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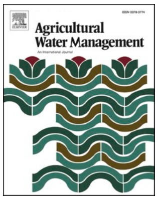

Carbon incentives and farm economics: A study of peatland drainage optimization

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ABSTRACT

Natural, waterlogged peatlands are recognized as the most efficient carbon storage ecosystems, playing a critical role in climate regulation. However, in Europe, agriculture on drained peat soils — although comprising only 2.5 % of the agricultural area — contributes disproportionately, generating approximately 25 % of the EU's total agricultural greenhouse gas emissions. This study examines the potential of drainage optimization and rewetting as strategies to reduce emissions from peatlands while balancing agricultural productivity. We quantitatively analyse the production, land use, and economic implications for farmers in two different farm scenarios using economic modelling and dynamic optimization. Our analysis evaluates the impact of carbon subsidy pricing on crop diversity and farmer income. Results indicate that while carbon subsidy prices have minimal influence on crop rotation diversity, they significantly affect farmers' income. With a subsidy price of 30€ per ton of CO_2 equivalent, or 80€ per ton in the case of high-value crops, farmers transition into "carbon farmers", obtaining higher share of total net present value from carbon subsidies rather than traditional agricultural income. Furthermore, the majority of climate benefits, including GHG reduction, are realized already at the 30€/tCO_2e subsidy threshold. The findings suggest that carbon subsidies could offer a viable financial incentive for farmers to adopt peatland rewetting practices, which could reduce GHG emissions substantially. However, subsidy designs need careful calibration to ensure they do not distort agricultural practices or reduce crop diversity, while still delivering significant climate benefits.

1. Introduction

Natural, waterlogged peatlands are globally the most area-effective carbon storage (Schäffer, 2009). Peatlands globally hold an estimated 650 billion tonnes of carbon, which is equal in magnitude to the amount of carbon in earth's vegetation and more than half of the carbon in atmosphere, although the land covered by peatlands accounts for only 3 % (FAO, 2020). Peat or organic matter is accumulated in pristine undrained peatlands due to the slow decomposition of plant remains in anaerobic conditions (Haddaway et al., 2014). Approximately 15 % of peatlands globally have been drained for agriculture livestock and forestry, including bioenergy plantations such as oil palm (Joosten, 2009). While it takes thousands of years for peatlands to develop (Ovenden et al., 1998), drainage of these systems has resulted in strong degradation by enhancing oxygen intrusion which leads to aerobic decomposition of organic matter and carbon emission. Moreover, drainage contributes to land subsidence (1–2 cm yearly) which increases drainage costs, leads to higher flood risks, as well as to the degradation of productive land (Bonn et al., 2016; Joosten et al., 2012).

Agriculture on drained peatland soils accounts for only 2.5 % of the total agricultural area but generates approximately 25 % of the total agricultural GHG emissions in the EU (Tanneberger et al., 2021). The largest peatland emitters (share of the GHG emissions from peatlands out of the total GHG emissions from agriculture) in the EU are Finland (62 %), Poland (42 %), and Germany (37 %) GMC (2020). Out of the total land area of Finland 30 % is classified as peatland (Finnish Forest Research Institute, 2014). As such, two-thirds of the stored carbon in Finland is found in peatlands (Turunen, 2008). Although peatlands account for 11 % of agricultural land, they produce over 50 % of the total GHG emissions from agriculture and 75 % of the emissions from agricultural land use in Finland (Kekkonen et al., 2019).

Rewetting drained peatlands is considered an effective and efficient

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strategy to reduce GHG emissions created in peatlands (Krimly et al., 2016, Buschmann et al., 2020). Rewetting implies a high water table, which can be achieved by blocking drainage ditches, construction of dams or disabling drainage pump facilities. However, farmers are often sceptical when it comes to raising the water table close to the surface because it restricts both the choice of cultivated crops and the machinery use on the farm due to very wet and soft peatlands (Wichtmann et al., 2016).

