Rethinking Peatland Futures for Latvia: Life Cycle Thinking Approach Integrated Within Multicriteria Analysis

Maksims Feofilovs(✉), Dace Araja, and Francesco Romagnoli

Institute of Energy Systems and Environment, Faculty of Electrical and Environmental Engineering, Riga Technical University, Riga, Latvia
info.videszinatne@rtu.lv

Abstract. Latvia relies on its peat resources economically, environmentally, and culturally, but with increasing pressure from climate targets and biodiversity commitments, there is a growing urgency to rethink how degraded peatlands are managed. This study evaluates various restoration and after-use strategies for extracted peatlands by applying an integrated Life Cycle Sustainability Assessment (LCSA) framework that combines environmental (LCA), economic (LCC), and social (S-LCA) evaluation dimensions. A Multi-Criteria Decision Analysis (MCDA) approach using the TOPSIS method is employed to compare ten after-use scenarios, including renaturalization, afforestation, water body creation, wetland crop cultivation, and renewable energy installations. The analysis highlights trade-offs across sustainability dimensions and supports informed land-use planning by identifying which options deliver the most balanced performance. The proposed method provides a structured and adaptable tool for policymakers and land managers to guide post-extraction peatland recovery in line with national and EU sustainability goals.

Keywords: Life cycle thinking · peat exctraction · sustainability · multi-criteria analysis

1 Introduction

Peatlands are unique and long-evolving ecosystems formed by the accumulation of partially decomposed plant matter in waterlogged environments. These ecosystems develop slowly [1]. The constantly saturated conditions limit decomposition, allowing peat to build up over thousands of years, layer by layer. As a result, peatlands have become one of the most carbon-dense terrestrial ecosystems on Earth [2]. Although they cover only about 3% of the planet's land surface, peatlands store an estimated 30% of the world's soil carbon, far more than any other ecosystem relative to their size [3]. However, when peatlands are drained (e.g. for extraction or agricultural use) this carbon stock becomes a source of emissions. As oxygen reaches the peat layers, microbial activity accelerates decomposition, releasing large quantities of CO_2 into the atmosphere.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15899, pp. 219–229, 2026.
https://doi.org/10.1007/978-3-031-97663-6_19

The scale of this problem is particularly evident in the European Union, which emits around 220 million tonnes of CO_2 equivalent annually from drained peatlands, equal to 15% of global peatland related emissions. In 2017, this accounted for roughly 5% of the EU's total greenhouse gas emissions [4]. Major emitting countries include Germany, Finland, Poland, Ireland, Romania, Sweden, Latvia, Lithuania, and the Netherlands. In many of these nations, drained peatlands are responsible for more than a quarter of emissions from the land use, agriculture, and forestry sectors [5]. Restoration strategies for degraded peatlands are now embedded in both EU and national-level planning. However, decisions about the most appropriate type of restoration are still typically guided by climate and biodiversity outcomes, while the economic and social cycle dimensions remain underrepresented in actual policy and planning frameworks [6].

In Latvia, peatlands have been both ecologically significant and economically utilized. As of the early 21st century, fully or partially extracted peatlands covered more than 37,000 hectares, which is about 0.57% of national territory [7]. Of these, 36% are classified as degraded and no longer in active use, at the same time lacking a clear after-use strategy. Meanwhile, 30% are still under extraction. Only a small portion, about 5%, is undergoing natural regeneration. The remaining land has been converted into forests, meadows, water bodies, or in rare cases, commercial berry cultivation [8].

According to researchers, the resource has not been used to its full potential. Inefficiencies in processing, lack of innovation, and missed opportunities in land reuse suggest that peat could be managed more intelligently. This includes developing new peat-based products, modernizing extraction practices, and restoring or repurposing exhausted peatlands through sustainable land-use strategies [7].

While sustainability has become a key guiding principle in both national policy and business strategy, the challenge often lies in its practical implementation. Over recent decades, the focus of environmental science has gradually expanded—from pollution control and resource conservation to a broader understanding of sustainability that integrates environmental, economic, and social dimensions. This shift has led to the development of Life Cycle Sustainability Assessment (LCSA), a comprehensive approach for evaluating long-term impacts across the full life cycle of a product, service, or land-use option [9].

