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Circularity assessment of alternatives to peatland harvesting for a just transition

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Circularity assessment of alternatives to peatland harvesting for a just transition

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Abstract

Climate-neutrality targets have intensified scrutiny on Finland's peat sector, necessitating a just transition to halt peat harvesting. This study evaluates four peatland use pathways:business-as-usual extraction, unused peatlands, reed canary grass (RCG) paludiculture, and willow-based biochar production; using Lifecycle Assessment (GWP100), Weighted Environmental Impacts (WEI), and a Generalised Eco-Efficiency Index (GEI) across 43 scenario permutations. Results demonstrate that paludiculture significantly enhances regional GDP by up to 20% while meeting climate goals, leveraging the EU Emissions Trading System (ETS) for carbon credits.

Keywords: life cycle assessment, circularity assessment, just transition, peatlands

1 Introduction

Climate change represents one of the greatest challenges confronting global societies, with critical implications for ecological systems and human well-being. Recent research indicates that even a modest increase in global warming, specifically a rise of 0.5°C

above pre-industrial levels, could trigger an irreversible cascade of climate disruptions [1]. In alignment with international commitments under the Paris Agreement, participating nations have pledged to limit temperature increases to below +1.5°C by drastically reducing greenhouse gas (GHG) emissions.

Finland has set an ambitious national target: achieving carbon neutrality by 2035 [2], necessitating a comprehensive decarbonization strategy across all economic sectors. Among these, the peat industry, a historically significant contributor to Finland's energy and agricultural systems, faces growing scrutiny due to its environmental impacts.

Peatlands are classified as semi-fossil natural resources, composed of partially decomposed organic matter [3]. These ecosystems represent the densest terrestrial carbon storage on Earth, with Finnish peatlands alone accumulating 5.3 gigatonnes (Gt) of carbon since the last Ice Age across approximately 9.3 million ha, or roughly 27% of Finland's land area [4]. Of this vast resource, 1.2 million ha (13%) are protected, while the remaining peatlands are allocated to forestry (∼500,000 ha), agriculture (∼250,000 ha), and peat extraction (∼60,000 ha) [5, 6].

Approximately 90% of extracted peat is used in the energy sector, contributing 5,500 GWh (1.5%) to Finland's total energy supply in 2024, marking a 22.3% decline from the previous year [7]. The remainder serves diverse applications, including animal bedding, horticultural substrates, soil conditioning agents, landfill cover materials, and spill absorbents [6, 8].

Peatlands exhibit exceptional carbon sequestration capacity, retaining organic matter far more effectively than they decompose [9]. They also possess some of the world's highest irrecoverable carbon densities which once lost, these emissions are irreversible over centuries and pose severe climate risks [10, 11]. In Finland, peatlands store nearly three times more carbon than living forests and soils combined, making them the most

critical carbon sinks in the country [12]. Consequently, peat has emerged as a central focus of national climate mitigation efforts [13].

Despite Finland's rapid transition away from peat energy, the sector remains economically significant, particularly in rural regions such as Ostrobothnia and Central Finland, where it supports ∼2,500 annual person-years, including 1,200 directly tied to extraction [14]. In South Savo (Etelä Savo), the industry contributes €11 million annually to a GDP of €5.8 billion [6]. However, this economic reliance is under threat as demand declines, necessitating a just transition that aligns with the Paris Agreement and the EU's Green Deal [13, 15, 16].

While energy crop production in peatlands could theoretically address energy security concerns, existing studies highlight its unsustainability without subsidies [17]. Similarly, commercial forestry within peatlands is impractical due to high water levels, stunted tree growth, and substantial carbon emissions from drainage, which release 50% more CO_2 over 1,000 years than undrained systems [18]. Traditional forest management thus exacerbates climate vulnerability.

