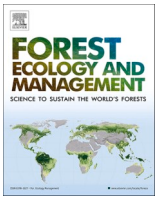
Forest Ecology and Management 619 (2026) 124137

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



Estimating the impact of peatland forest management on heterotrophic carbon dioxide emissions in southern Finland

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ARTICLE INFO

Keywords:
Peatland forestry
Greenhouse gas emissions
Soil simulation
Continuous cover forestry
Rotation forestry
Selection harvesting
Clearcutting

ABSTRACT

Peatland forest management using different harvesting methods, such as rotation forestry (RF) and continuous cover forestry (CCF), affects soil organic matter decomposition and greenhouse gas emissions. In this study, a process-based model, Estimate Carbon in Organic Soils – Sequestration and Emissions (ECOSSE), developed for organic soils was applied to simulate the impact of stand harvesting on heterotrophic carbon dioxide emissions (R_h-CO_2) in two Norway spruce dominated drained peatland forests in southern Finland (Ränskälänkorpi and Lettosuo). Both forests were split into a control area and two differently harvested areas: a clear-cut representing RF, and a selection harvest representing CCF. The output from the model simulation was evaluated against field measurements (2020–2022 in Ränskälänkorpi and 2020–2021 in Lettosuo), and the model was further applied to assess the long-term (50 years) impacts of the harvesting methods on R_h-CO_2 in future climatic conditions. Results from the simulation showed that the model accurately estimated the trends in R_h-CO_2 at the two sites across different management practices, with correlation coefficients ranging from 0.7 to 0.99. There was no significant model bias between the modelled and measured values from the two sites. In Lettosuo, CCF and RF initially produced higher R_h-CO_2 levels compared to the non-harvested control, but these levels declined steadily over time. In Ränskälänkorpi, CCF area resulted in higher R_h-CO_2 levels after 20 years compared to the control and RF areas. By the end of the simulation, R_h-CO_2 levels from CCF and RF were lower compared to the control. These findings highlight the long-term and varied impacts of peatland forestry management practices in reducing R_h-CO_2.

1. Introduction

Peatlands cover about 9 000 000 ha of the land surface area in Finland, and more than half of this area has been drained, mostly for forestry purposes (Päivänen and Hånell, 2012; Korhonen et al., 2024). Drainage of peatlands for forestry was a common practice in Finland around the 1960s and resulted in accelerated decomposition of organic matter of peat soils. This has resulted in increased greenhouse gas (GHG) emissions, with estimated annual emissions of 8 Mt CO_2 eq yr^{-1} for 4.3 Mha of drained peatlands in Finland (Alm et al., 2023), thereby constituting serious threats to climate change mitigation.

On peatland forests, different management and harvesting methods have been practiced for timber production, and they also affect the GHG balance of the peatland ecosystems. In Finland, rotational forestry (RF), which involves clear-cutting and forest regeneration, is the most common method of forest management (Korkiakoski et al., 2019). At the stand level, clear-cutting may remove nearly 100% of the aboveground tree biomass, whereas in CCF 50%- 70% of the merchantable timber is removed (Lehtonen et al., 2023). As a result, the evapotranspiration of the remaining tree stands helps maintain the water table depth (WTD) optimal for tree growth (Sarkkola et al., 2013; Leppä et al. 2020). In contrast, clear-cutting in peatland forests involves the ditch-network maintenance followed by stand regeneration through site preparation and sowing or planting of seedlings. The CCF relies on natural regeneration and does not require site preparation, which reduces the costs associated with regeneration (Leppä et al., 2020).

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https://doi.org/10.1016/j.foreco.2026.124137
Received 13 May 2026; Received in revised form 5 July 2026; Accepted 28 July 2026
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Peatland forest management practices and harvesting have the potential to alter soil temperature, WTD, water runoff and transport, soil microbial activity, and vegetation cover (Kritzberg et al., 2020). In peatland forests, the WTD rises when tree biomass is reduced (Sarkkola et al., 2010; Leppä et al. 2020). This is due to reduced transpiration, which raises WTD and may reduce peat decomposition rate. In general, continuous cover forestry (CCF) and RF result higher WTD than the control (unharvested treatment) (Korrensalo et al., 2026). However, CCF was reported to raise WTD less (10 – 14 cm) than RF, with the WTD generally below – 30 cm (Korkiakoski, 2020). Post-harvest reductions in annual heterotrophic soil respirations were observed with the harvesting methods, which varied according to sites. CCF resulted in 14% lower annual soil heterotrophic respirations while RF resulted in 26% lower heterotrophic soil respirations (Korrensalo et al., 2026). CCF and RF were reported to result in increased soil temperature (Korkiakoski, 2020; Korrensalo et al., 2026) with the potential to accelerate the decomposition of organic matter in peatland. After clear-cutting, forest understorey vegetation recovers rapidly in peatland forests (Ojanen et al., 2017). However, the rapid vegetation recovery rate is usually insufficient to offset the high ecosystem respiration, which is mostly driven by high peat decomposition rates (Ojanen et al., 2017). The decomposition of logging residues, such as foliage biomass, branches, and stumps left on site, as well as the increased soil organic matter decomposition under these residues, facilitates an increase in ecosystem respiration (Ojanen et al., 2017).

Soil process-based models have been developed to estimate the impact of management practices on soil carbon (C) sequestration and GHG emissions. These models were developed based on knowledge of how soil C sequestration is affected by changes in soil properties, land use and weather. These models are of great importance and have been successfully applied in predicting the effects of land-use changes on soil C and GHG emissions at both field and regional scales (Bell et al., 2012; Dondini et al., 2014; Smith et al., 1997). However, the availability of adequate field data for evaluating and validating these models is a serious limiting factor, leading to high uncertainty in model assumptions, calibration and data inputs. As a result, there is a need to validate these models in order to increase their usefulness and potential applications in policy-making both at the field, regional and national scales (Grassini et al., 2015).