Given peatlands' critical role in carbon storage, biodiversity support, and water regulation, their degradation poses risks not only to local environments but also to broader climate stability. Thus, this study addresses helps to tackle the challenges related to sustainable peatland management by assessing different restoration and after-use scenarios for Latvian peatlands, using life cycle-based sustainability methods to inform better decisions for the future.

2 Methodology

To address the gaps identified in literature, the present study applies the full LCSA approach [10], evaluating three core dimensions: environmental impacts through Life Cycle Assessment (LCA), social effects through Social impact indicators, and economic performance through Life Cycle Costing (LCC). Together, these provide a multi-layered understanding of how different peatland after-use options perform in sustainability terms.

The study methodology is structured in alignment with the ISO 14040 and 14044 standards, which define the LCA process in four interlinked stages: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. To capture all relevant aspects of peatland recovery strategies, the study follows the conceptual model of Professor Walter Klöpffer, who in 2008 proposed the integration of LCA, LCC, and S-LCA sustainability assessment [11].

The sustainability evaluation covers ten peatland after-use scenarios identified through literature analysis and real-world case studies in Latvia. These are:

- Renaturalisation,
- Creation of water bodies,
- Afforestation,
- Cultivation of paludiculture (wetland crops),
- Cultivation of large-berry cranberries,
- Cultivation of blueberries (Vaccinium species),
- Establishment of perennial grasslands,
- Conversion to arable land,
- Installation of wind farms, and
- Installation of solar farms.

Each scenario is analyzed across all three sustainability dimensions, with specific indicators selected based on published sources and context-specific expertise.

To compare the alternatives and determine which restoration strategies offer the best balance of long-term sustainability, the study uses a Multi-Criteria Decision Analysis (MCDA) approach, applying the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method [12]. TOPSIS calculates how close each option is to an ideal solution and ranks them accordingly. The results of this approach helps landowners, peat extraction site managers, and policymakers identify the most viable, science-based paths for peatland recovery.

The combination of LCSA and MCDA enables a comprehensive yet practical framework grounded in international standards and adaptable to various peatland contexts. This integrated method not only supports evidence-based decisions but also ensures that ecological, economic, and social factors are considered together, as part of a truly sustainable strategy for restoring degraded peat landscapes.

2.1 Environmental Life Cycle Assessment

The environmental LCA in this study is carried out using the ReCiPe method, applied through the SimaPro software and using the Ecoinvent database. The LCA examined ten peatland after-use scenarios, assessing their environmental impacts based on three key indicators: human health impact, effects on ecosystems, and resource depletion are assessed at the endpoint level from midpoint categories as foreseen in ReCiPe method (Fig. 1). The developed approach allows to consider the avoided emissions from renewable energy production. For instance, in scenarios involving wind turbines or solar panels, the benefit of replacing fossil-based electricity in the national grid is accounted for in the total climate impact value.