If using adjustable damming or blocking, or installing adjustable subsurface drainage, the water table can be adjusted throughout the year depending on farm activities. For instance, decreasing water table (e.g. down to 60 cm below surface) during sowing and harvesting season allows mobility of agricultural machinery and equipment, and the water-table can be increased (e.g. up to 10–30 cm below surface) after the field operations for the rest of the year, reducing soil emissions. Adjustable drainage is usually operated by control wells with a simple mechanism for adjusting the discharge pipe height (Flessa et al., 1998; Myllys, 2019; Regina et al., 1996).

Rewetting implies costs and benefits for a farmer. Costs and benefits of different peatland restoration and conservation practices, which aim to reduce GHG emissions, have been studied in different regions in Europe. Stachowicz et al. (2022) assessed the costs of rewetting drained peatlands on the basis of available data on rewetting actions, such as blocking the drainage ditches, located within peatlands in the Neman River Basin. Average construction costs of a single dam (peat and wooden dam) were derived from the actual costs of these actions performed in Belarus, Lithuania, and Poland. The cost of rewetting options ranged from €90 per action to €3680 per action with ditch blocks with bags filled with peat being the cheapest and with equipping ditch blocks with flow regulation being the most expensive (Stachowicz et al., 2022).

Grossmann and Dietrich (2012) provided estimates of the benefits of restoration in terms of the shadow price of carbon and the GHG abatement costs of wetland restoration measures. They found the mean current emissions across 35 wetland sites to range between 17.5–25.5 tCO_2e/ha and the median abatement costs for restoration scenarios €7–14/tCO_2e. Their results show that fen wetland restoration can potentially contribute to mitigation targets at low cost.

Currently, agri-environmental payments are used to incentivise high water table on agricultural peatlands in Finland. These payments are designed to reduce nutrient leaching from peatlands and include an annual payment 77€/ha for field parcels where adjustable subsurface drainage is applied, and 214€/ha payments for fields where also subsurface irrigation is applied (Ministry of Agriculture and Forestry, 2022). In addition, a farmer is eligible for 40 % investment subsidy when investing in adjustable sub-surface drainage in Finland. Despite these subsidies, investments in adjustable subsurface drainage have remained relatively low, as have investments in other options that facilitate higher water tables on agricultural peatlands. Earlier, Purola and Lehtonen (2022) investigated incentives for adjustable subsurface drainage investments, which imply 3000€/ha net costs for farmers, in net terms, considering 40 % investment subsidy. They found that an additional 150–200€/ha subsidy (20–30€/tCO_2e.) is needed for the investment to be profitable. They also found that crop yield gains, possible to be reached due to adjustable drainage, may provide some but limited economic benefits for farmers. Such benefits, however, are not likely to be sufficient to make the drainage investments profitable. However, recent studies have brought up also other possibilities for water management on agricultural peatlands. Miettinen and Saarnio (2024) presented how simple damming of open ditches could be a low-cost method of increasing groundwater table and thus reducing GHG emissions on agricultural peatlands. This option, however, may not improve production possibilities or crop yields especially if the existing drainage is insufficient and the water table remains at too high levels, harming field work.

This study analyses a broader set of water management options on peatlands, open ditches, dams, subsurface drainage, adjustable drainage, and irrigation, and extends the set of crops at different farm types compared to earlier studies (e.g. Purola and Lehtonen, 2022). The modelled case farms are located in Northern Ostrobothnia, region in the middle and northern parts of Finland where peatlands are abundant, and where agriculture and related food industry is an important part of local and regional economy. While focusing on specific region with abundant peatlands and considering the characteristics of the agriculture and typical farm types on that region, this study aims to provide a more comprehensive and relevant perspective on the farm economy and climate policy aspects of water management in agricultural peatlands. Hence the objective of this study is to analyse, through economic dynamic optimization modelling over 30 years, under which conditions the different water management options are profitable for a farmer. We focus on water management options for peatlands which significantly reduce GHG emissions and are particularly relevant for climate policy decision-makers.

We quantitatively analyse the production, land use, and economic implications of soil drainage for farmers in two different farm scenarios using economic modelling. Based on the results, we discuss the climate policy implications of providing carbon payments to farmers for reducing GHG emissions. The results show how carbon payments affect the optimality of each drainage option, and how efficient the payments are in reducing GHG emissions. In addition, we address questions related to specific water management options and production and income effects. Answering these questions is relevant and interesting from agricultural and climate policy perspectives in many countries.