ECOSSE model is a process-based model developed to simulate soil C dynamics and GHG emissions in both highly organic soils and mineral soils. It is driven by meteorological data and soil properties (Smith et al., 2010). This model has the potential to predict the impacts of land-use and climate change on soil C and nitrogen (N) stores in organic and mineral soils. The processes of soil C and N turnover in the soil are incorporated in this model, but these processes are simulated using simple equations that are driven by commonly available input variables. It can function optimally at national and field scales, allowing results to be employed in policy decisions (Bell et al., 2012). The model uses measured soil C to estimate the activity of SOM and the amount of plant inputs needed to achieve those values. Data describing soil water, plant inputs, application of nutrients and timing of management activities are applied in driven the mode, thereby attributing the factors influencing SOM activity accurately. In the absence of these variables, the model can still estimate SOM turnover with reasonable accuracy due to reduced input variables. ECOSSE model has been validated and applied successfully to simulate GHG emissions at different European peatlands (Abdalla et al., 2014), simulate soil C under different short rotation forestry in Britain (Dondini et al., 2014), and applied spatially to simulate the impact of land-use change on soil C and GHG emissions in different soil types and simulate GHG emissions in European cropland sites (Bell et al., 2012; Smith et al., 2010). In addition, Smith et al. (2010) applied ECOSSE to estimate the net change in soil C in response to land-use change from grassland and arable to forested peatland.

The use of CCF instead of RF to maintain CO_2 sink and litter inputs of the tree stand while increasing WTD and reduced soil heterotrophic respirations was proposed (Lehtonen et al., 2023). However, there is little or no empirical evidence on the potential impact of the different harvesting methods on heterotrophic carbon dioxide emissions (R_h-CO_2) under different environmental and weather conditions. In this study, the ECOSSE model was applied to simulate the impact of CCF and RF on R_h-CO_2 at two peatland forests in Finland. The focus of this study is to determine the long-term impacts (2020–2070) of CCF and RF on R_h-CO_2 at two Finnish peatland forests, after evaluating the model against field measurements in a future climatic condition. This is important in supporting climate-informed management decisions targeted at reducing greenhouse gas emissions in peatland forests. Therefore, the objectives of this study were (a) to simulate R_h-CO_2 at the two selected peatland forestry sites across the different management practices (b) evaluate the performance of the modelled output to field measurements from the selected peatland forestry sites (c) assess the impact of the different harvesting practices on R_h-CO_2 in a future climate.

2. Materials and methods

2.1. Study sites

Data from two peatland forest experimental sites were used in this study. The first site, Ränskälänkorpi experimental peatland forest (ca. 25 ha), is located in the Asikkala municipality in Southern Finland (N61°10.966′, E25°15.985′) (Table 1). Ränskälänkorpi was drained for forestry before 1960, and the current network of ditches was created in the early 1960s. The thickness of the peat layer is > 1 m. To demonstrate the impacts of different forest management on tree stand development, hydrology and GHG fluxes, the site was divided into three blocks in 2019: CCF (ca. 10.0 ha), RF (ca. 6.1 ha), and a non-harvested control area (ca. 7.3 ha). In 2019, the monitoring of the site started, and between March and June 2021, the harvesting of the tree stands according to treatment was carried out. During the selection harvesting process (CCF), about 60% of trees were removed, with harvest residues left on site. The dominating tree species was Norway spruce (*Picea abies*), with smaller proportions of Scots pine (*Pinus sylvestris*) and downy birch (*Betula pubescens*). A full description of this experimental setup at Ränskälänkorpi is described in (Laurila et al., 2021).

The second site, Lettosuo experimental peatland forest, is located in Tammela municipality, Southern Finland (N60°0.641′, E23°0.959′) (Table 1). At the Lettosuo site, CCF and RF were carried out between 29 February and 16 March 2016. During this period, the dominant pine trees (ca. 75% of the tree biomass) were removed in CCF, while harvest residues were left at the site. Scots pine (*Pinus sylvestris*) and downy birch (*Betula pubescens*) trees were the dominant tree species before the harvest, while the dominant tree species after the selection harvest include Norway spruce (*Picea abies*) and downy birch (*Betula pubescens*). In the north-east of the CCF area, the non-harvested area was left as non-managed control. More details about the site and the harvests can be found in (Korkiakoski et al., 2017; 2023).

2.2. Measurements of heterotrophic and total respiration

In Ränskälänkorpi site, forest floor respiration (R_{total}-CO_2) was measured between July 2020 and May 2022, while in Lettosuo, heterotrophic respiration (R_h-CO_2) fluxes were measured from June 2020 to November 2021 biweekly on the CCF and non-harvested control blocks, using the trenching method as described in Korrensalo et al. (2026). In measuring the R_h-CO_2, experimental root-exclusion (trenching) plots were established to exclude soil respiration originating from the decomposition of soil organic matter. These plots excluded autotrophic respiration from above- and belowground plant tissues, as well as heterotrophic respiration associated with fresh litter inputs, surface organic material, and root exudates. Plots were selected to capture spatial variability within each study site and were typically arranged in groups

Table 1
Site coordinates, water table depth (WTD), type of peatland, management and weather data, WTD at start denotes the initial depth of the peatland at the beginning of the model simulation.

Site/location	Coordinates	WTD (cm) at start	Maximum WTD (cm)	Peatland type	Management type	Average air temperature	Total annual precipitation (mm)
Ränskälänkorpi, Finland	N61°10.966' E25°15.985'	61 cm	103 cm	Drained fen	Continuous cover forestry, clear-cutting, control	3.8 °C	600 mm
Lettosuo, Finland	N60°0.641', E23°0.959'	21 cm	70 cm	Drained fen	Continuous cover forestry, clear-cutting, control	4.6^0C	627 mm

of 2–5 plots. Root exclusion was achieved using either polypropylene root-exclusion fabric installed around square plots (60 × 60 cm) or metal cylinders inserted vertically into the peat surrounding circular plots (31.5 cm diameter). The barriers were installed to depths of 60 cm for fabric plots and 30 cm for cylinder plots. All aboveground vascular plant biomass was removed, and plots were maintained free of vascular plants throughout the measurement period. To remove autotrophic moss respiration and associated respiration from fresh litter, living moss and loose, undecomposed litter were also removed. In fabric-based plots, the moss and overlying litter layer was carefully cut from the plot, placed on a polypropylene sheet, and returned to the plot surface. In cylinder-based plots, moss and loose litter were completely removed, and these plots were maintained without moss or litter regrowth. Plots were not established in drainage ditches or areas directly disturbed by harvesting activities. The measured RHS therefore represents respiration from pre-existing soil organic matter only and excludes contributions from harvest residues or litter that accumulated after measurements began. Consequently, the measurements capture the effect of harvesting on the decomposition of soil organic matter that was present prior to disturbance.