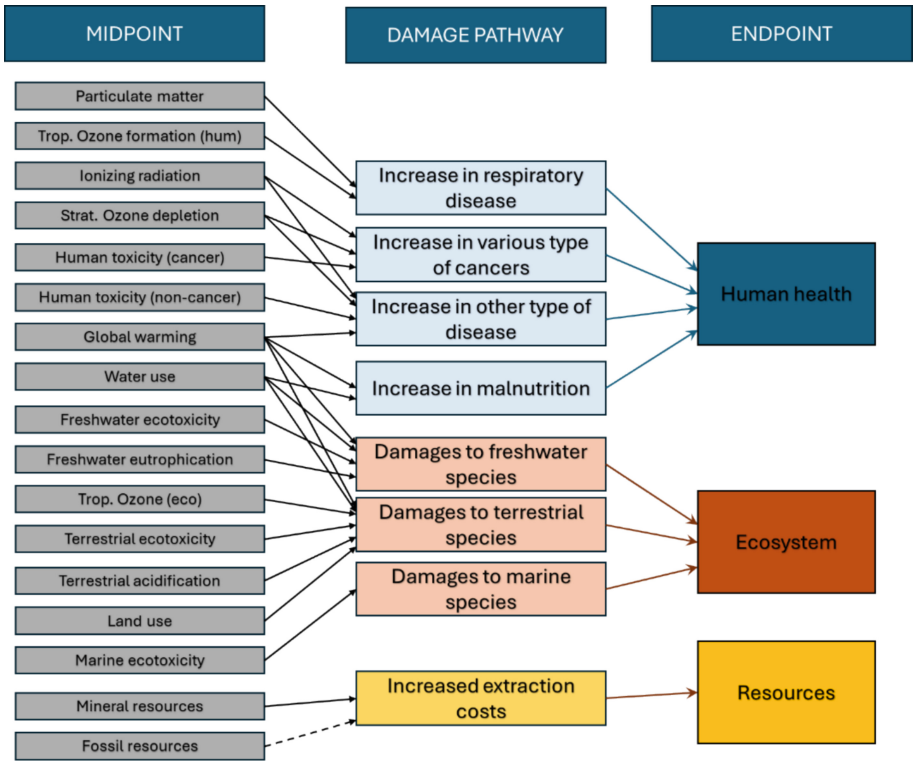

Fig. 1. Overview of the impact categories that are covered in the ReCiPe2016 method, adopted from [13].

Impacts on human health were measured in disability-adjusted life years (DALYs), representing years of life lost due to exposure to harmful environmental effects. Ecosystem damage was calculated in terms of species loss per year, while resource use was evaluated as future economic costs of resource depletion, presented in USD (2013 value).

2.2 Life Cycle Costing

The LCC in this study evaluates the long-term financial feasibility and value generation of various peatland after-use strategies. Four key indicators were selected for this purpose: net present value (NPV), internal rate of return (IRR), profitability index (PI), and the monetary value of ecosystem services. Together, these indicators offer a multi-perspective view of how economically viable each scenario is over its operational lifespan.

The selection of economic indicators was guided by three key criteria: relevance to sustainability decision-making, data availability and consistency, and comparability across land use alternatives. Relevance ensures that each indicator meaningfully reflects long-term economic performance under varying after-use conditions. Indicators such as NPV and IRR provide clear signals about financial viability, while profitability

index offers a normalized basis for comparing projects of different scales. The inclusion of ecosystem service valuation reflects an effort to integrate non-market economic contributions of restored peatlands.

The NPV was calculated to assess whether the investment in a given land-use option would generate positive returns over time according to Eq. (1):

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{1}$$

where:

C_t is the net cash flow in year t.
r is the discount rate (in this case, the weighted average cost of capital),
n is the number of periods in the analysis timeframe, and
t is the year index, starting from 0 (the initial investment).

This formula allows for a time-adjusted comparison of future economic returns, accounting for the cost of capital and risk over time. It ensures that scenarios with delayed or uncertain cash inflows are appropriately evaluated in terms of present-day value. The standard discounted cash flow formula was used, taking into account future cash flows adjusted by a discount rate, which in this case corresponds to the weighted average cost of capital (WACC). WACC was determined based on both equity and borrowed capital components, reflecting realistic financing conditions for land rehabilitation projects.

In addition to NPV, the IRR used to evaluate the expected return rate generated by each scenario's projected cash flow. The profitability index, defined as the ratio between total NPV and the initial investment, provided an additional metric to compare different investment options with varying cost levels.

The fourth component of the LCC—ecosystem service valuation—addressed the broader economic benefits delivered by restored peatlands. Although detailed economic valuations for Latvian peatland ecosystem services are limited in scientific literature, which estimated values for provisioning, regulating, and cultural ecosystem services across several land use types. For renewable energy scenarios (solar and wind), no ecosystem service value was assigned, due to lack of data and methodological limitations.

2.3 Social Dimension

The social dimension of sustainability is often considered the least developed within life cycle-based assessments. Nonetheless, it remains a vital component for understanding the broader impacts of land use strategies. In this study, a assessment of social indicators was applied to evaluate ten peatland use scenarios, using four indicators: direct employment, employment generated over the life cycle, workplace injuries, and dependence on external suppliers. The combination of data from public literature, national statistics, professional databases is used.

