the MCDA framework. Growth dynamics, therefore, represent generalised ecological trajectories rather than fully calibrated stand-level yield models.

Ecosystem service indicators

Five ecosystem service indicators were selected to represent the major dimensions of multifunctional forest management (Table 3).

(i) Wood production indicator (P). Wood production represents the provisioning function of the forest ecosystem and was simulated using simplified empirical stand growth assumptions derived from Central European forestry practice. Production in each simulation period was calculated using Equation (1):

$$P_t = V_t - V_{t-1} + H_t \quad (1)$$

where:
P_t – production during the time period t;
V_t – growing stock at time t;
V_{t-1} – growing stock at previous time step;
H_t – harvested timber volume.

Relative production values were subsequently normalised to the interval 0–1.

In the non-intervention scenario, no timber is harvested; however, the forest stand continues to accumulate biomass through natural growth. For the purposes of MCDA normalisation, the production indicator therefore reflects biological increment rather than harvested timber volume. Assigning a strictly zero value would distort the min–max normalisation procedure and reduce comparability among scenarios. The small production value at-

https://doi.org/10.17221/43/2026-JFS

Table 3. Ecosystem service indicators selected to represent the major dimensions of multifunctional forest management

Indicator	Ecosystem service category
Wood production (*P*)	provisioning
Carbon stock (C)	regulating
Soil erosion risk (*E*)	regulating
Biodiversity index (*RAFL*)	supporting
Cultural value (*KUL*)	cultural

All indicators were normalised to a 0–1 scale before MCDA (multi-criteria decision-making) aggregation

tributed to the non-intervention scenario thus represents natural stand growth, not timber extraction.

(*ii*) Carbon stock indicator (*C*). Carbon stock quantifies the regulating ecosystem service associated with climate regulation and carbon sequestration. Living biomass carbon was estimated according to IPCC (2006, 2019), see Equation (2):

$$C_{biomass} = V \times \rho \times f_c \times (1 + R_{rs}) \quad (2)$$

where:
$C_{biomass}$ – living biomass carbon
V – growing stock volume;
ρ – wood density;
f_c – carbon fraction coefficient (0.5);
R_{rs} – the root–shoot ratio used to account for belowground biomass.

Total ecosystem carbon stock was estimated as shown by Equation (3):

$$C_{total} = C_{biomass} + C_{dead} + C_{soil} \quad (3)$$

where:
C_{total} – total ecosystem carbon stock;
C_{dead} – deadwood carbon;
C_{soil} – soil carbon.

Table 4 shows the simplified coefficients used.

Annual carbon balance changes were evaluated across simulation periods.

(*iii*) Soil erosion risk indicator (*E*). Soil erosion risk was estimated using a simplified version of the Universal Soil Loss Equation (USLE), see Equation (4) below:

$$E = R \times K \times LS \times C_f \times P \quad (4)$$

where:
R – rainfall erosivity factor;
K – soil erodibility factor;
LS – slope length and steepness factor;
C_f – vegetation cover factor;
P – protective management factor.

Vegetation cover coefficients varied among management scenarios, as shown in Table 5. Higher erosion indicator values represent higher environmental risk.

(*iv*) Biodiversity indicator (*RAFL*). The biodiversity indicator represents structural and compositional diversity of forest stands. The composite biodiversity index was defined according to Equation (5):

$$RAFL = \frac{D_s + H + M + S + F}{5} \quad (5)$$

where:
D_s – species diversity;
H – vertical structure heterogeneity;
M – age mosaic diversity;
S – proportion of old-growth structures;
F – fragmentation factor.

Each component was normalised to a 0–1 scale prior to aggregation. The indicator represents potential biodiversity conditions rather than direct biological inventory measurements.

(*v*) Cultural ecosystem service indicator (*KUL*). The cultural indicator evaluates recreational and aesthetic forest functions. The index was calculated according to Equation (6):

$$KUL = \frac{R_a + S_q}{2} \quad (6)$$

where:
R_a – recreational attractiveness;
S_q – scenic and aesthetic quality.