2. Materials and methods

2.1. DEMCROP model

We utilize dynamic optimization framework to combine crop production with crop rotation and farm economics with various technical data and response functions (Purola et al., 2018, Purola and Lehtonen, 2022, Rämö et al. 2024). The model, specified for a typical crop farm located in Finland through Eqs. (1)-(5), maximizes net present value of a farm over a 30-year time horizon. The modelled farm is assumed to have 10 field parcels at different distances from farm-centre. Explicit crop rotations with pre-crop yield effects and logistic costs, as well as costs and yield effects of liming, are considered per field parcel. The model produces an optimal whole-farm land use and management plan for a 30-year time period at given input and output prices and farm subsidy levels. We denote the interest rate with r and discount factor with $b = 1/(1+r)$, assuming 6 % competitive interest rate: average annual rate of return from Helsinki stock exchange 1921–2020 minus transaction costs typical for small-scale investors such as farmers. The optimization problem, considering market revenues (crop prices multiplied by yields) (Wejberg et al., 2024) and farm subsidies (Finnish Food Authority, 2024) of several crops (i) cultivated at each field parcel (p) at each year (t), as well as costs of production, can be given as follows:

$$\max_{D_p, A_{tpi}, N_{tp}, L_{tp}, F_{tp}} \sum_{t=0}^{T} \sum_{p=1}^{P} \sum_{i=1}^{n} b^t \left(\mu_i Y_{ti}(\ldots) + S_i - C_{tpi}(\ldots) + \mu_c \chi_i \left(D_p\right)\right) A_{tpi} \tag{1}$$

subject to

$$C_{tpi} = V_i + G_p + C_D + C_L\left(L_{tp}\right) + C_F\left(F_{tp}\right) + C_N\left(N_{tp}\right) \tag{2}$$

$$Y_{tpi} = \widehat{Y}_i \, \delta\left(D_p\right) \left(\alpha_i \left(N_{tp}, L_{tp}, F_{tp}\right) \beta_{ij} A_{t-1,p,j} + \sum_{d=t-5}^{t} \gamma_i A_{dpi} \right) \tag{3}$$

$$\sum_{p=1}^{P} \sum_{i=1}^{n} A_{pit} = 1 \ \forall \ t \tag{4}$$

$$\sum_{1}^{m} D_{p_{peat}} = 1 \ \forall p_{peat}, \ D_p \in \mathbf{Z} : [0,1] \tag{5}$$

where μ_i is the price of crop i, Y_{ti} the yield of crop i at time t, S_i is the agricultural subsidies for crop i, C_{tpi} the total costs of cultivating crop i on parcel p at time t. Denoting carbon price with μ_c and emission factor of crop i *with* χ_i, subject to drainage D_p on parcel p, and A_{tpi} is the land allocation of crop i on parcel p at time t. Denoting drainage investment, nitrogen fertilizer use, fungicide use, and liming at parcel p at time t respectively with D_p, N_{tp}., F_{tp}, and L_{tp}, with C_{D}, C_{L}, C_F and C_N the respective cost functions. Finally, V_i and G_p denote the variable and logistic costs.

Denoting the baseline yield for crop i with $\widehat{Y}_i$ and δ as the yield effect of drainage option D_p on parcel p. We denote α_i as the crop-specific effects of nitrogen use (N), liming (L) and fungicide (F) on yield on parcel p at time t, β_{ij} the pre-crop value of crop j on crop i, γ_i the yield losses due to monoculture to calculate the yields of each crop, and p_N is the price of nitrogen fertilizer. The functions for calculating the crop yield effects of nitrogen use are presented in detail in Appendix A. Finally, Eq. (4) defines that all land must be assigned to some cultivation, and (5), with m denoting the total number of drainage alternatives, defines that only one drainage can be utilized in each parcel.

For numerical analysis, we utilize DEMCROP-model (Dynamic Economic Model of CROP rotations and farm management) (Liu et al., 2016; Purola et al., 2018; Purola and Lehtonen, 2022; Rämö et al. 2024), extended in this study for optimization of several drainage options. Input data for all cultivation options, and parameters specific to investment costs and annual costs of different water management options are based on Wejberg et al. (2024), and are presented in detail in the following sections.