Fluxes were measured with a closed-chamber system in both sites using an opaque cylindrical chamber (height 30.5 cm, diameter 32 cm), with a mixing fan. The concentrations of these fluxes were measured every 5 s using a LI−7810 (LI-COR Inc., Lincoln, NE, USA).

2.3. ECOSSE model

The ECOSSE Model (v. 6.4.0.1) describes soil organic carbon (SOC) using a pool-type approach representing soil organic matter as five pools. Soil organic matter in the ECOSSE is structured into five pools; decomposable plant material (DPM), resistant plant material (RPM), biomass (BIO), humus (HUM) and inert organic matter (IOM). These pools are distinguished by their rate constants (DPM = 10 y^{-1}, RPM = 0.30 y^{-1}, BIO = 0.66 y^{-1}, HUM = 0.02 y^{-1}, IOM = 0 y^{-1} – inert). The DPM, RPM, BIO and HUM pools decompose to produce BIO and HUM. The BIO pool includes only soil organic matter; the living biomass in the forest stand is considered separately. Annual losses from living biomass contributes to inputs of DPM and RPM according to the DPM/RPM ratio specified for the land use type; for forestry this is 0.25 (i.e. 20% DPM, 80% RPM). The total amount of plant input is estimated from a spin-up run, assuming steady state conditions and adjusting plant inputs until the simulated SOC matches measured SOC. Details of the model structure are provided by Smith et al. (2010). This model was developed from the concepts originally derived for mineral soils in the RothC and SUNDIAL models (Smith et al., 2010). However, the main difference in the simulation of soil C dynamics in ECOSSE compared to RothC and SUNDIAL is that, unlike RothC and SUNDIAL models, the ECOSSE model simulates soil C and N dynamics to 1 m soil depth and can be applied for highly organic soils. ECOSSE has the capability to be run with limited input data if site-specific details are not available. More detailed and complete model description can be found in Smith et al. (2010).

2.4. Input data

The input data required to run the model include: (a) weather data (30-year-averaged monthly rainfall and temperature; monthly temperature, potential evapotranspiration and rainfall for the simulated years), (b) soil data: initial soil C content, soil bulk density and soil pH (for each simulated soil layer) and (c) Land use data such as land-use type and plant litter C input to the soil for each simulated year.

Both sites investigated in this study comprised one control experimental field (with no harvesting of trees) and two different management practices (CCF and RF). WTD was also measured manually during the gas flux measurement using water table meter in the piezometer installed near each reference plot during the seasons 2020–2022 at both sites.

Climatic data from the two weather stations closest to the sites ('Jokioinen Ilmala' for Lettosuo and 'Hämeenlinna Lammi Pappila' for Ränskälänkorpi) were extracted from an open data service managed by the Finnish Meteorological Institute. At each site, the long-term (30 years) average precipitation and air temperature were calculated from data spanning the 30 years preceding the simulation start (1989–2019) detailed in the supplementary materials (Table S1).

In 2022 and 2023, soil samples were collected from different layers (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–60 cm, 60–70 cm, 70–80 cm, 80–90 cm and 90–100 cm) at five replicates. The average values from the analysis and measurement of soil C, soil bulk density and soil pH from each of these soil layers were collated for each site and management types and used as input to the model (Table 2).

Plant litter falls (ground vegetation litters) were extracted from different plots as described in (Laurila, 2021) before harvesting (control) and after harvesting (RF and CCF) in all the treatments. In Ränskälänkorpi, litter fall was measured in 2020 before harvesting and in 2021–2022 after treatments. In each treatment, 3 litter traps (diameter 27.5 cm) were installed on ground surface and litter fall inside traps were collected 5–6 times during the growing season, then air-dried and weighed the dry mass in the laboratory. The measured values were collated, and the annual average of the plant litter (kg C ha^{-1} yr^{-1}) was calculated and used as input to the model (Table 3).

For the model spin up, the plant inputs are estimated by calculating a combination of the net primary production (NPP) model MIAMI and land management practices of the initial land (Lieth, 1972, 1973). The overall turnover rate is modified by the decomposition rate modifier, estimated by numerically solving the analytical solution of the decomposition equations (Bradbury et al., 1993) and continuously updating the decomposition rate modifier using long-term climate data until the system reaches a stable equilibrium and the change in soil carbon was zero, which was applied to create this solution (Dondini et al., 2014). This strategy generates relative five carbon pool sizes as described in previous section (Wong et al., 2013).

2.5. Model evaluation and statistical analysis

For the purpose of this study, the R_h-CO_2 used in the model evaluation for Ränskälänkorpi locations were estimated using the equation below:

$$Rh - CO_2 = Rtotal - CO_2 \times \%Rh/100 \quad (1)$$

Where %*Rh* is the contribution of heterotrophic respiration on total respiration at Lettosuo site calculated using the equation below:

Table 2
Measured soil carbon (C) (kt C ha^{-1}), bulk density (g cm^{-3}), at 0 – 30 cm and 0 – 100 cm soil depth for different treatments at the sites.

		0 – 30 cm soil depth			0 – 100 cm soil depth		
Site	**Management**	**Soil C (kt C ha^{-1})**	**Bulk density (g cm^{-3})**	**pH**	**Soil C (kt C ha^{-1})**	**Bulk density (g cm^{-3})**	**pH**
Ränskälänkorpi	Control	79	0.15	3.92	80	0.15	3.92
Ränskälänkorpi	Rotational forestry	80	0.15	3.98	86	0.15	4.94
Ränskälänkorpi	Continuous cover forestry	79	0.15	4.34	86	0.15	5.86
Lettosuo	Control	53	0.30	2.84	68	0.24	3.12
Lettosuo	Rotational forestry	55	0.32	2.87	63	0.22	3.19
Lettosuo	Continuous cover forestry	53	0.26	2.84	68	0.22	3.12

Table 3
Measured plant litter C input (kg ha^{-1} yr^{-1}) used as input in model simulation. No values for plant litter C in 2020 at the Ränskälänkorpi sites.