Table 4. The simplified coefficients used

Component	Coefficient approach
Deadwood carbon	percentage of living biomass
Soil carbon	empirical site coefficient
Belowground biomass	root-shoot ratio

The coefficients represent generalised empirical assumptions suitable for conceptual simulation purposes

https://doi.org/10.17221/43/2026-JFS

Table 5. Vegetation cover coefficient values according to management scenarios

Forest condition	Cover coefficient
Closed mature forest	0.1
Partially open canopy	0.3
Clear-cut area	0.6

The assessment incorporated:
– accessibility,
– visual diversity,
– stand naturalness,
– landscape attractiveness,
– continuity of forest cover.

Scores were initially evaluated on a 0–10 scale and subsequently normalised to 0–1.

Indicator normalization

To enable aggregation of heterogeneous ecosystem service indicators, all variables were normalised to a common interval between 0 and 1 using min–max normalization according to Equation (7):

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{7}$$

For erosion risk, inverse normalisation was applied because lower erosion values represent preferable environmental conditions.

Criteria weighting using AHP

Criteria weights were determined using AHP developed by Saaty (1980).

Pairwise comparisons were performed based on expert judgement reflecting multifunctional forest management priorities under Central European conditions. The weighting procedure considered production, ecological, and social forest functions simultaneously. The resulting weights are shown in Table 6.

Table 6. The weights resulting from the analytical hierarchy process (AHP)

Criterion	Weight
Wood production (*P*)	0.25
Carbon stock (C)	0.25
Erosion risk (*E*)	0.20
Biodiversity (*RAFL*)	0.20
Cultural value (*KUL*)	0.10

The pairwise comparison matrix achieved a consistency ratio (*CR*) below 0.1, indicating acceptable consistency of expert evaluations.

Composite sustainability index (*CSI*)

The composite sustainability index integrates all normalised ecosystem service indicators into a single synthetic measure of multifunctional sustainability. The index was calculated according to Equation (8):

$$CSI = 0.25\,P + 0.25\,\mathrm{C} + 0.2\,(1 - E) + 0.2\,RAFL + 0.1\,KUL \tag{8}$$

where:
CSI – composite sustainability index;
P – wood production;
C – carbon stock;
E – erosion risk;
RAFL – biodiversity index;
KUL – cultural value.

Higher *CSI* values indicate higher overall multifunctional sustainability.

TOPSIS ranking procedure

Management scenarios were ranked using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The relative closeness to the ideal solution was calculated according to Equation (9):

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-} \tag{9}$$

where:
C_i^* – relative closeness to the ideal solution;
S_i^+ – distance from ideal solution;
S_i^- – distance from anti-ideal solution.

Higher values indicate more preferable management alternatives.

PROMETHEE was additionally used as a complementary dominance-based ranking method for comparative verification of scenario ordering.

Sensitivity analysis

Sensitivity analysis was conducted to evaluate the robustness of the ranking results under varying weighting assumptions.

Criterion weights were systematically varied by ± 20% while maintaining proportional normalisation of the remaining criteria weights.

https://doi.org/10.17221/43/2026-JFS

The analysis evaluated:
– ranking stability,
– sensitivity of TOPSIS scores,
– dominance changes among scenarios.

This procedure allowed assessment of the robustness and uncertainty of the proposed MCDA framework under alternative management priorities.

RESULTS

Overview of simulation outputs. The pilot simulation evaluated the long-term development of five ecosystem service indicators under four contrasting forest management scenarios over a 100-year planning horizon. The scenarios represented different management intensities and forest structural dynamics, ranging from intensive rotation forestry to non-intervention management.

The evaluated indicators included:
– wood production (*P*),
– carbon stock (C),
– erosion risk (*E*),
– biodiversity index (*RAFL*),
– cultural ecosystem value (*KUL*),
– composite sustainability index (*CSI*).

All values were normalised to a 0–1 scale to enable direct comparison among indicators and management scenarios.

The simulation demonstrated substantial long-term differences among management approaches and revealed clear trade-offs between provisioning, regulating, ecological, and cultural ecosystem services.

Initial state of the forest stand (Year 0). At the beginning of the simulation, all scenarios started from identical initial stand conditions representing a moderately productive mixed Central European forest with medium structural diversity and moderate carbon stock. The initial normalised indicator values are presented in Table 7.