The direct employment indicator reflects the number of workers engaged during implementation and operation phases, rated on a qualitative scale from 1 (very low) to 5 (very high). Labor-intensive options, such as blueberry and cranberry cultivation,

received high scores due to the significant manual effort required for planting, maintenance, and harvesting. In contrast, renaturalization, wetland restoration, and afforestation were associated with minimal labor needs.

The life cycle employment indicator measures job creation across the entire operational timeline, including seasonal labor and value-chain effects. For example, forest-based scenarios considered employment in nursery operations, planting, forest management, and harvesting. Agricultural options are evaluated based on typical labor input per hectare, while job creation in solar and wind energy is estimated using international conversion factors per MW of installed capacity, due to the lack of Latvian-specific data.

Worker safety is assessed using the annual number of occupational injuries reported in each sector. For agriculture, data from the State Labour Inspectorate were used. For solar and wind energy sectors, international statistics were applied to approximate typical injury rates, acknowledging that sector-specific data in Latvia is currently unavailable. This approach enabled a relative risk comparison across all land use scenarios.

The supply chain dependency indicator highlights risks linked to sourcing materials or services from outside Latvia, particularly from regions with lower labor rights standards or political instability.

2.4 Life Cycle Sustainability Assessment

To determine which peatland after-use strategy offers the most sustainable outcome, a multi-criteria decision analysis (MCDA) was carried out using the TOPSIS method. This approach compares each option against an ideal solution across three key dimensions: environmental, economic, social.

Each option is assessed across several indicators, forming a matrix where each element represents the performance of a specific alternative according to a particular criterion. The importance of each criterion is reflected through assigned weights, ensuring the total influence across all criteria sums to one.

Initially, the data is normalized to eliminate scale effects, followed by multiplying each normalized value by the respective criterion weight. The weights assigned to each sustainability criterion (environmental, economic, and social) were derived through a qualitative scoring process informed by expert judgment and iterative internal discussions within the research team. Each dimension was evaluated for its relative importance in the context of post-extraction peatland restoration in Latvia. In this study, equal weights were initially assumed for the environmental, economic, and social dimensions to ensure a balanced assessment in the absence of conclusive stakeholder priorities. This approach provides a neutral baseline, allowing each dimension to contribute equally to the composite sustainability score. Future applications of this method may incorporate context-specific weighting derived from stakeholder engagement or policy-driven prioritization. This produces a weighted decision matrix, forming the basis for the analysis.

Next, two benchmark solutions are determined: one representing the most favorable outcome across all criteria, and the other representing the least favorable. Each alternative is then compared to these benchmarks by calculating the distance to both the best and worst theoretical solutions.

Finally, a relative performance score is derived for each alternative as given in Eq. 1, indicating its closeness to the optimal solution and distance from the least desirable one:

$$(P_i) = \frac{A_i^-}{A_i^+ + A_i^-} \text{with } i = 1, \ldots, m \quad (1)$$

Pi – Relative closeness of alternative i to the ideal solution. This is the final score that indicates how good an alternative is compared to others. It ranges between 0 and 1. The closer it is to 1, the better (closer to the ideal solution).

Ai+ represents the ideal value of alternative *i.*

Ai− represents the anti-ideal value of alternative *i.*

i− index of the alternative. The variable i goes from 1 to m, where m is the total number of alternatives being evaluated.

This enables a ranking of the options, supporting informed decision-making on the preferred course of action. In this context, it helps identify the most suitable approach for peatland reclamation, guided by sustainability criteria and life cycle considerations.

3 Results

These LCA finddings shown in Table 1 confirm that renewable energy recovery best solution in environmental dimension due to higher avoided impact benefits in energy sector for fossil-based electricity generations, while agricultural and grassland conversion carry the highest ecological costs. The moderate environmental performance of renaturalization, afforestation, and wetland crop scenarios supports their consideration as environmentally viable strategies for post-extraction peatland management.