For the carbon subsidy system, we assume avoided emissions approach. In this system, the amount of carbon subsidies is calculated by comparing the emissions to the baseline, and carbon subsidies are paid based on the amount of emissions that have been reduced. Theoretically in this system it would be possible to have carbon tax for options with higher emissions, but in this study all alternatives are improvements over baseline.

The optimization problem presented by Eqs. (1)-(5) was solved using relaxed mixed integer nonlinear programming using the CONOPT4 solver of the General Algebraic Modelling System (GAMS) software. Typical time to solve the problem is under 10 seconds.

2.2. *Input data*

This study focuses on Ostrobothnia region in middle-west and northern parts of Finland. Peatlands are common in this region. Agricultural land with thick peat layer (>60 cm) constitutes 26 % of the total agricultural land in the region, on average, but this share can be substantially higher in some municipalities and some farms (Kekkonen et al., 2019; Räsänen et al., 2023). The value of agricultural production in the region is traditionally dominated by dairy and beef production, but cereals and some other crops, e.g. food potatoes and oilseed crops have been commonly produced in some parts of the region as well. Cereal farms are more flexible in terms of land use and water management compared to livestock farms which face stringent constraints specific to feed requirements (e.g. sufficient good quality roughage) and environmental regulations and permits that require sufficient area for manure spreading for suitable crops. The relative share of cereal farms has been increasing in the region due to structural change, i.e. decreasing number and increasing size of livestock farms. It is common that earlier livestock farms still carry on crop production after exiting livestock business (Kässi et al., 2015). We focus on cereals farms, which are more potentially responsive to climate and water policy incentives in this study.

In this paper we study two farms. The first farm is a cereal farm which can cultivate spring wheat, spring barley for feed (feed barley), spring barley for malting (malting barley), spring oats, winter wheat, and spring turnip rape. This cereal farm is assumed to have no access to food potato production contract (access depends on the ability to fulfil the contract conditions and this may depend e.g. on soil type, or knowledge, skills and references of a farm), hence no food potato is cultivated. In addition, the farm has two forms of set asides, fallow and nature managed field (NMF), where the latter has stricter requirements on e.g. tillage timing and species mixtures (Finnish Food Authority, 2024). The second farm has the same crops as the first farm, and additionally it has food potatoes as an option, i,e. it has a possibility to make potato production contracts with food industry companies which carefully select the contract producers. In Finland, not all farms can produce potatoes due to e.g. limited availability of production contracts. Potatoes are more lucrative than cereals, thus farms with a possibility of cultivating potatoes have also higher incentive to invest into e.g. sub-surface irrigation.

Both farms are assumed to have 50 % peatlands and 50 % mineral soils. While the share of peatlands is quite high, it still is a rather typical case in Northern Ostrobothnia region (Räsänen et al., 2023). The 5 main water management options mentioned in Section 2.2 are assumed to be available at each peat soil parcel. The distances from the farm-centre and soil types are given in Table 1. The longer the distance from the centre of the farm implies higher logistic costs. Input data for all cultivation options, e.g. variable costs and crop prices, are based on Wejberg et al. (2024) and CAP subsidies (Finnish Food Authority, 2024), and are given in Table 2.

Yield penalties for monoculture cultivation (γ_i), calculated over 5 years, were set to −5 % p.a. for cereals and −30 % p.a. for rapeseed and potatoes, which are particularly prone and sensitive to plant pests and diseases. To account for yield effects specific to the Northern Ostrobothnia region, we apply pre-crop effects, i.e. effect of the preceding crop on yields of crops sown at subsequent years on same parcel, based on Peltonen-Sainio et al. (2024).

If no value is given for specific combination because of very few or no observations, we assume that the combination is not viable, due to e.g. requirements of soil preparation conflicting with harvests. In these cases, the pre-crop value is set to zero. The pre-crop values are presented in Table 3.