The non-intervention scenario showed the highest initial *CSI* value due to relatively high carbon stock, biodiversity, and cultural ecosystem values. The selective management scenario also achieved relatively high multifunctionality because of lower erosion risk and higher structural diversity.

By contrast, the clear-cutting scenario exhibited the lowest initial sustainability value. Although production potential remained moderate, biodiversity and cultural values were low, and erosion risk was high due to stand fragmentation and intensive intervention structure.

The shelterwood scenario represented an intermediate condition balancing moderate production with relatively favourable ecological characteristics.

Mid-term development (Year 50). After 50 years of simulated development, substantial differentiation among management scenarios became apparent (Table 8).

Table 7. Ecosystem service indicators at Year 0

Scenario	*P*	C	*E*	*RAFL*	*KUL*	*CSI*
Clear-cutting (HOL)	0.40	0.30	0.70	0.30	0.40	0.335
Shelterwood (POR)	0.50	0.40	0.40	0.50	0.50	0.495
Selective (VYB)	0.45	0.50	0.30	0.60	0.60	0.558
Non-intervention (BEZ)	0.20	0.70	0.20	0.70	0.70	0.595

P – wood production; C – carbon stock; *E* – erosion risk; *RAFL* – biodiversity index; *KUL* – cultural value; *CSI* – composite sustainability index

Table 8. Ecosystem service indicators at Year 50

Scenario	*P*	C	*E*	*RAFL*	*KUL*	*CSI*
Clear-cutting (HOL)	1.00	0.60	0.50	0.40	0.50	0.630
Shelterwood (POR)	0.80	0.75	0.30	0.70	0.70	0.738
Selective (VYB)	0.75	0.85	0.20	0.85	0.85	0.815
Non-intervention (BEZ)	0.15	0.95	0.15	0.95	0.95	0.730

P – wood production; C – carbon stock; *E* – erosion risk; *RAFL* – biodiversity index; *KUL* – cultural value; *CSI* – composite sustainability index

https://doi.org/10.17221/43/2026-JFS

The clear-cutting scenario achieved the highest relative production value (*P* = 1.00), reflecting the strong short- to medium-term productivity of rotation forestry systems. However, this scenario simultaneously exhibited relatively high erosion risk and comparatively low biodiversity values.

The selective management scenario achieved the highest overall multifunctional performance at Year 50 (*CSI* = 0.815). This scenario combined high carbon storage, low erosion risk, and strong biodiversity and cultural ecosystem values while maintaining relatively high production levels.

The shelterwood scenario showed balanced performance across all evaluated indicators and achieved the second-highest production values after clear-cutting. Ecological indicators were substantially more favourable than in the clear-cutting scenario.

The non-intervention scenario reached maximum carbon accumulation and biodiversity potential but maintained very low production values throughout the simulation period.

Long-term development (Year 100). At the end of the 100-year simulation period, long-term differences among management approaches became even more pronounced (Table 9).

The selective management scenario achieved the highest long-term sustainability score (*CSI* = 0.855). The scenario maintained high production capacity while simultaneously maximising regulating, ecological, and cultural ecosystem services.

The results suggest that continuous-cover forest management may provide the most balanced long-term multifunctional forest structure under Central European conditions. Permanent canopy cover, lower disturbance intensity, and continuous regeneration contributed positively to both ecological stability and cultural ecosystem value.

The shelterwood scenario also maintained relatively high multifunctionality and represented a compromise between production-oriented and ecological management approaches.

The non-intervention scenario maximised carbon storage and biodiversity values but remained strongly limited in provisioning services. Although its *CSI* value remained relatively high, the absence of production reduced its overall ranking within the integrated sustainability framework.

The clear-cutting scenario exhibited the lowest long-term sustainability. Despite maintaining moderate production performance, repeated high-intensity disturbances increased erosion risk and reduced long-term biodiversity and cultural ecosystem values.

Long-term trajectories of ecosystem services. The simulation revealed characteristic temporal trajectories for individual ecosystem services under different management systems.