An emerging alternative is paludiculture, or wetland farming, which leverages peatlands' natural hydrology while preserving below-ground carbon storage through sustainable harvesting practices [19, 20]. Research demonstrates that paludiculture can mitigate climate impacts by cultivating above-ground biomass while maintaining peat formation [21–23].

In Finland, viable species include cattail (*Typha*), willow (*Salix*), reed (*Phragmites*), reed canary grass (*Phalaris arundinacea*), and peat moss (*Sphagnum*) [22]. Reed Canary Grass (RCG) replaces peat in animal bedding sustainably [22, 24], while willow's rapid growth under short-rotation coppicing makes it a top candidate for bioenergy production [25].

Prior studies have primarily examined the economic [14, 26] environmental [27, 28], and social impacts of peat use [13, 17]. While research on alternative agricultural

methods exists [22, 29], a holistic assessment integrating environmental and economic trade-offs remains lacking.

This study addresses this gap by conducting a circularity analysis of peatland usage scenarios, evaluating alternatives through global warming potential over 100 years (GWP100), weighted environmental impacts (WEI), and general eco-efficiency index (GEI). These indicators, expressed in CO_2 equivalents (CO_2e) and euros (€), provide a unified economic-environmental metric, offering a flexible framework for comparing peatland management strategies under the constraints of climate mitigation, economic viability, and sustainability.

GWP100 quantifies the climate change contributions derived from LCA, WEI demonstrates its economic cost, while GEI evaluates whether a product or scenario delivers value proportionally to its environmental cost. These indicators together balance economic value against environmental and resource efficiency, these indicators provide a holistic framework; where GWP100 quantifies carbon footprints, WEI assesses their financial burden, and GEI determines proportional eco-efficiency.

By systematically evaluating the alternatives, this research aims to identify the most optimal option from an environmental and circularity perspective, contributing critical insights towards Finland's transition away from peat while ensuring equitable societal benefits.

2 Results

Table 1 presents the minimum and maximum values derived from sub-scenarios for each alternative, highlighting their relative strengths and vulnerabilities across different metrics.

When examining environmental impacts solely through GWP, willow biochar emerges as the most promising option under extreme assumptions. In the best-case scenario, its potential carbon sequestration ranges from -6 to -6,600 tCO_2e/ha,

demonstrating exceptional negative emissions when optimized for soil remediation and bioenergy co-production. Conversely, peat energy exhibits highest GWP (138,009–138,028 tCO_2e/ha) as the worst possible alternative.

From WEI, RCG outperforms alternatives in minimum scenario. While willow biochar achieves its best performance under maximum assumptions, due to the scenario's potential to revitalize marginal lands. Across the total circularity assessment (GEI) of the all the use cases, RCG yields the best performance in minimum scenario and willow (biochar) has the best performance in maximum scenario.

The analysis reveals contrasts within peat scenarios. Unused peatlands consistently outperform other scenarios across GWP and WEI metrics in both minimum and maximum cases, Except when economic contributions are evaluated, where their lack of revenue generation nullifies their advantages. In contrast, peat for energy presents an extreme outlier, its emissions (138,009–138,028 tCO_2e/ha) dwarf all other alternatives by a factor of approximately 7 million times worse than even the worst-case willow biochar scenarios. This disparity highlights the critical need to avoid peat extraction for energy in favour of restoration or low-impact uses.

Willow biochar demonstrates both its strengths and limitations. While it achieves the lowest GWP in maximum scenarios (-6,600 tCO_2e/ha), its potential GEI spans a wide range from -386,070 to +344,010 €/ha, reflecting sensitivity to soil remediation practices and market conditions. RCG, though robust in minimum scenarios (-3.75 tCO_2e/ha), shows lower output in maximum cases compared to alternatives, emphasizing its low-risk, low-rewards characteristics.