2.3. *Drainage options*

We analysed five different drainage options on peatland parcels. Details of drainage alternatives are given in Table 4, based on the data derived from Salaojayhdistys (2024), Finnish Food Authority (2024), and Wejberg et al. (2024). Yield effect refers to the impact each of the rewetting options have on the typical, close to regional average yields. The area effect refers to the effect each drainage option has to the cultivated area. The data for annual labour cost, and water management subsidies are applicable only to adjustable drainage (AD) and adjustable drainage with irrigation (Irri). Emission factors are based on the national

Table 1
Distance of each parcel from the farm centre in kilometres (km) and soil types.

Parcel	Distance (km)	Soil Type
Parcel 1	0,5	Mineral
Parcel 2	0,5	Peat
Parcel 3	2	Mineral
Parcel 4	2	Peat
Parcel 5	4	Mineral
Parcel 6	4	Peat
Parcel 7	8	Mineral
Parcel 8	8	Peat
Parcel 9	12	Mineral
Parcel 10	12	Peat
AVERAGE	5,3	

Table 2
Input data for all cultivation options.

Crop	Price, €/kg	Baseline yield, kg/ha/a	Subsidies, €/ha/a	Variable costs, €/ha/a	Parcel treatment times
Spring wheat	0,185	3634	483,39	801,00	5
Winter wheat	0,185	3872	483,39	777,05	6
Feed Barley	0,148	3472	483,39	752,60	4
Malting Barley	0,169	3472	483,39	777,62	6
Spring Oats	0,171	3190	483,39	800,56	4
Oilseed	0,393	1416	703,39	707,30	7
Fallow	-	-	473,39	296,40	2
Nature Managed Field	-	-	538,39	296,40	3
Potatoes	0,188	25048	433,39	2079,00	7

greenhouse gas inventory (IPCC, 2014; Wejberg et al., 2024). For mineral parcels, which are excluded from Table 4, emissions from the cultivation of any annual crops were set to 1.8 t CO_2e/ha/a, and to zero if land was allocated to either setaside, following Purola and Lehtonen (2022).

The five different drainage alternatives analysed in this paper are

(1) Open ditches (OD). This is a typical initial, or business as usual situation for peatlands. Due to the open ditches, cultivated area is 10 % smaller compared to mineral soils, or drainage options with subsurface drainage. Soil emissions are high (Kekkonen et al., 2019).

(2) Low-cost damming or blocking of open ditches at peatlands (Dams). In this option the water table rises due to the dams which leads to significantly reduced yields due to wet conditions (Wejberg et al., 2024) resulting in similar cultivated area as in open ditches and decreased soil emissions.

(3) Subsurface drainage (SD). This option requires 3000€/ha investment costs which implies appr. 2100 €/ha investment costs for a farmer due to investment subsidy. Subsurface drainage implies 10 % more land available since there are no longer open ditches. We assume the height of the water table to be similar to those in fields with open ditches, thus we assume GHG emissions to be similar as well.

(4) Adjustable drainage (AD). This option entails dense and effective drainage allowing for the adjustment of the water table. Reducing the water table from high levels is possible due to effective drainage. However, increasing the water table from low levels is possible under suitable hydrological conditions. This option requires 5000€/ha investment costs which implies appr. 3000 €/ha investment costs for a farmer due to 40 % investment subsidy. Compared to open ditches, subsurface drainage leads to increased cultivated area and lower soil emissions, attributed to the higher water table (IPCC, 2014).

(5) Adjustable drainage + subsurface irrigation (Irri). This option combines adjustable drainage, plus additional irrigation equipment (water pump based on e.g. solar energy, and related equipment). This requires a total investment of 4250€/ha for a farmer, in net terms. This option may imply some yield gains compared to regional average yields and produce less soil emissions than open ditches (IPCC, 2014). Effects of yield gains will be studied using sensitivity analysis.

3. Results

Examining how the optimality of drainage solution changes with carbon price (Table 5), we can see that for farms both with and without potatoes, the optimal choice at a zero carbon price is to maintain the use of standard open ditches. Increasing carbon price to 10 €/tCO_2e has no impact, but at 20€/tCO_2e it becomes optimal for farm with no potatoes to install dams on the furthermost peatland parcel. In this case, NMF is concentrated on this parcel in almost all 30 years (Fig. 1) as the lower

Table 3
Pre-crop values for each crop combination, based on Peltonen-Sainio et al. (2024).