Table 1. Life Cycle Assessment Results

Indicator/Land Use Type	Global Warming Potential kg CO2 eq ha-1 y-1	Human Health DALY	Ecosystem Impact species/year	Resources USD2013
Renaturalisation	6,70E+03	3,53E−05	−3,33E−04	1,36E+00
Paludiculture	5,61E+03	5,03E−03	8,20E−06	7,25E+02
Water Bodies	2,38E+03	4,12E−03	6,10E−06	3,02E+02
Solar Panels	−1,02E+07	−5,42E+00	−2,59E−03	−1,23E+06
Wind Turbines	−2,45E+07	−2,27E+01	−3,60E−02	−2,59E+06
Agriculture (Winter Wheat)	1,94E+06	3,42E+00	2,81E−02	1,08E+05
Grasslands	6,53E+05	1,70E+00	5,61E−04	5,31E+04
Afforestation	1,74E+04	7,23E−04	−3,23E−03	1,47E+01
Blueberries	1,84E+05	4,82E−01	3,66E−03	1,51E+04
Cranberries	−1,04E+03	3,19E−03	3,25E−03	3,02E+02

The findings from LCC shown in Table 2 emphasize the tension between direct financial returns and broader ecosystem value. While infrastructure and market-driven strategies such as energy production and berry cultivation offer revenue potential, nature-based solutions like renaturalization and afforestation deliver substantial non-market benefits. This highlights the need for supportive financial and policy instruments, such as carbon credits or agri-environmental schemes to make ecologically valuable strategies more economically attractive for landowners and investors.

Table 2. Lice Cycle Costing Results

Indicator/Land Use Type	NPV EUR	IRR %	PI %	Monetary value of ecosystem services EUR/ha
Renaturalisation	−4,95E+03	0,00E+00	0,00E+00	2,20E+05
Paludiculture	−2,13E+03	0,00E+00	8,00E−02	1,80E+05
Water Bodies	−5,29E+03	0,00E+00	0,00E+00	1,37E+05
Solar Panels	−6,24E+04	5,00E−02	8,40E−01	0,00E+00
Wind Turbines	7,46E+04	8,40E−02	1,15E+00	0,00E+00
Agriculture (Winter Wheat)	4,66E+03	1,40E−01	3,10E−01	3,12E+03
Grasslands	−2,79E+03	0,00E+00	−2,30E−01	4,50E+03
Afforestation	−4,64E+03	0,00E+00	0,00E+00	1,98E+05
Blueberries	4,72E+04	2,70E−01	3,70E−01	4,65E+04
Cranberries	6,48E+03	9,00E−02	3,60E−01	5,74E+04

The results of social impacts (see Table 3) show renewable energy options were having high a dependency on external suppliers due to their reliance on imported components like turbines and solar panels, often sourced from China, Germany, and other EU countries. Conversely, land uses such as renaturalization, water bodies, and afforestation scored low on this indicator, as they require minimal external inputs. Moderate dependence was identified for berry plantations and paludiculture, largely due to the need for quality planting materials sourced abroad. Labor-intensive land uses, particularly berry cultivation, stand out for their job creation potential. On the other hand, low-intervention solutions like renaturalization and wetland restoration score well in terms of safety and supply chain autonomy but contribute less to employment.

After calculating the combined normalized scores across all three sustainability dimensions (Fig. 2), wind energy development emerges as the most sustainable solution, with a Pi value of 0.750, clearly closest to the ideal. This was followed by solar panels (Pi = 0.426) and blueberry plantations (Pi = 0.416), both of which offered a balanced trade-off between ecological and economic performance.

Conversely, converting peatland into arable farmland, specifically for winter cereals, was found to be the least sustainable option (Pi = 0.251), with grassland establishment (Pi