Table 1 Comparison of alternatives per hectare per year

	GWP_min tCO_2e/ha	GWP_max tCO_2e/ha	WEI_min €/ha	WEI_max €/ha	GEI_min €/ha	GEI_max €/ha
Peat (unused)	1.18	6.66	-61.00	-346.00	-61.00	-346.00
Peat (bedding)	239.70	259.14	-13,484	-12,464	-411.00	2,579.00
Peat (energy)	138,009.00	138,028.00	-7.18M	-7.18M	-7.18M	-7.18M
RCG (bedding)	-3.75	4.30	**-255.00**	71.00	**10,377.00**	20,372.00
Willow(biochar)	7,440.00	**-6,600.00**	-386,880.00	**343,200.00**	-386,070.00	**344,010.00**
Willow(energy)	**-6.00**	9.56	-9,532.00	19,120.00	-9,512.00	19,140.00

In a hypothetical scenario from South Savo, the integration of willow cultivation for biochar production on marginal lands could yield transformative results. Under optimal conditions, this system could sequester 27 $MtCO_2e$/year, generating up to 1.39 billion euros annually in combined environmental and economic benefits (Table 2). This highlights the scalability of biochar-based circularity when paired with high-value applications such as soil enhancement, emission trading.

Table 2 Yearly Yields in South Savo

	GWP_min $ktCO_2e$	GWP_max $ktCO_2e$	WEI_min M€	WEI_max M€	GEI_min M€	GEI_max M€
Peat (unused)	4.77	27.00	-0.25	-1.40	-0.25	-1.40
Peat (bedding)	966.95	1,045.00	-54.40	-50.28	-1.66	10.41
Peat (energy)	966.94	1,046.00	556.73	556.81	-28,953.91	-28,953.90
RCG	-15.11	17.00	**-1.03**	0.28	**41.86**	82.18
Willow(biochar)	30,012.96	**-26,624.00**	-1,560.67	**1,384.47**	-1,557.41	**1,387.74**
Willow(energy)	**-24.20**	39.00	-38.45	77.13	-38.37	77.21

2.1 Sensitivity Analysis

The analysis reveals that WEI and GEI are highly sensitive to underlying assumptions across all scenarios as seen from Table 4. In peat cultivation, restoration methods can alter GWP by ± 1.96 tCO_2e/ha/yr as seen from Table 3, illustrating the difference between afforestation and natural peatland restoration. For peat bedding, market price fluctuations dominate GEI variability (±3,000 €/ha), while RCG's performance is heavily influenced by animal species selection and methane offsets (±5,998–14,375 €/ha). In willow biochar scenarios, SOC remediation accounts for the most substantial fluctuations (±730,080 €/ha), reflecting its dual role as both a carbon sink and economic driver.

2.2 Sensitivity Analysis

The analysis reveals that WEI and GEI are highly sensitive to underlying assumptions across all scenarios as seen from Table 4. In peat cultivation, restoration methods

Table 3 Sensitivity Analysis Peat

Scenario	Detail	Amount	Change	Unit
Peat	NAT-EXT-AFF	23.97	base	tCO_2e/ha/yr
	FOR-EXT-AFF	24.00	±0.03	
	NAT-EXT-REW	25.91	±1.94	
	FOR-EXT-AFF	25.93	±1.96	

Table 4 Fluctuations causes in GEI

Scenario	Factor	Difference (€/ha)
Peat, bedding	Harvest scenario	± 102
	Animal, bedding usage	± 18
	Methane offset	± 41–59
	Market Price	± 3,000
RCG, biochar	Irrigation method	± 106
	SOC inclusion	± 537
	Animal, bedding usage	± 4,324–5,998
	Methane offset	± 10,051–14,375
	Market Price	± 110
Willow, biochar	SOC	± 730,080
	Market Price	± 1,860
Willow, energy	SOC, Willow cultivation	± 4,108
	SOC, Digestate	± 16,120
	Market Price	± 90

can alter GWP by ± 1.96 tCO_2e/ha/yr as seen from Table 3, illustrating the difference between afforestation and natural peatland restoration. For peat bedding, market price fluctuations dominate GEI variability (±3,000 €/ha), while RCG's performance is heavily influenced by animal species selection and methane offsets (±5,998–14,375 €/ha). In willow biochar scenarios, SOC remediation accounts for the most substantial fluctuations (±730,080 €/ha), reflecting its dual role as both a carbon sink and economic driver.