Wood production. Clear-cutting management produced the highest short- and medium-term timber outputs due to intensive harvesting cycles and artificial regeneration. However, production stability gradually decreased over longer time horizons due to repeated disturbance cycles and simplified stand structures.

Selective and shelterwood systems produced slightly lower peak production values but maintained more stable long-term production trajectories.

Non-intervention management maintained minimal timber production throughout the simulation.

Carbon stock. Carbon accumulation increased continuously in the non-intervention and selective management scenarios due to permanent forest cover and lower harvesting intensity.

The selective management scenario achieved high carbon values while still maintaining economically relevant timber production.

Clear-cutting management exhibited the lowest long-term carbon storage because of repeated biomass removal and disturbance-related carbon losses.

Table 9. Ecosystem service indicators at Year 100

Scenario	*P*	C	*E*	*RAFL*	*KUL*	*CSI*
Clear-cutting (HOL)	0.60	0.50	0.60	0.40	0.50	0.485
Shelterwood (POR)	0.70	0.80	0.30	0.75	0.75	0.740
Selective (VYB)	0.80	0.90	0.20	0.90	0.90	0.855
Non-intervention (BEZ)	0.10	1.00	0.15	1.00	1.00	0.745

P – wood production; C – carbon stock; *E* – erosion risk; *RAFL* – biodiversity index; *KUL* – cultural value; *CSI* – composite sustainability index

https://doi.org/10.17221/43/2026-JFS

Table 10. Ranking of the management scenarios based on the final *CSI* values at Year 100

Rank	Scenario	*CSI*
1	selective management	0.855
2	non-intervention	0.745
3	shelterwood management	0.740
4	clear-cutting management	0.485

CSI – composite sustainability index

Erosion risk. Erosion risk remained highest under clear-cutting management throughout the simulation period due to repeated canopy removal and soil exposure.

Selective management achieved the lowest erosion values because permanent forest cover reduced runoff and stabilised soil conditions.

Shelterwood management maintained intermediate erosion risk values.

In the non-intervention scenario, erosion risk remained consistently low throughout the entire simulation period. Because no harvesting operations occur and permanent canopy cover is maintained, soil disturbance is minimal and vegetation cover remains high, resulting in very low values of the erosion indicator. This scenario therefore represents the most stable long-term erosion-mitigation pathway among all evaluated management systems.

Biodiversity and cultural ecosystem services. Biodiversity and cultural indicators showed very similar trajectories across scenarios.

Non-intervention and selective management produced the highest ecological and cultural values due to:
– structural heterogeneity,
– permanent forest cover,
– mixed age structure,
– higher visual naturalness,
– greater habitat continuity.

Clear-cutting management maintained the lowest biodiversity and cultural values because of simplified stand structures and repeated large-scale disturbances.

Ranking of management scenarios. Based on the final *CSI* values at Year 100, the management scenarios were ranked as shown in Table 10.

TOPSIS and PROMETHEE produced highly consistent ranking results (Table 11). Both methods identified selective management (VYB) as the most preferable multifunctional management strategy and clear-cutting management (HOL) as the least sustainable alternative. Minor differences occurred only in the relative distances among intermediate scenarios, but no rank reversals were observed. The consistency between the compensatory TOPSIS approach and the outranking-based PROMETHEE method supports the robustness of the proposed MCDA framework under varying evaluation principles.

Sensitivity analysis. Sensitivity analysis demonstrated relatively high robustness of the final ranking structure under changing weighting assumptions (Table 12).

Weights of all criteria were individually varied by ± 20%, and the resulting changes in ranking positions were evaluated.

The selective management scenario remained the highest-ranked alternative in nearly all tested weighting combinations, indicating relatively strong robustness of its multifunctional performance.

Only under strongly increased weighting of production indicators did the shelterwood scenario occasionally approach selective management performance. Similarly, substantial increases in biodiversity weighting improved the relative position of the non-intervention scenario.

The clear-cutting scenario consistently remained the lowest-ranked alternative across all tested weighting configurations.

Overall, the sensitivity analysis suggests that the proposed MCDA framework produces relatively stable rankings despite moderate uncertainty in weighting assumptions.