Management	**Plant litter C (kg ha^{-1} yr^{-1})**					
	Ränskälänkorpi			**Lettosuo**		
	2020	2021	2022	2020	2021	2022
Control	3034	710	864	1073	1429	165
Rotational forestry		147	326	27	93	14
Continuous cover forestry		300	524	560	667	67

$$\%Rh = (\mathrm{Rh} - \mathrm{CO_2}/\mathrm{Rtotal} - \mathrm{CO_2})\mathrm{x}100 \quad (2)$$

To account for the seasonal variability, the seasonal average of $\%Rh$ (spring, summer and winter) was calculated and used in estimating R_h-CO_2 in Ränskälänkorpi locations as described above.

The ECOSSE model was run for both sites and all managements over the 2020–2022 growing seasons. R_h-CO_2 values were compared against measured R_h-CO_2 values to assess the model performance in estimating R_h-CO_2 at the study sites. The model was evaluated by comparing the outputs to the field measurements of the R_h-CO_2 fluxes from the two sites.

Statistical analysis was performed to determine the coincidence and association between the measured and modelled values as described in (Smith and Smith, 2007; Smith et al., 1997). Using the Pearson's correlation coefficient (R), the degree of association between the modelled and measured values was determined. The standard error was used to quantify the statistical significance of the differences between the modelled and measured values. To determine the degree of difference between the modelled and measured values, an analysis of coincidence was performed. This was determined by using the lack of fit statistics (LOFIT), and its significance was assessed using the *F-test*. This indicates if the difference in the paired values of the two datasets is significant. All statistical results were considered statistically significant at $P < 0.05$. The total difference between the measured and modelled values, which indicates the average error magnitude, was calculated as the root mean square error (RMSE) and expressed in the same units as the analysed data. The model bias was expressed as a percentage using the relative error, E. The significance of the bias was determined by comparing it to the value of E obtained at the 95% confidence interval of the replicated values. All statistical analyses were carried out using MODEVAL program described in (Smith et al., 1996).

2.6. Model applications

The ECOSSE model was applied to simulate the impact of different management practices on R_h-CO_2 emissions and SOC sequestration in a future climate scenario between 2020–2070 at the study sites. Weather data (air temperature and precipitation data) at each location for this period were extracted from the CRU TS:Data (Climatic Research Unit gridded Time series), High-resolution gridded datasets provided by the UK National Centre for Atmospheric Science (NCAS) (Harris et al., 2020). The ECOSSE model can estimate plant litter inputs calculated from a combination of the NPP based on a variation of MIAMI model (Lieth, 1972, 1973), as described in (Dondini et al., 2014). Therefore, for the control site, the plant litter inputs for the years of the simulation were estimated by the ECOSSE model and presented in the supplementary materials. For the management projections (CF and RF), future yearly plant litter input (Px) was estimated by first calculating the ratio of estimated plant input in the control site to the measured plant input for each management type, expressed in percentage, using the formula below:

$$Px = c/m \quad (3)$$

Where c is the estimated plant litter input for the control, m is the measured plant litter input for each management from the previous year.

Estimated plant litter input (Ex) was then calculated using the formula below:

$$Ex = c/m * Px \quad (4)$$

The change in R_h-CO_2 emissions (ΔCO_2) was calculated as the difference between the emissions from the control and the emissions from each management. The monthly emissions for each year were averaged to determine the average annual emissions over the simulation period (e.g. 50 years).

3. Results

3.1. Model simulations and evaluation

The model simulations of the two sites under different management practices showed a good fit with measured soil R_h-CO_2 emissions (Fig. 1). The results indicate that the model generally predicted accurately the peak of R_h-CO_2 at the study sites. The results also showed a more accurate prediction of the model outside the peak than during the peak period. However, it occasionally over- or under-estimated R_h-CO_2 during the warm climate in summer (July – August) and cold period in autumn (September – November), compared to measured R_h-CO_2. This trend was observed in both the control area and across the different management systems at each site.

Strong correlation coefficients between the model and measured values (R = 0.7–0.95) were observed across the different management practices at both the Ränkälänkorpi and Lettosuo sites (Fig. 2). The results indicated that the modelled values were consistent with the measured values (Table 4). In Ränkälänkorpi site, correlation coefficients of 0.84, 0.99, and 0.80 for the control, CCF, and RF treatments, respectively, demonstrated significant associations ($P < 0.05$) between the modelled and measured R_h–CO_2 fluxes. Similarly, at the Lettosuo site, the correlation coefficients of 0.95, 0.95, and 0.70 for the control, CCF, and RF treatments, respectively, also showed significant correlations ($P < 0.05$) between the modelled and observed R_h–CO_2 (Fig. 2; Table 4).

The model's predictions are not significantly biased compared to the measured values. The calculated error (E) is within the 95% confidence limit (E_{95}) (there was no significant model bias ($E < E_{95}$) between the modelled and measured R_h-CO_2) at the two experimental sites under the different management practices (Table 4). Analysis of the lack-of-fit