3 Figures

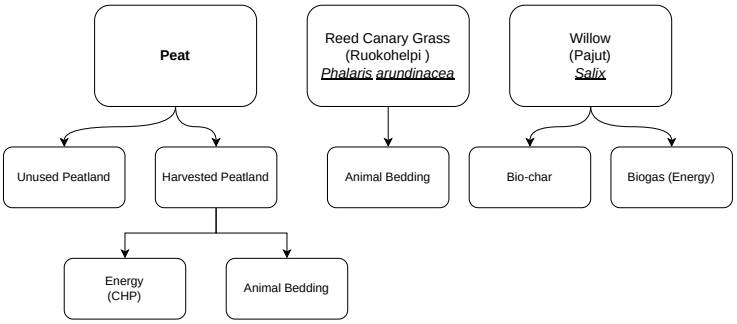

Fig. 1 System boundaries and end product scenarios considered in the study

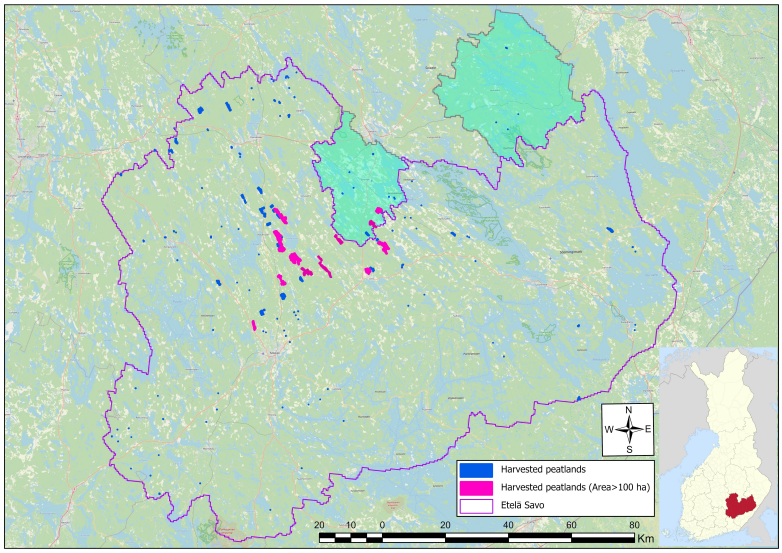

Fig. 2 Harvested Peatlands in South Savo, with location of South Savo in Finland inset.

4 Methods

4.1 Study area

The study was conducted in South Savo region in Finland. The software ArcGIS pro (Version 3.4.0) was used to map the harvested peatlands using data from Finnish National Land Survey. Data on emissions were collected from previous studies, economic valuations were based on market prices in 2024.

4.2 Assessment Framework

Life Cycle Assessment (LCA), Weighted Environmental Impacts (WEI), and the General Eco-Efficiency Index (GEI) were used as key indicators for assessment. For climate change impacts, LCA provided the Global Warming Potential (GWP100) over a 100-year time-frame. WEI served as the economic indicator for climate impacts; while GEI, derived from LCA (ISO 14040/44) and eco-efficiency metrics (ISO 14045), assessed circularity. The GEI integrates economic and environmental trade-offs into a single metric [30], with lower LCA scores and higher WEI/GEI values being preferable.

GWP100 calculations were based on previously conducted LCA. GWP100 values, were calculated were calculated using the weight factors from the sixth assessment report of the intergovernmental panel on climate change [31]. WEI and GEI were calculated based on the methods introduced by Shrestha et al. [30]. Value added required for GEI was calculated based on the market price of each alternative in Finland. The market price was assumed to include life cycle costs. Liable emission taxes were not taken into account while estimating this market price.