Table 3. Social Life Cycle Assessment Results

Indicator/Land Use Type	Direct Employment (Employed Persons)	Life Cycle Employment (Jobs Created)	Workplace Injuries (Number of Injuries)	Dependence on External Suppliers (Rating from 1 to 5)
Renaturalisation	1,00E+00	0,00E+00	0,00E+00	1,00E+00
Paludiculture	1,00E+00	0,00E+00	0,00E+00	3,00E+00
Water Bodies	1,00E+00	0,00E+00	0,00E+00	1,00E+00
Solar Panels	3,00E+00	4,25E+02	1,10E+01	5,00E+00
Wind Turbines	3,00E+00	3,27E+02	1,02E+01	5,00E+00
Agriculture (Winter Wheat)	2,00E+00	1,00E+01	5,50E+01	2,00E+00
Grasslands	2,00E+00	5,00E+00	5,50E+01	1,00E+00
Afforestation	2,00E+00	8,50E+01	3,20E+01	1,00E+00
Blueberries	4,00E+00	6,30E+01	5,50E+01	3,00E+00
Cranberries	4,00E+00	4,20E+01	5,50E+01	3,00E+00

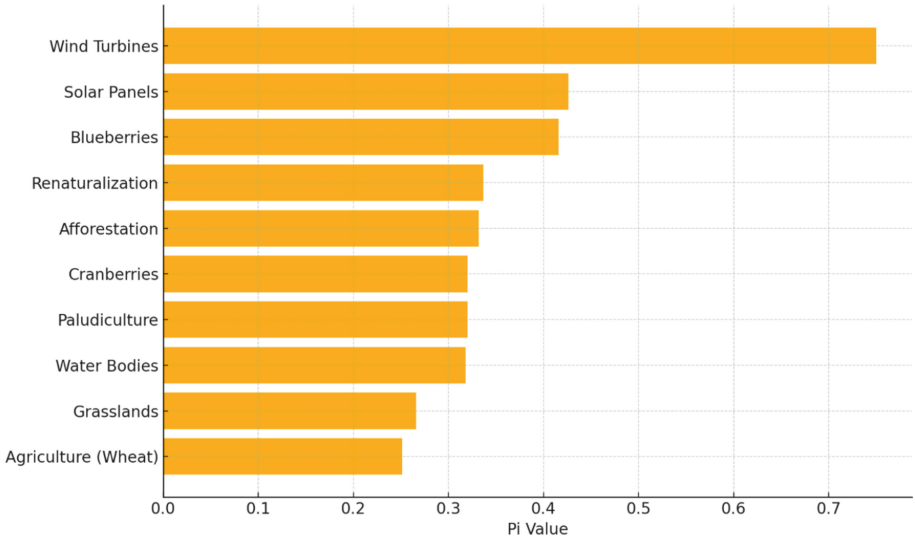

Fig. 2. Ranking of Peatlant Use Alternatives Based on Relative Closeness to the Ideal Solution

= 0.266) ranking only slightly higher. These land uses had relatively poor environmental and social outcomes, despite modest economic returns.

In the context of this assessment, the Pi value represents how close each after-use option comes to the ideal sustainability scenario, as defined by the highest performance across all evaluated criteria. A higher Pi value indicates better overall sustainability,

meaning the option performs well across environmental, economic, and social dimensions. Conversely, a lower Pi value reflects a greater distance from the ideal and suggests trade-offs or shortcomings in one or more areas of performance.

4 Conclusion

This study developed a new analytical tool for assessing peatland restoration strategies using a life cycle sustainability approach. The tool integrates environmental, economic, and social dimension, offering a comprehensive evaluation method that had not previously been applied to the full range of potential after-use options for degraded peatlands. Its novelty lies in unifying all three sustainability perspectives into a single assessment. Among the ten evaluated options, wind turbine installation emerged as the most sustainable solution, followed by solar energy, renaturalization, and paludiculture. However, the potential to combine or layer multiple strategies, such as integrating natural rewetting with energy infrastructure, should also be considered in broader planning.

One of the study's key challenges was assessing the social dimension, particularly due to limited available data and the evolving nature of S-LCA methodologies. As such, part of the analysis was guided by expert judgment based on practical experience and literature. A second difficulty was the valuation of ecosystem services, which remains under-researched in Latvia, especially in the peatland context. The study relied on results from the LIFE Restore project, but this area clearly requires further empirical development.