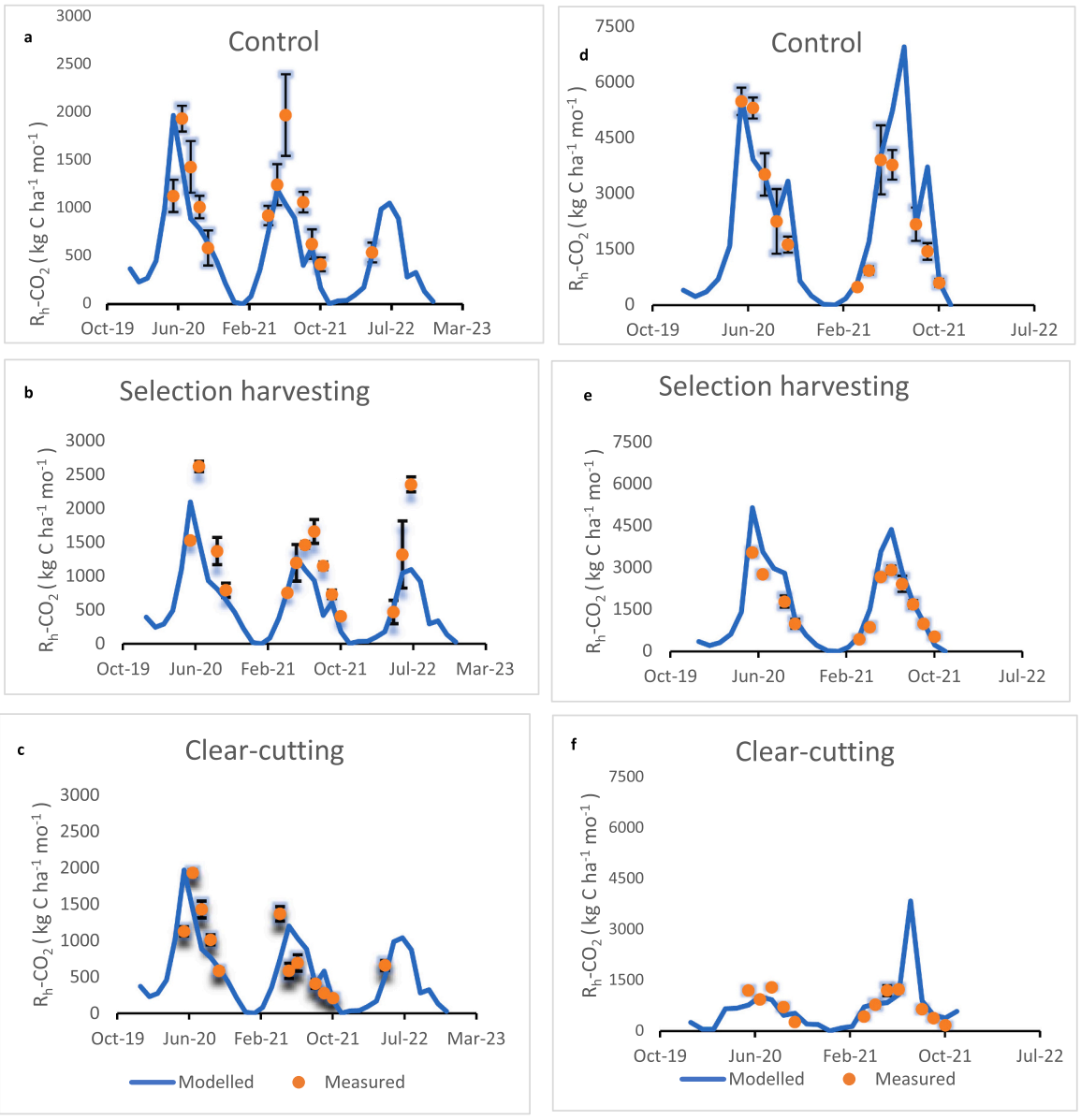

Fig. 1. Measured (orange) and modelled (blue) heterotrophic respiration (R_h-CO_2) across the different practices (a. Control, b. selection harvesting and C. clear-cutting at Ränskälänkorpi (left) and Lettosuo (right) (d. control, e. selection harvesting and f. clear-cutting) peatland forestry sites. Error bars on the measurements indicate 95% confidence interval.

(LOFIT) showed no significant error between the modelled and measured values $F < F$ (critical at 5%) at any of the treatments (Table 4). The Root Mean Squared Error (RMSE) indicated no significant total error between the modelled and measured values in all the treatments.

3.2. *Impact of management practices and future climate on Heterotrophic respiration*

Results of this analysis indicate that the management practices led to an increase and reduction in R_h-CO_2, which vary across the management practices and experimental sites, over the 50-year simulation period, indicating seasonal or environmental variability (Fig. 3).

At the Ränskälänkorpi sites, estimated R_h-CO_2 values from the control were estimated to be higher (1716 kg C ha^{-1} yr^{-1}) compared to the R_h-CO_2 from the CCF and RF harvesting practices (904 kg C ha^{-1} yr^{-1} and 821 kg C ha^{-1} yr^{-1} respectively) after 10 years. After this period, the model estimated that the R_h-CO_2 decreased significantly for the next few years in both CCF and RF harvesting sites compared to the control area. This trend continued until 20 years after the simulation, when a peak in R_h-CO_2 (the point where the highest emission of R_h-CO_2 was recorded) was observed with CCF resulting in highest R_h-CO_2 values of 2221 kg C ha^{-1} yr^{-1} compared to the RF (345 kg C ha^{-1} yr^{-1}) and control area (1134 kg C ha^{-1} yr^{-1}). However, this estimated increase Rh-CO_2 reduced significantly and consistently after this period at the end of the simulation resulting to a clear difference in R_h-CO_2 between the management practices compared to the control. The estimated R_h-CO_2 from the control area remained higher at the end of the simulation (988 kg C ha^{-1} yr^{-1}) compared to the beginning of the simulation (579 kg C ha^{-1} yr^{-1}).

At the Lettosuo sites, the model estimated a significant increase in R_h-CO_2 across the management practices in the first year of simulation (Fig. 3). However, this sharp increase in R_h-CO_2 decreased consistently with a few instances of fluctuations over the simulation years and was reduced significantly at the end of the simulation compared to the start, although there was no major difference in R_h-CO_2 between the management practices.