4.3 Goal and Scope Definition

The objective of this study was to estimate current area of harvested peatlands in South Savo, assess and compare suitable replacement for peatland farming on the basis

of environmental and circularity performance. Peat harvesting was the business-as-usual (BAU) scenario. This was compared with the alternative land use case scenarios including where peat harvesting is ceased and the land is restored. Paludiculture of RCG, and willow were the considered alternative. RCG was considered as the replacement for peat usage as animal bedding. Willow as biochar was considered as replacement of peat in energy. Biochar from willow's usage as soil remediation agent was also considered. The different usage of peatland, and final usage case are present in Figure 1. 43 different scenario permutations were considered in total. The functional unit of this study was 1 ha of peatland. Additional detail on the system boundaries are present in supplementary materials.

4.4 Peat

Cultivation and Harvest

Peat life cycle was divided into three phases; Initial state of peatland, extraction phase, and restoration phase. Initial state can be natural peatland or forested peatland. Natural peatland requires drainage and ditching. Forested peatland is harvested once the forest is cleared. The economic and environmental impacts of forestry was not taken into account in this study. Harvest period was 17 years, using tehoturve method [32]. Harvesting is followed by restoration period of 100 years. 2 scenarios of restoration were considered; afforestation, and rewetting. The total life cycle of peat is either 117 or 120 years depending on the initial state of peatland. Since peatland is harvested only 17 out of these 117 or 120 years, this was factored in the calculation. An average of 84 km of transportation with a diesel powered truck with a load capacity of 44 tonnes is included in the cultivation and harvest phase. From Mälkki and Frilander [32], peat harvested is 300-1000 m^3 per ha per year. Best case scenario of 1000 m^3 per ha was assumed. Moisture content of 50% was assumed.

Usage

3 different usage were studied. First, was restoration where peatland is not harvested any further with 2 sub-scenarios; restored natural peatland, and drained and forested peatland. Second scenario was usage in energy in a combined heat and power plant (CHP) producing heat and electricity. Peat can also be used in power-plants to only produce heat or electricity, which were not included in the study as they are less efficient than CHP. Peat is usually mixed with other material when used as fuel source, the study takes only the effects of peat through allocation. Third scenario used was peat as animal bedding. Harvested peatland was used as bedding material for 4 different animal types: horse, cattle (dairy), cattle (beef), and chicken. The manure combined with the bedding material was used in anaerobic digester (AD) to produce biomethane and upgraded (97%), which was used in transportation. The digestion period was 30 days, only well to tank was considered. Biomethane used in transportation was considered to replace equivalent natural gas, which was taken as offset. An average of 100 km of transportation (50 km each way) to and from the farm with a 44 tonnes capacity diesel truck was considered in the scenario.

Considering 2 unused peatland sub-scenarios, 4 harvest methods, and 5 different use cases (4 animal bedding, 1 energy use), 22 different scenario permutations for peat were studied.

4.5 Reed Canary Grass

Two scenarios of irrigation method of RCG were studied: rainfed and irrigated. For each scenario, additional sub-scenario where soil organic carbon fixation during RCG farming was also calculated according to models proposed by Iordan et al. [33]. A lifecycle of 15 years was considered, with yearly harvest. Usage of bedding material was similar to peat, the bedding material were studied in 4 different animal types

and the bedding material waste was used in AD to produce biomethane to be used in transportation. 16 total scenario permutations were studied for RCG.

4.6 Willow

Cultivation and harvest

Two different use case of Willow were studied and each use case required different harvesting method. Willow for biochar requires small chunks of biomass hence can be harvested starting 1 year after plantation and can be harvested semi annually (twice a year). The total life of 4 years was considered with total of 6 harvests.