Although the sustainability assessment offers a structured comparison of peatland after-use strategies, local site characteristics play a crucial role in shaping which options are actually feasible or beneficial. These physical and ecological conditions can vary widely and should be considered during planning. Key factors include the type of peatland, peat layer thickness, and degree of decomposition, all of which affect suitability for specific land uses like paludiculture, afforestation, or technical installations. Soil pH and hydrological conditions, such as groundwater level and flood duration, are also critical—particularly for rewetting or cultivation. Additional aspects like terrain roughness and underlying soil structure can influence both implementation costs and long-term stability. For instance, uneven or root-dense ground may complicate solar or wind infrastructure, while poor drainage or substrate instability can limit agricultural options.

Looking forward, the inclusion of a sensitivity analysis would strengthen the robustness of the proposed approach for its application in practice. Since sustainability priorities may vary across policy agendas, funding schemes, or local stakeholder preferences, testing how changes in indicator weightings affect the final rankings would help assess the model's stability. This would also make the tool more adaptable to different planning contexts by revealing how outcomes shift when greater emphasis is placed on environmental, economic, or social criteria. Incorporating such an analysis could further support its use in participatory decision-making and policy development.

Acknowledgments. The work has been developed as part of the Fundamental and Applied Research Project "Sustainable Strategies for the Restoration of Peat Mining Sites (Peat4Res)", project no. lzp-2022/1-0405, within the framework financed by Latvian Science Council.

References

1. Ozola, I.: Holocēna organogēnie nogulumi un to uzkrāšanās apstākļu izmaiņas purvos Ziemeļvidzemē. Latvijas Universitāte (2013). https://dspace-dev.lu.lv/server/api/core/bitstreams/a88c3d25-d715-43d7-aaa4-3566fcfa50cf/content
2. Salimi, S., Almuktar, S., Scholz, M.: Impact of climate change on wetland ecosystems: a critical review of experimental wetlands. J. Environ. Manage. **286** (2021). https://doi.org/10.1016/J.JENVMAN.2021.112160
3. Lefèvre, C., Rekik, F., Alcantara, V., Wiese, L.: Carbone organique du solrichesse invisible une (2017)
4. EUKI. Reporting Greenhouse Gas Emissions from Organic Soils in the European Union: Challenges and Opportunities. https://www.euki.de/en/euki-publications/greenhouse-gas-emissions-from-organic-soils/
5. O'Brolchain, N., Peters, J.: CAP Policy Brief Peatlands in the new European Union Version 4.8 (2022). https://www.researchgate.net/publication/340829681_CAP_Policy_Brief_Peatlands_in_the_new_European_Union_Version_48
6. International Peatland Society. Peatlands. https://peatlands.org/peatlands/
7. Kalniņa, L.: https://enciklopedija.lv/skirklis/27677-purvi-Latvij%C4%81
8. Life Restore. Latvijas degradēto kūdrāju inventarizācija un datu bāzes izveide. https://restore.daba.gov.lv/public/lat/jaunumi/e_zinotajs1/e_zinotajs_nr_3_par_degradeto_kudraju_inventarizaciju_latvija/
9. LIFE REstore - Rokasgrāmata "Kūdras ieguves ietekmētu teritoriju atbildīga apsaimniekošana un ilgtspējīga izmantošana. https://restore.daba.gov.lv/public/lat/aktivitates_un_rezultati/rokasgramata_kudras_ieguves_ietekmetu_teritoriju_atbildiga_apsaimniekosana_un_ilgtspejiga_izmantosana/
10. UNEP. Towards a life cycle sustainability assessment: making informed choices on products/UNEP - UN Environment Programme (2011). https://www.unep.org/resources/report/towards-life-cycle-sustainability-assessment-making-informed-choices-products
11. Finkbeiner, M., Schau, E., Lehmann, A., Traverso, M.: Towards life cycle sustainability assessment. Sustainability **2**(10), 3309–3322 (2010). https://doi.org/10.3390/SU2103309
12. Krohling, A., Pacheco, A.: A-TOPSIS – an approach based on TOPSIS for ranking evolutionary algorithms. Procedia Comput. Sci. **55**, 308–317 (2015). https://doi.org/10.1016/J.PROCS.2015.07.054
13. Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., et al.: ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. **22**, 138–147 (2017). https://doi.org/10.1007/s11367-016-1246-y