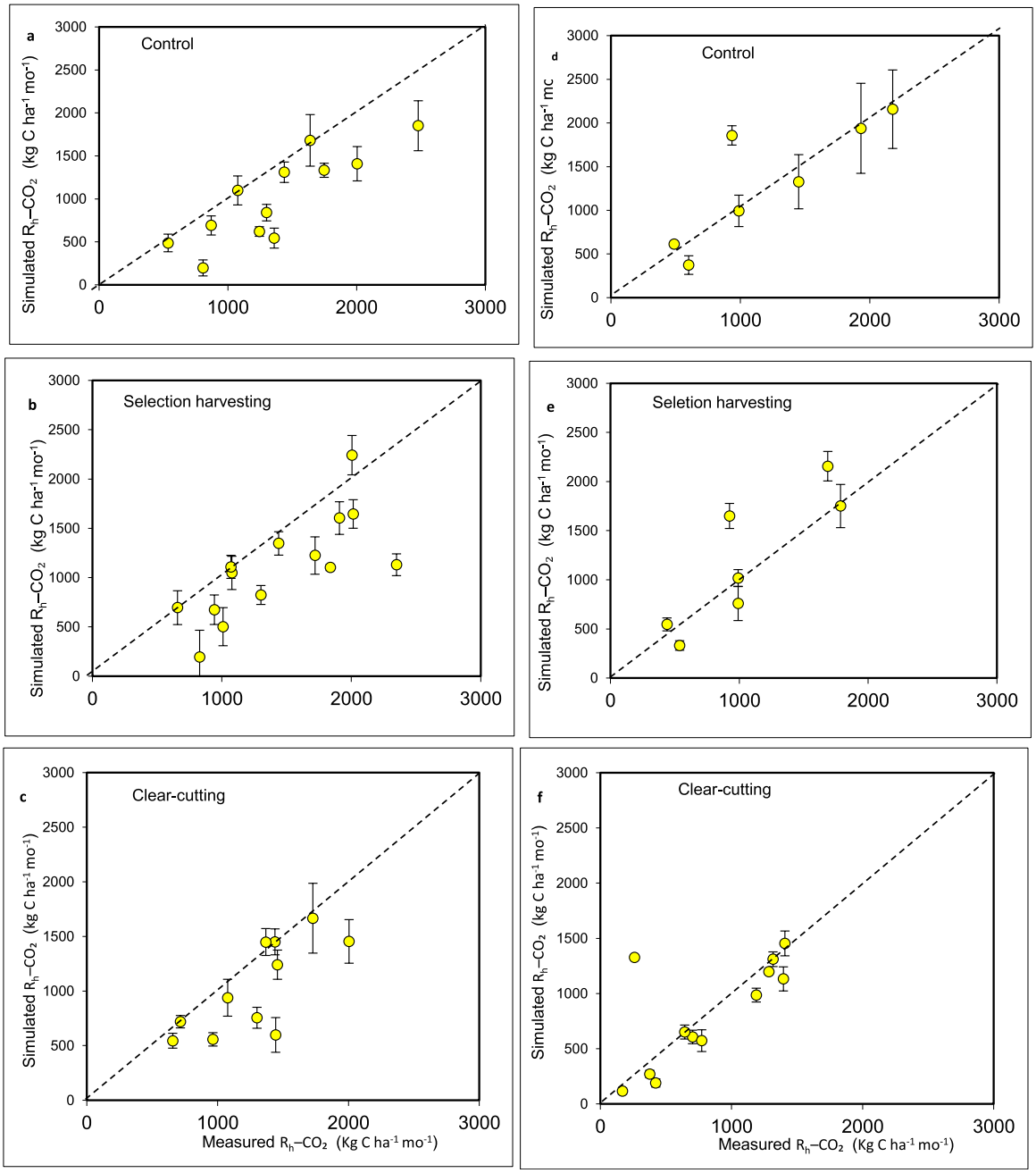

Fig. 2. Comparison between the monthly modelled and measured heterotrophic respiration (R_h-CO_2) across the different practices (a. Control, b. selection harvesting and C. clear-cutting at Ränskälänkorpi (left) and Lettosuo (right) (d. control, e. selection harvesting and f. clear-cutting) peatland forestry sites. Error bars represent 95% confidence interval of measured values. Dotted lines represent 1:1 correlation between measured and modelled values.

Table 4
Summary of ECOSSE model performance in simulating heterotrophic respiration (Rh–CO_2) at the two study sites. Model bias is considered not significant when the calculated error (*E*) is less than the 95% confidence limit (E_{95}) (E < E95). The association between modelled and measured values is considered significant when the t-statistic exceeds the critical t-value at P = 0.05. Differences between modelled and measured values are considered not significant when the F-statistic is less than the critical F-value at the 5% significance level.

site	Management	*R*	*t* value	*t* value at P = 0.05	*E*	*RMSE*	*E* (95%) confidence Limit	*F* value	*F* value (critical at 5%)
Ränskälänkorpi	Control	0.84	4.23	2.23	27	34	68	0.63	1.97
	Continuous cover	0.99	3.40	2.18	24	35	117	0.79	5.91
	Clear cut	0.8	2.26	2.26	20	29	40	1.50	2.03
Lettosuo	Control	0.95	1.20	2.23	−8.67	23	49	0.18	2.03
	Continuous cover	0.95	2.72	2.23	−23.37	41	23	0.54	1.98
	Clear cut	0.7	0.11	2.23	12	16.74	20	0.35	2.03