Table 11. Comparison of TOPSIS and PROMETHEE ranking results

Scenario	*CSI*	TOPSIS score	TOPSIS rank	PROMETHEE net flow (Φ)	PROMETHEE rank
Selective management (VYB)	0.855	0.842	1	+0.412	1
Non-intervention (BEZ)	0.745	0.691	2	+0.185	2
Shelterwood management (POR)	0.740	0.673	3	+0.142	3
Clear-cutting management (HOL)	0.485	0.318	4	–0.739	4

TOPSIS – Technique for Order Preference by Similarity to Ideal Solution; *CSI* – composite sustainability index

https://doi.org/10.17221/43/2026-JFS

Table 12. Sensitivity analysis of ranking stability

Weight variation	Ranking stability
± 20% production weight	stable
± 20% carbon weight	stable
± 20% biodiversity weight	stable
± 20% erosion weight	minor variation
± 20% cultural weight	stable

DISCUSSION

The presented study demonstrates the potential of MCDA as a transparent and integrative framework for evaluating ecosystem services within forest management planning. The proposed methodology combines forest growth simulation, ecosystem service indicators, and MCDA methods into a unified decision-support system capable of evaluating trade-offs among production, ecological, regulatory, and cultural forest functions. The results confirm that different forest management strategies generate fundamentally different long-term ecosystem service trajectories and that no single management system simultaneously maximises all ecosystem services.

A central finding of the study is the strong trade-off between provisioning services, particularly timber production, and ecological or regulating services such as carbon storage, biodiversity conservation, and erosion mitigation. This pattern is consistent with numerous international studies evaluating multifunctional forest management under MCDA frameworks (Başkent 2018; Kangas, Kangas 2005; Nilsson et al. 2016). The clear-cutting scenario achieved the highest short- and medium-term production values due to intensive harvesting and simplified stand dynamics, but this occurred at the cost of increased erosion risk, lower structural diversity, and reduced cultural ecosystem value. Repeated canopy removal and disturbance cycles produced unstable ecological conditions and reduced the long-term multifunctionality of the forest ecosystem. These findings correspond with studies demonstrating that intensive rotation forestry may maximise provisioning services while simultaneously weakening regulating and supporting ecosystem services (Mori et al. 2017; Paletto et al. 2021).

In contrast, selective management consistently achieved the highest overall sustainability values throughout the simulation. The results suggest that continuous-cover forestry systems may provide an effective compromise between economic production and ecological stability under Central European conditions. Permanent canopy continuity reduced erosion risk, improved carbon retention, and supported higher biodiversity and cultural values while maintaining relatively high production capacity. Similar conclusions have been reported in studies focused on close-to-nature silviculture and continuous-cover forestry, where structurally heterogeneous stands were found to increase ecological resilience and multifunctionality (Pretzsch 2009; Başkent 2020). The results therefore support the growing argument that future forest management under climate uncertainty should increasingly prioritise ecosystem stability and adaptive capacity rather than maximising short-term production outputs alone.

The non-intervention scenario achieved the highest values for carbon stock, biodiversity, and cultural ecosystem services. These results are ecologically expected because the absence of harvesting allows long-term biomass accumulation, deadwood formation, and increasing structural heterogeneity. However, the scenario simultaneously produced very low provisioning values and therefore did not achieve the highest composite sustainability score. This finding highlights an important methodological and practical issue in multifunctional forest management: maximising a single ecosystem service does not necessarily produce optimal multifunctional outcomes. Forest ecosystems managed exclusively for ecological conservation may lose significant provisioning and socio-economic functions, whereas production-oriented systems may compromise ecological integrity. MCDA approaches are therefore particularly valuable because they explicitly quantify these trade-offs and allow decision-makers to evaluate alternative management priorities transparently.

An important contribution of this study is the integration of multiple ecosystem service categories into a single operational evaluation framework adapted to Czech forestry conditions. Existing Czech forest management planning systems (LHP/LHO) primarily focus on production indicators and harvest regulation, while ecosystem services are frequently addressed only indirectly or qualitatively. The proposed framework demonstrates that standard forestry datasets can be expanded through

https://doi.org/10.17221/43/2026-JFS

the integration of GIS layers, inventory information, and ecosystem service indicators to support more comprehensive multifunctional planning. This is particularly important under ongoing climate change, increasing disturbance frequency, and growing societal pressure for non-production forest functions.