	Preceding crop								
Current crop	Spring wheat	Winter wheat	Feed barley	Malting barley	Spring oats	Oilseed	Fallow	Nature managed field (NMF)	Potatoes
Spring wheat	1	0	1,001	1,001	0,970	1,018	0	0	0
Winter wheat	0	1	0	0	0	0	0	0	0
Feed barley	0,999	1,076	1	1	0,990	1,030	0,913	0,919	1,034
Malting barley	0,999	1,076	1	1	0,990	1,048	0,913	0,919	1,034
Spring oats	0,951	0	1,024	1,024	1	1,024	0,918	0,939	1,078
Oilseed	1,134	0	1,003	1,003	0,983	1	0	0	0
Fallow	0	0	0	0	0	0	1	0	0
NMF	0	0	0	0	0	0	0	1	0
Potatoes	0	0	1,066	1,066	1,106	0	0	0	1

Table 4
Investment costs, yield effect, area increment, labor costs and subsidies for all drainage options for peatland parcels. *varied in analysis.

Drainage option	Investment cost, €/ha	Yield effect	Area effect	Annual labor cost, €/ha/a	Water management subsidy, €/ha/a	Cereal emissions[e]) t CO_2e/a	Set aside /grassland emissions t CO_2e/a
Open ditches[a]) (OD)	0	0 %	−10 %	0	0	35	25
Dams[b])	1000	−40 %	−10 %	0	0	25	15
Subsurface dr. (SD)	2100	0 %	0 %	0	0	35	25
Adjustable dr. (AD)[c])	3000	0 %	0 %	34	77	25	15
AD + Irrigation (Irri)[d])	4250	0 %*	0 %	102	214	25	15

[a]) Area effect 10 % assumed based on the estimate 10–25 % estimated by Salaojayhdistys (2024); [b]) Yield effect estimated by Wejberg et al., (2024); [c]) Investment costs and labour costs for a farmer estimated by Wejberg et al., (2024); [d]) Investment costs and labour costs for a farmer estimated by Wejberg et al., (2024). [e]) There is no emission factor for a shallow-drained cropland. Thus, we assume, following the case of 10tCO_2e/ha emission reduction with increased water table on grassland a similar reduction of 10 tCO_2e/ha of emissions on annual crop with increased water table.

Table 5
Optimal drainage option in each peatland parcel with different carbon prices. OD = Open ditches, Dams = Dams in open ditches, AD = Adjustable subsurface drainage.

	No potatoes								
Carbon price, €/tCO$_2$e	0	10	20	30	40	50	70	100	150
Parcel 2	OD	OD	OD	AD	AD	AD	AD	Dams	Dams
Parcel 4	OD	OD	OD	Dams	Dams	Dams	Dams	Dams	Dams
Parcel 6	OD	OD	OD	Dams	Dams	Dams	Dams	Dams	Dams
Parcel 8	OD	OD	OD	Dams	Dams	Dams	Dams	Dams	Dams
Parcel 10	OD	OD	Dams	Dams	Dams	Dams	Dams	Dams	Dams
	Potatoes								
Carbon price, €/tCO$_2$e	0	10	20	30	40	50	70	100	150
Parcel 2	OD	OD	AD	AD	AD	AD	AD	AD	AD
Parcel 4	OD	OD	AD	AD	AD	AD	AD	AD	AD
Parcel 6	OD	OD	AD	AD	AD	AD	AD	AD	AD
Parcel 8	OD	OD	AD	AD	AD	AD	AD	AD	AD
Parcel 10	OD	OD	AD	AD	Dams	Dams	Dams	Dams	Dams

yields (Table 4) resulting from a high water table are irrelevant for NMF, as it is not harvested. Additionally, it generates substantial carbon subsidy income due to reduced emissions (Table 4). For farm with potatoes, with 20€/tCO$_2$e carbon price, it's optimal to install adjustable subsurface drainage on all peatland parcels. This is due to the high income from cultivating potatoes, combined with lower emissions from adjustable drainage system (Table 4).(Fig. 2)