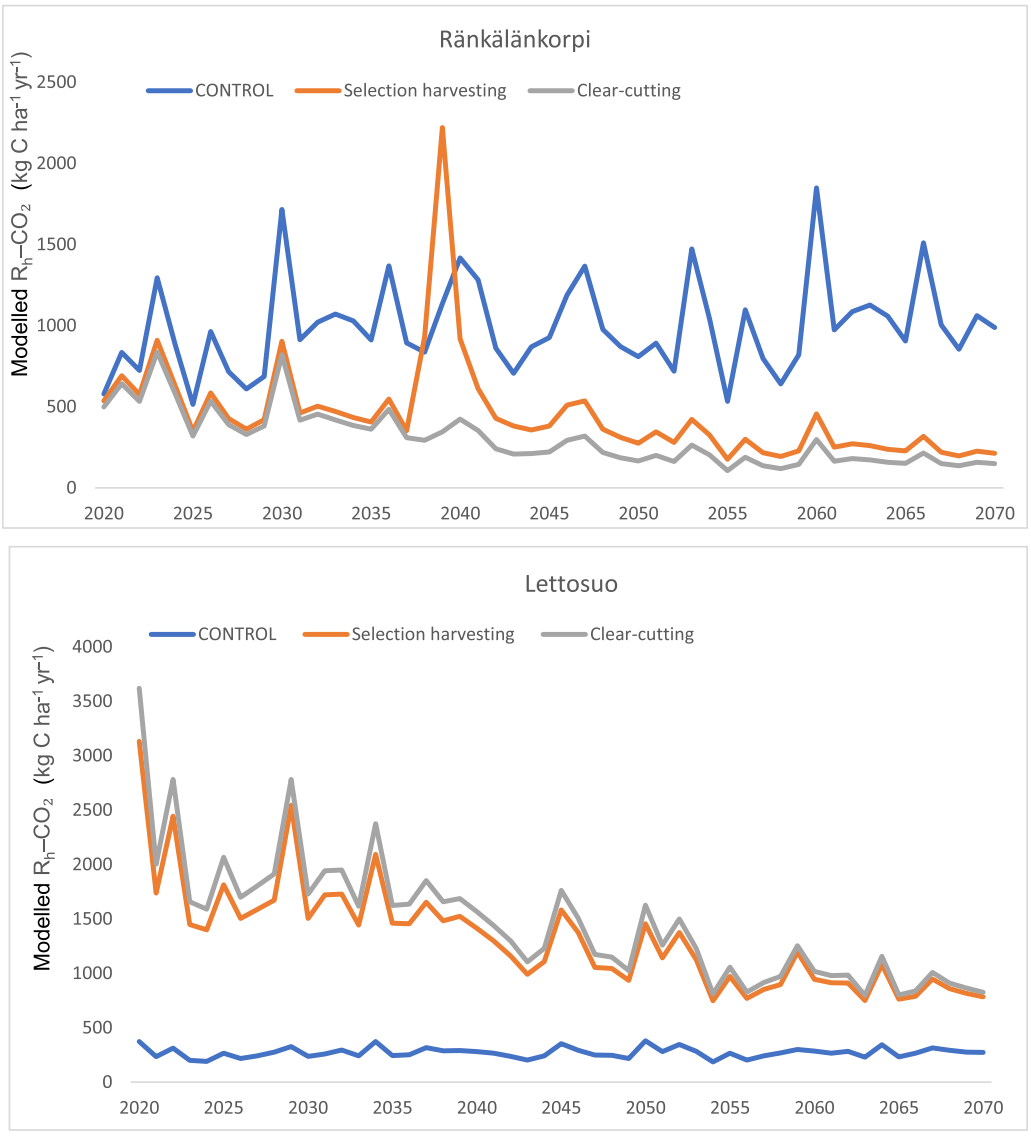

Fig. 3. Modelled R_h-CO_2 from the different management practices compared to control over a 50-year period (2020 – 2070) in Ränskälänkorpi and Lettosuo sites across the different management practices. The monthly average of R_h-CO_2 each year was calculated to determine the annual R_h-CO_2 over a long-term period.

4. Discussion

4.1. ECOSSE simulation and evaluation

The results of this study show a strong correlation between measured and modelled R_h-CO_2 emissions from two experimental peatland forest sites in Finland. The results of this study demonstrate that the model predicted accurately the monthly trends and peaks of R_h-CO_2 fluxes in the majority of cases at the two experimental peatland forest sites. However, the model over- or underestimated R_h-CO_2 fluxes, especially at the peak of the warm climate. Although the reasons are unclear, the under- and overestimations could be due to seasonal variability and other environmental factors such as weather conditions and soil temperature, pH, bulk density and soil carbon which was not included in the model.

The novelty of this study is in applying ECOSSE to estimate the impact of different harvesting practices on R_h-CO_2 in boreal peatland forests. The results of the simulation and evaluation of this model in this study is in agreement with previous studies using the ECOSSE model, and its ability to simulate carbon dynamics (Smith et al., 2010) in peatlands (Abdalla et al., 2014) and forests (Dondini et al., 2014). Smith et al. (2010) applied data from the National Soil Inventory of Scotland to evaluate the ability of the ECOSSE model to simulate soil C at the national scale. Similarly, Abdalla et al. (2014) successfully applied the ECOSSE model to simulate R_h-CO_2 fluxes at six European peatland sites. In addition, Dondini et al. (2014) showed good model performance in simulating soil carbon changes under short-rotation forestry in Britain using measured data from eleven sites comprising 29 transitions representing land-use change from non-woodland land uses to short-rotation forestry.

The occasional overestimation and underestimation of the R_h-CO_2 fluxes across the management practices observed in the two sites agree with findings by (Abdalla et al., 2014). They reported that across the six European peatland sites, the ECOSSE model was able to predict the peak of R_h-CO_2 correctly and seasonal trends, but occasionally over/under-estimated the flux values during the warm weather in spring and summer. Also, Lindroth et al. (2007) observed the highest R_h-CO_2 respiration rates at the southernmost warmest site in northern Europe and the lowest at the northernmost coldest site (Kaamanen in the study). Abdalla et al. (2014) reported that over/under-estimation of R_h-CO_2 fluxes across the different management practices in peatland forests during the warm weather and winter period was mainly due to the high

soil temperature and moist soil conditions during the study period. The loss of water from the soil, either by evaporation from the soil surface or by transpiration from plant leaves, affects air temperature which has a direct effect on emissions of Rh-CO_2 (Lindroth, 2007). On drained peatland, soil water level is directly affected by functioning of the ditch network. However, further research is required to improve the model to account for this loss of water from the soil or from the plant leaves.

The statistical analysis of the results across the different management practices at both study sites indicated no significant error between the modelled and measured R_h-CO_2 fluxes. The results revealed that there was no model bias, which indicates that the model cannot be further improved with the available data, especially since this study is an independent evaluation of the ECOSSE model. This further provides confidence and justification for applying this model to estimate the long-term impacts of management practices on R_h-CO_2.

4.2. Estimation of R_h-CO_2 fluxes

Results from the present study indicated a rapid increase in R_h-CO_2 fluxes in both CCF and RF experimental sites at Lettosuo sites at the beginning of harvest, compared to the control area within the sites. The differences in R_h-CO_2 between the management practices compared to the control and the observed repeated fluctuations and peaks could be because of seasonal or environmental variability across the study sites and management practices.

At the Ränskälänkorpi site, CCF resulted in highest R_h-CO_2 peak after 20 years. There were also consistent fluctuations with multiple peaks in annual R_h-CO_2 across the management period, accompanied by a gradual reduction in R_h-CO_2 at the end of the simulation period in all treatments. The peaks in emissions were observed during specific times of the year, typically during warmer periods and autumn. This could be due to higher soil temperature and moist soil conditions because higher air temperature affects evapotranspiration which has a direct impact on R_h-C0$_2$ (Christensen et al., 1999). However, the control area remained consistently lower compared to the management practices in Lettosuo. The RF resulted in highest R_h-CO_2 values compared to CCF, but emissions from both management practices were still higher than the control. Both management practices resulted in lower emissions than the control at Lettosuo. However, the difference between the management practices was small at Lettosuo, and R_h-CO_2 levels reduced consistently over time, but without repeated peaks as observed in Ränskälänkorpi. Northern forested peatlands are rich sources of terrestrial C. They may become sources of C or act as C sinks when drained for forestry. However, these vary based on the nutrient level of the site, weather conditions and average WTD (Lampela et al., 2023).