The results also illustrate the importance of structural complexity and stand continuity for long-term ecosystem stability. Biodiversity and cultural indicators showed strong positive relationships with uneven-aged structure, permanent canopy cover, and reduced disturbance intensity. These relationships are consistent with ecological studies emphasising the importance of structural heterogeneity for habitat diversity, microclimatic stability, and resilience against disturbances (McElhinny et al. 2005; Mori et al. 2017). The selective and non-intervention scenarios produced the highest ecological stability because they maintained greater continuity of forest structure throughout the simulation period.

The carbon indicator revealed another important aspect of multifunctional forest management. Carbon accumulation was highest under non-intervention and selective management due to lower harvesting intensity and longer biomass retention. This finding is increasingly relevant under climate mitigation policies and expanding carbon accounting frameworks. However, the results also demonstrate that high carbon storage alone does not necessarily maximise overall multifunctionality. The selective management scenario achieved nearly comparable carbon values while still maintaining economically significant timber production, suggesting that integrated management approaches may provide more balanced long-term outcomes than either intensive production forestry or complete non-intervention.

The sensitivity analysis demonstrated relatively high robustness of the proposed MCDA framework. Ranking results remained stable under moderate changes in criteria weighting, particularly for the selective management scenario. This suggests that the observed superiority of structurally diverse and continuous-cover management systems is not merely an artefact of the selected weighting configuration. At the same time, the sensitivity analysis illustrates the importance of societal and stakeholder preferences in multifunctional forest management. Increasing the weight of production indicators improved the relative ranking of shelterwood systems, whereas emphasising biodiversity and ecological criteria strengthened the position of non-intervention management. This confirms that ecosystem service evaluation cannot be considered entirely objective because final rankings always depend partly on normative assumptions regarding management priorities.

Despite these promising results, the study has several important limitations. First, the presented pilot application is conceptual and simulation-based rather than fully calibrated using operational forest growth models. The growth trajectories and ecosystem service dynamics, therefore, represent generalised ecological trends rather than exact predictions for specific forest stands. Second, several ecosystem service indicators rely on simplified empirical assumptions and generalised coefficients. This limitation is particularly important for carbon, biodiversity, and cultural ecosystem service assessment, where uncertainties remain relatively high due to insufficient stand-level data and the absence of standardised methodologies.

The biodiversity indicator represents a particularly important limitation. Although stand structure, species composition, and age diversity can be partially derived from LHP/LHO databases, many ecologically important structural characteristics, such as deadwood volume, vertical stratification, microhabitat availability, and species-specific habitat quality, are not directly available within standard forest planning datasets. Consequently, the RAFL index should be interpreted as a proxy for biodiversity potential rather than a direct ecological inventory. Similar limitations have been reported in ecosystem service studies across Europe, where biodiversity assessment often requires supplementary field inventories or remote sensing data (Holušová, Holuša 2025; Mori et al. 2017).

A comparable limitation applies to cultural ecosystem services. Recreational attractiveness and aesthetic quality are inherently subjective and spatially heterogeneous. Forest management plans do not contain sufficient information on recreational infrastructure, visitor intensity, visual landscape composition, or public preferences. Future implementation of cultural ecosystem service assessment will therefore require integration of additional spatial datasets, visitor monitoring, and potentially participatory social surveys.

https://doi.org/10.17221/43/2026-JFS

The erosion model also represents a simplification of real hydrological processes. Although USLE-based approaches are widely used in forest ecosystem service studies, reliable erosion assessment requires detailed climatic, pedological, and topographic datasets together with local calibration of parameters. The presented methodology therefore demonstrates conceptual applicability rather than precise quantitative prediction of erosion processes.