When carbon price is further increased to 50€/tCO$_2$e, on farm with no potatoes, dams are installed in all peatland parcels apart from the one closest to the farm centre, where adjustable drainage system is installed. At this carbon price, higher portion of total NPV is obtained from carbon subsidies than from crop cultivation (Fig. 3). On the potato farm, as potatoes are very profitable, it's optimal to maintain adjustable subsurface drainage on most parcels, while on the parcel furthest away it's optimal to install Dams (Table 5). This is similar to the results related for farm type 1, where NMF is concentrated in this parcel (Figs. 1–2). A further increase in the carbon price causes the last non-dammed parcel in farm type 1 to turn to using dams. However, for farm with potatoes, an increase in carbon price up to 150€/tCO$_2$e, has no effect on optimal drainage solution.

It is worth to note that, assuming no yield benefits, it is never optimal to utilize subsurface drainage without water table adjustment possibility, or irrigation. Subsurface drainage has similar soil emissions as open ditches, and the only benefit is the small increment in cultivated area on peatland parcels. This does not provide enough benefits to offset the costs. Similarly, irrigation, assuming no positive yield effects, provides no further benefits compared to adjustable drainage, thus it's never optimal due to the higher costs.

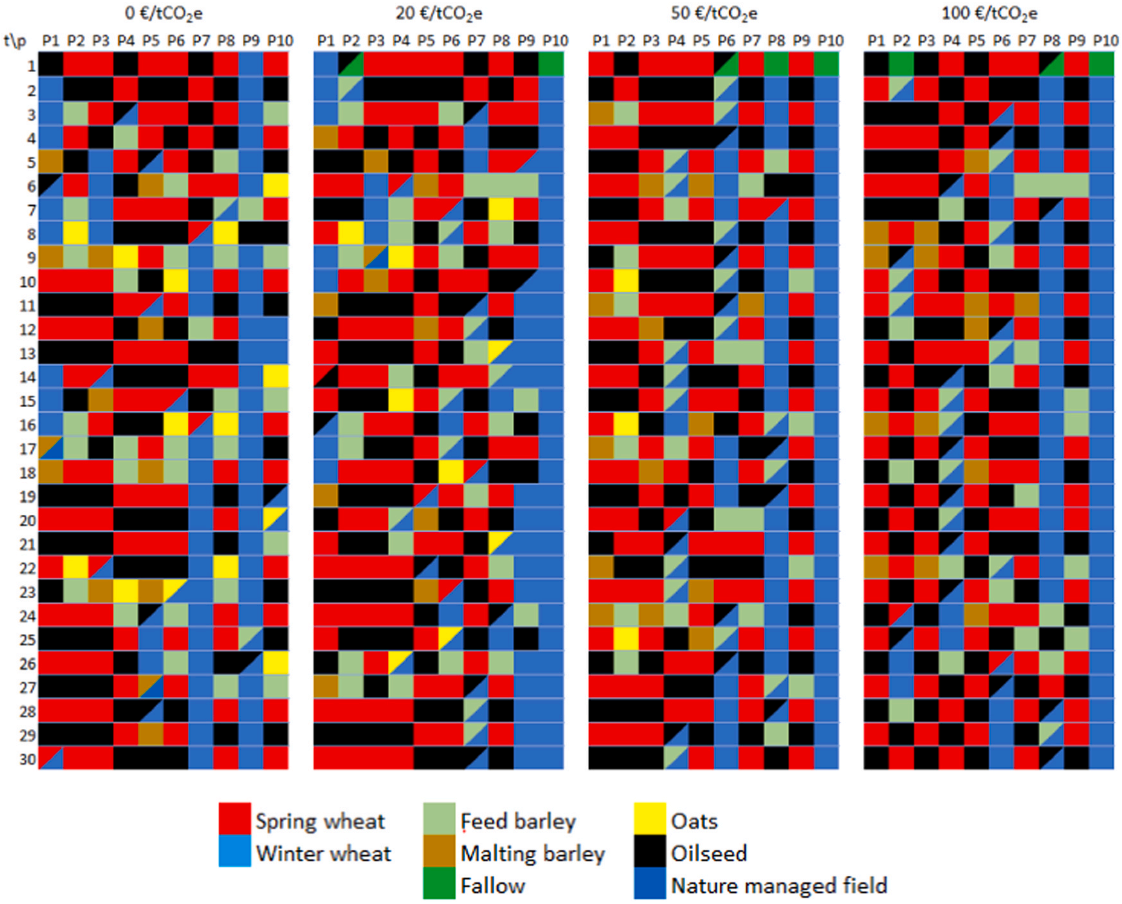

Fig. 1. Economically optimal 30-year land-use of a farm with no potatoes available, with carbon prices 0, 20, 50 and 100 €/tCO$_2$e.