For willow as energy, the willow biomass needs to be bigger than that used for biochar, hence harvest is done every 3 years on average. A life cycle of 25 years was considered where first harvest is after 4 years of plantation and subsequent harvest every 3 years with 8 total harvests.

Usage

First usage case was biochar, where willow chips are converted to biochar using pyrolysis. The process produces heat which can be used in energy production. A sub-scenario was studied where electricity is produced from the heat of pyrolysis. The produced biochar has a market value without further usage, as the carbon credits of produced biochar can be certified and traded. The biochar can be used in soil remediation of marginal lands. The second sub-scenario considers the soil carbon fixation during the soil remediation.

In the second use case, willow is converted into chips, mixed with manure and fed to AD to produce biomethane which is used in a gas turbine to produce heat and electricity, the digestate is used in soil remediation. Only the contribution of willow is considered. This was done by calculating the effects of output when only manure is used in AD, and calculating the difference [25]. Two scenarios are considered, one with

soil carbon fixation and one without. Willow chips can also be directly used for energy production however, it was reported to be less efficient, and hence not considered in this study. 5 total sub-scenarios were studied for willow.

5 Discussion

5.1 Environmental and Economic Impacts

This study's results indicate that peat harvesting (business-as-usual) is the worst scenario both environmentally and economically, causing potential environmental damage up to €7.18M per ha annually. Only when used as bedding, it has a positive GEI in the best case scenario as the economic contribution outweighs the environmental damage.

Considering only the environmental impacts, using the peatland for RCG paludiculture is the best option followed next by restored peatlands. Reed canary grass is generally the best overall as a low risk option. Willow (biochar) represents high-risk, high-reward option because its economic viability depends strongly on biomass prices and carbon credit values.

Unused peatland still produces methane emissions which causes a negative WEI. Methane emissions are shown to be prevalent in the early stages of rewetting [34, 35]. Yet, these emissions are outweighed by the long-term reductions in CO_2 and N_2O emissions as drained peatland can release these emissions when detritus decompose [36]. Recent study demonstrate measurable changes in environmental impacts of restored impacts, approximately 10 years after the restoration process [37].

5.2 Suitable alternatives

Rewetting of peatland and commercial forestry are not compatible, primarily because tree species are not adapted for high water levels and logging machinery cannot easily operate in waterlogged area. This could be mitigated by using suitable species such as black alder (*Alnus Glutinosa*), which have been used in paludiculture [38]. Access

of machinery may become feasible in the future with technologies such as tree-to-tree robots [39] and spider robots [40]; enabling controlled and selective thinning, felling, and transportation without disturbing the wetlands. Further research is needed to assess the techno-economic feasibility and environmental impacts of such operations.

The alternatives were chosen in this study for their suitability as market replacement of peat and for meeting demand. Reed Canary Grass has additional market value as it can be used in packaging and disposable tableware, panels, fodder, and decorative materials. Willow can additionally be used as weaving materials (e.g. for baskets).

Other species that have market value and can be viable alternative in smaller scale are: reed (*Phragmites*) as thatching insulation, and construction material, packaging and disposable tableware, fodder, paper; Peat moss (*Sphagnum*) as growing media, substrates in carnivorous plants, base for vivaria; Cattail (*Typha*) as Insulation, filling, construction materials, packaging and disposable tableware, growth media; and Cranberry (*Vaccinium oxycocous; Vaccinium carocarpon*) as food (fresh berries, juice) [38]. These alternatives could be suitable in small scale operations for landowners.

5.3 Limitations

GWP100, GEI, and WEI only considers climate change as impacts. Hence, the study does not account for biodiversity effects, water quality impacts, or water availability issues. GWP quantifies the contribution of a product or system to global warming and climate change. GEI visualises combined economic and environmental benefits and circularity; WEI expresses environmental impacts from an economic perspective. The results are derived from a mathematical optimization approach that quantifies best and worst-case scenarios based on predefined input parameters, including biomass productivity, carbon credit prices, and market-driven economic valuations. However, the reliability of these projections rely upon the realism of underlying assumptions

including fluctuating commodity markets (e.g., peatland alternatives) and the long-term stability of carbon credit mechanisms within regulatory frameworks such as the EU Emissions Trading System (EU-ETS). Such dependencies indicate the theoretical nature of the analysis, where deviations from assumed conditions could substantially alter estimated impacts.