An important methodological limitation concerns the weighting process itself. Although AHP provides a transparent framework for criteria weighting, the resulting weights remain partly subjective and depend on expert judgement and stakeholder priorities. Different stakeholder groups, such as forest owners, conservation organisations, public administrations, or local communities, would likely produce different weighting configurations and therefore different scenario rankings. This subjectivity is not a weakness of MCDA itself but rather reflects the inherently normative nature of multifunctional forest management.

The study nevertheless demonstrates several important practical implications for future forest planning. First, it confirms that multifunctional forest management requires explicit evaluation of trade-offs among ecosystem services rather than implicit prioritisation of timber production alone. Second, it shows that structurally diverse and continuous-cover management systems may provide relatively stable multifunctional performance under long-term conditions. Third, it demonstrates that existing Czech forestry datasets provide a sufficiently strong foundation for the development of operational ecosystem service assessment frameworks, although additional ecological and spatial datasets remain necessary.

Future research should therefore focus on several key directions. The first priority is the calibration of ecosystem service indicators using operational forest inventory and monitoring data. The second is the integration of advanced spatial datasets including remote sensing, LiDAR, and dynamic disturbance monitoring. The third is the incorporation of participatory stakeholder processes to derive socially representative weighting schemes and management preferences. Finally, future studies should extend the framework toward spatially explicit landscape-level planning and dynamic climate adaptation scenarios.

Overall, the presented framework demonstrates that MCDA can provide a scientifically robust and operationally relevant basis for integrating ecosystem services into forest management planning. Although the current pilot study remains conceptual, it establishes an important methodological foundation for the transition from production-oriented forest regulation toward multifunctional ecosystem-based forest management under conditions of increasing climatic and societal uncertainty.

CONCLUSION

The presented study proposed and demonstrated a practical MCDA framework for the evaluation of selected ecosystem services within Czech forest management planning. The framework integrates forest growth simulation, ecosystem service indicators, GIS-supported spatial information, and MCDA methods into a unified decision-support approach capable of evaluating multifunctional forest management under long-term conditions.

The results confirmed that different forest management strategies produce fundamentally different ecosystem service trajectories and that strong trade-offs exist among provisioning, regulating, ecological, and cultural forest functions. Intensive clear-cutting management maximised short-term timber production but simultaneously increased erosion risk and reduced biodiversity and cultural ecosystem values. In contrast, non-intervention management achieved the highest carbon storage and biodiversity potential but maintained very low provisioning capacity. Among the evaluated scenarios, selective management achieved the highest long-term multifunctional sustainability because it combined relatively high production with strong ecological stability, low erosion risk, and high cultural ecosystem value.

These findings support the growing international consensus that future forest management should increasingly emphasise resilience, structural diversity, and ecosystem stability rather than maximising short-term production alone. Under accelerating climate change, increasing disturbance frequency, and growing societal demands for ecosystem services, multifunctional and continuous-cover management systems may provide more robust long-term outcomes than simplified production-oriented forestry systems.

https://doi.org/10.17221/43/2026-JFS

An important contribution of the study lies in adapting internationally recognised MCDA approaches to the Czech forestry environment and linking them directly to existing forest management planning datasets (LHP/LHO), NFI data, and GIS information. The proposed methodology demonstrates that currently available Czech forestry data provide a strong foundation for ecosystem service assessment and multifunctional planning, although additional spatial, ecological, and socioeconomic datasets remain necessary for operational implementation.

The study further demonstrates the usefulness of MCDA as a transparent framework for integrating heterogeneous ecosystem service indicators into a single evaluation system. By explicitly quantifying trade-offs and allowing flexible weighting of management objectives, MCDA can significantly improve transparency and stakeholder communication within forest planning processes. The sensitivity analysis additionally showed relatively stable ranking results under moderate changes in weighting assumptions, indicating that the proposed framework is sufficiently robust for conceptual planning applications.

Nevertheless, several limitations remain. The presented pilot application is simulation-based and conceptual rather than fully operational or spatially calibrated. Several ecosystem service indicators, particularly biodiversity and cultural services, rely on simplified empirical assumptions due to limitations of currently available forest planning data. Similarly, the weighting process remains partly subjective and dependent on stakeholder preferences. Future development should therefore focus on calibration using operational forestry data, integration of advanced remote sensing and spatial datasets, and implementation of participatory stakeholder-based weighting procedures.