Harvesting in drained peatland forests is generally expected to reduce heterotrophic respiration (R_h-CO_2) due to an increase in water table depth (WTD), which decreases the volume of oxygen-rich soil available for aerobic decomposition of organic matter (Shanin et al., 2021). This pattern was observed in the present study; however, the magnitude and direction of the response varied between sites and harvesting methods. At Lettosuo, R_h-CO_2 showed a consistent decline following harvesting, although emissions remained slightly higher than those observed in the unharvested control. In contrast, at Ränskälänkorpi, both harvesting treatments resulted in reduced R_h-CO_2 emissions compared with the control. Despite the higher harvesting intensity associated with RF, no substantial differences in R_h-CO_2 reduction were observed compared with CCF. Nevertheless, both harvesting approaches resulted in significantly lower R_h-CO_2 emissions than the control by the end of the simulation period.

The contrasting responses between sites highlight the influence of site-specific environmental conditions on the response of R_h-CO_2 to forest management. Factors such as soil moisture, soil temperature, and hydrological conditions may contribute to differences in emission patterns among sites. However, the relatively small differences between harvesting treatments suggest that the overall reduction in R_h-CO_2 was primarily associated with the hydrological changes induced by harvesting. Additional site characteristics including SOC, pH, bulk density, and plant litter inputs, also varied among treatments and may have contributed to the observed differences in R_h-CO_2 responses. Overall, the results indicate that harvesting practices can reduce heterotrophic respiration in drained peatland forests, but the magnitude of this effect is strongly influenced by local environmental conditions and site characteristics. Furthermore, post-harvest changes in R_h-CO_2 were observed across the different treatments and study sites. In Lettosuo, higher increases in R_h-CO_2 were observed following both RF and CCF compared with the control, whereas only minor increases were observed across treatments at Ränskälänkorpi. These differences suggest that peat decomposition responses following harvesting are strongly influenced by site-specific conditions and that decomposition may remain stable or even decline after disturbance under certain conditions.

Clear-cut harvesting can initially increase R_h-CO_2 emissions due to the rapid decomposition of residual tree biomass left on site and the reduction in carbon uptake associated with the removal of tree stands. These processes can temporarily increase net carbon losses following harvesting. However, over the longer term, a consistent decline in R_h-CO_2 was observed across treatments, particularly at Lettosuo. Overall, the temporal changes in R_h-CO_2 following harvesting indicate that initial increases in emissions may occur due to disturbance-related carbon losses, but these effects can diminish over time as vegetation recovery progresses and alters carbon inputs and ecosystem processes.

Although there is limited literature estimating the impacts of peatland forest management on R_h-CO_2 making it is difficult to compare the results of this study against similar studies. However, the reduction and increase of R_h-CO_2 in Ränskälänkorpi and Lettosuo from the management practices observed in this study is similar to the observation reported by Korrensalo et al. (2026). Korrensalo et al. (2026) reported lower post-harvest reductions in annual R_h-CO_2 in nutrient-rich sites (sites dominated by Norway spruce) than nutrient-poor sites (sites dominated by Scots pine). In nutrient-rich sites, CCF resulted to 14% lower annual Rh-CO_2 than the control (unharvested site) while the RF resulted in 26% lower annual R_h-CO_2 than the control. In contrast, increase in annual R_h-CO_2 of 14% was recorded in nutrient-poor site in RF than the control. The ECOSSE model was applied in previous studies to estimate the impact of land-use change, management practices on soil C, soil C change and CO_2 fluxes (Abdalla et al., 2014; Dondini et al., 2014; Smith et al., 2010) and the novelty of this study is in applying ECOSSE to estimate the impact of different management practices on R_h-CO_2 fluxes in boreal peatland forests.

The predicted reduction in emissions of R_h-CO_2 due to changes in management practices in future climate shows the role of management practices in the increase or decrease of anthropogenic factors which could significantly influence R_h-CO_2 emissions. The climate change impacts of RF and CCF are significant in drained forest ecosystem and soil C pools. In drained peatland forests, predicted future climate warming has the potentials to accelerate the decomposition of soil organic matter and subsequent increase in R_h-CO_2. It is therefore important to understand how harvesting can affect emissions of GHG from drained peatland forests in a future climate scenario. Under future warmer and possibly drier condition scenario, it is increasingly important to maintain high WTD because enhanced peat decomposition could result in an increase in loss of soil C. Harvesting of trees in forested peatland is expected to result in reduction of R_h-CO_2. This is because of increase in WTD which potentially decrease the soil volume where aerobic decomposition occurs. However, in this study, this was only in Ränskälänkorpi and varied across the different management practices. This further highlights the impact of environmental variability that exists across and within sites. Therefore, this model can further be applied in the future to assess the impact of potential future peatland forestry management practices on peatland forestry GHG emissions and SOC.

5. Conclusion

This present study builds on previous studies to further justify the suitability in the application of ECOSSE model in simulating R_h-CO_2 fluxes following changes in boral peatland forests under different land management practices. The model reasonably estimated accurately R_h-CO_2 fluxes, monthly variations, major emission peaks from the two peatland forestry sites across the different management practices. Results of the statistical analysis revealed high correlation between the measured and simulated values with correlation factors ranging from 0.7 to 0.99 and no significant error between the simulated and measured values. The root mean squared error also indicates that there was no significant error between the simulated and measured values. The site differences in predicted reduction in emissions of R_h-CO_2 due to changes in management practices in future climate shows the role of management practices and site characteristics in the increase or decrease of anthropogenic factors which could significantly influence R_h-CO_2 emissions. Therefore, this model can further be applied in the future to assess the impact of potential future peatland forestry management practices on peatland forestry greenhouse gas emissions and SOC.

In addition, the application of ECOSSE in this study offers new insights into the potential impacts of peatland forest management on R_h-CO_2 fluxes in boreal environments. While ECOSSE was applied in the past to quantify changes in SOC because of land-use changes, the present study has extended the application of ECOSSE in evaluating management impacts on R_h-CO_2 due to changes in harvesting methods. Therefore, ECOSSE model provides an important framework for assessing impact of management decisions and their implications for GHG emissions and soil C sequestration in a future climate scenario. However, the model can still be improved for future use through the incorporation of additional environmental variables such as soil moisture and soil temperature variability.

CRediT authorship contribution statement

Raisa Mäkipää: Writing – review & editing. **Qian Li:** Writing – review & editing. **Vince Chukwu:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Aleksi Lehtonenb:** Writing – review & editing. **Mika Korkiakoski:** Writing – review & editing. **Marta Dondini**: Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgements

This is to acknowledge the financial support received from the European Union's Horizon 2020 Programme under Grant Agreements number 101000289 for the HoliSoils project.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2026.124137.

Data availability

Data will be made available on request.

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