5.4 Implications

South Savo contains 4,034 ha of harvested peatlands, of which 3,511 ha exceed 15 ha and 2,986 ha exceed 100 ha. The study site is shown in Figure 2; dark blue area indicates all harvested peatland, magenta marks harvested lands over 100 ha, and light green shows municipalities that were part of South Savo until 2021. The maximum annualized GEI (willow for biochar) is €1.39 billion when all peatlands are used, €1.27 billion when only lands $\geq$ 15 ha are used, and €1.02 billion for lands $\geq$ 100 ha, which are equivalent to 15%-20% of the local GDP.

In this study, only the market value of willow as biochar in carbon credits trading system was explored as that was the only known case in Finland. Other use cases can potentially be validated and have a market value in EU-ETS. Accreditation of restored peatlands or products of paludiculture, could also be explored in the future which could be an incentive for peatlands restoration.

Previous work has considered peatlands $\geq$ 15 ha for alternative uses [17]. A zoned approach to peatland rewetting and paludiculture proposes allocating selected areas to rewetting, forestry, or paludiculture; balancing climate goals with socio-economic benefits, enhancing carbon storage while delivering economic returns to landowners. This approach supports the creation of biodiversity corridors, strengthens ecosystem resilience, and balances rewetting and forestry objectives [41].

Usage in Marginal land restoration

Csikós and Tóth [42] in their literature review, point that definition of marginal land differs across regions, countries, and organizations due to the different management objectives of the areas of concern. In the last 30 years, it is usually used for lands that are unproductive and idle. A recent study estimates there are 118,684 ha (61,922 plots) of such marginal land in Finland, out of which 9,262 ha (484 plots) are discontinued peatlands. In South Savo, that is 6,901 ha (3,795 plots), out of which 766 ha (24 plots) are discontinued peatlands [43]. Paludiculture can restore and repurpose these marginal lands. This has the maximum potential to increase the GEI by additional €2.3 billion in South Savo and and €40.8 billion in Finland. However, this is just an estimate based on the calculation in the best case scenario. Some of the estimated marginal lands could be unfit for commercial paludiculture due to their small size. For instance, plots < 5 ha may lack economic viability. Other alternatives such as afforestation or other forms of agriculture could also yield a better profit margin. Further research is required to investigate the optimum usages of these lands based on their size and land types.

6 Conclusions

While restoring the peatlands and halting peat harvest is essential to mitigate global warming and climate change, it has economic ramifications in rural Finnish economies. Our assessment demonstrates that the paludiculture of certain species and their usage, as an alternative to peatland restoration, can mitigate the economic impacts while maintaining the climate goals. The possibility of carbon credit accreditation and trade can provide landowners additional incentive to transition from peat economy to restoration or paludiculture. This has the potential of increasing the GEI in South Savo by an amount equivalent to 20% of its GDP. Advancement in tree-to-tree forestry technology can also enable paludiculture of species such as black alder, making forestry

a viable option. Larger plots, above 100 ha, can use zoned approach to selectively conduct paludiculture, restoration, and forestry to optimize economic gains with net neutral emissions. Future studies can develop the perfect zoned approach model to optimize the environmental and economic benefits. Paludiculture could also be used to restore and repurpose Finnish marginal lands, which could increase the GEI in South Savo by an amount equivalent to 42% of its GDP and in Finland approximately 12% of the national GDP. Further research is required to investigate the optimal use of these lands based on their size and land types

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Supplementary Information. Detailed results are presented in supplementary materials.

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