Future research should also expand the framework toward spatially explicit landscape-scale analyses, climate adaptation scenarios, disturbance risk modelling, and integration of additional ecosystem services such as water regulation, habitat connectivity, or recreational carrying capacity. The incorporation of dynamic monitoring technologies, including remote sensing and digital forest inventories, may further improve the precision and operational applicability of ecosystem service assessment within forest management planning.

Overall, the proposed MCDA framework represents an important methodological step toward ecosystem-based and multifunctional forest planning in the Czech Republic. Although the presented pilot study primarily serves as a conceptual demonstration, the methodology establishes a reproducible and transparent basis for future operational implementation and offers potential applicability to other Central European forest management systems facing similar ecological, climatic, and societal challenges.

REFERENCES

Ananda J., Herath G. (2009): A critical review of multi-criteria decision making methods with special reference to forest management and planning. Ecological Economics, 68: 2535–2548.

Başkent E.Z. (2018): A review of the development of the multiple use forest management planning concept. International Forestry Review, 20: 296–313.

Başkent E.Z. (2020): A framework for characterizing and regulating ecosystem services in a management planning context. Forests, 11: 102.

Holušová K., Holuša O. (2025): Assessing the provision of ecosystem services using forest site classification as a basis for the forest bioeconomy in the Czech Republic. Forests, 16: 1242.

IPCC (2006): 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Hayama, Intergovernmental Panel on Climate Change: 21.

IPCC (2019): 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Kyoto, Intergovernmental Panel on Climate Change: 3050.

Kangas J., Kangas A. (2005): Multiple criteria decision support in forest management – The approach, methods applied, experiences gained. Forest Ecology and Management, 207: 133–143.

Kpadé C.P., Tamini L.D., Pepin S., Khasa D.P., Abbas Y., Lamhamedi M.S. (2024): Evaluating multi-criteria decision-making methods for sustainable management of forest ecosystems: A systematic review. Forests, 15: 1728.

Lorenz K., Lal R. (2010): Carbon Sequestration in Forest Ecosystems. Springer.

Marques M., Reynolds K.M., Marques S., Marto M., Paplanus S., Borges J.G. (2021): A participatory and spatial multicriteria decision approach to prioritize the allocation of ecosystem services to management units. Land, 10: 747.

McElhinny C., Gibbons P., Brack C., Bauhus J. (2005): Forest and woodland stand structural complexity: Its definition and measurement. Forest Ecology and Management, 218: 1–24.

https://doi.org/10.17221/43/2026-JFS

Mendoza G.A., Martins H. (2006): Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. Forest Ecology and Management, 230: 1–22.

Mori A.S., Lertzman K.P., Gustafsson L. (2017): Biodiversity and ecosystem services in forest ecosystems: A research agenda for applied forest ecology. Journal of Applied Ecology, 54: 12–27.

Nilsson H., Nordström E.M., Öhman K. (2016): Decision support for participatory forest planning using AHP and TOPSIS. Forests, 7: 100.

Paletto A., Pieratti E., De Meo I., Agnelli A.E., Cantiani P., Chiavetta U., Mazza G., Lagomarsino A. (2021): A multi-criteria analysis of forest restoration strategies to improve the ecosystem services supply: An application in Central Italy. Annals of Forest Science, 78: 7.

Panagos P., Borrelli P., Poesen J., Ballabio C., Lugato E., Meusburger K., Montanarella L., Alewell C. (2015): The new assessment of soil loss by water erosion in Europe. Environmental Science & Policy, 54: 438–447.

Pretzsch H. (2009): Forest Dynamics, Growth, and Yield: From Measurement to Model. Berlin, Springer: 664.

Saaty T.L. (1980): The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. New York, McGraw-Hill: 287.

Uhde B., Hahn W.A., Griess V.C., Knoke T. (2015): Hybrid MCDA methods to integrate multiple ecosystem services in forest management planning: a critical review. Environmental Management, 56: 373–388.

Received: May 18, 2026
Accepted: May 27, 2026
Published online: June 29, 2026