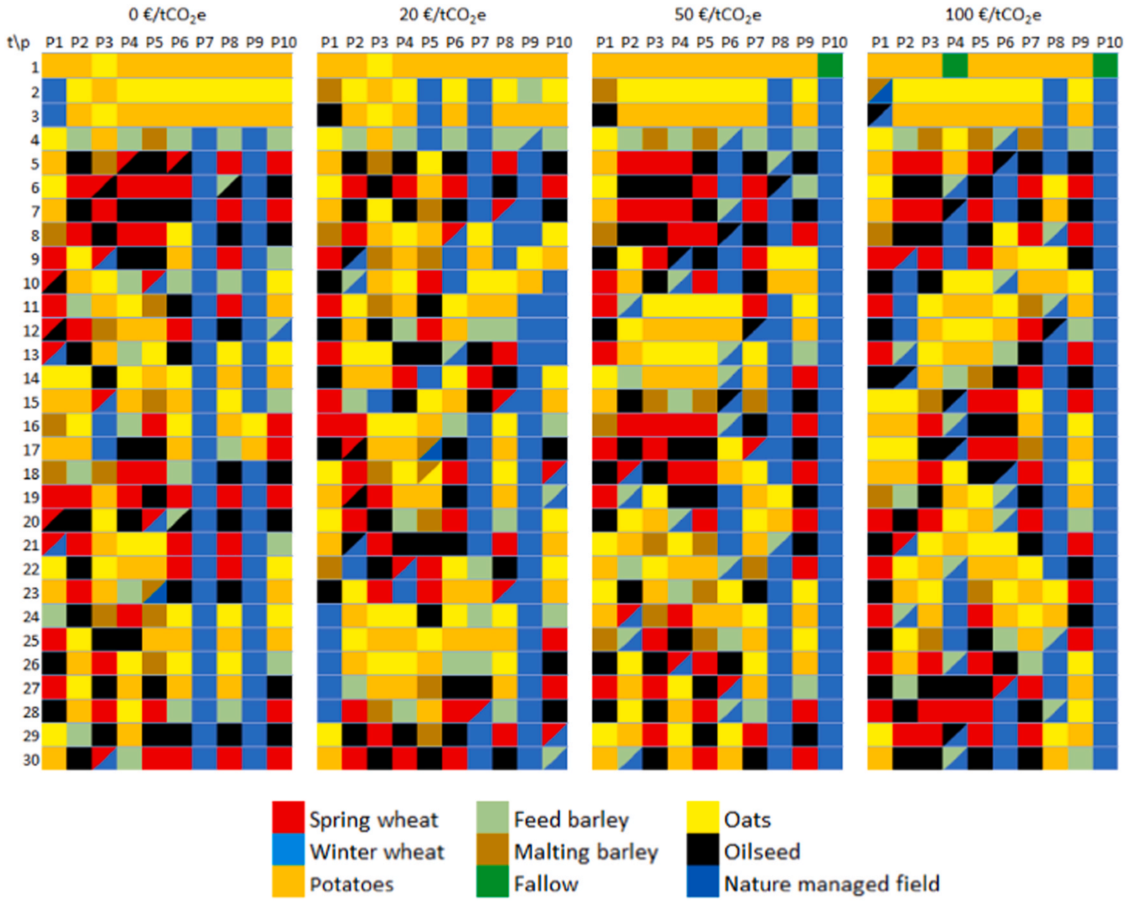

Fig. 2. Economically optimal 30-year land use of a farm with potatoes, with carbon prices 0, 20, 50 and 100 €/tCO$_2$e.

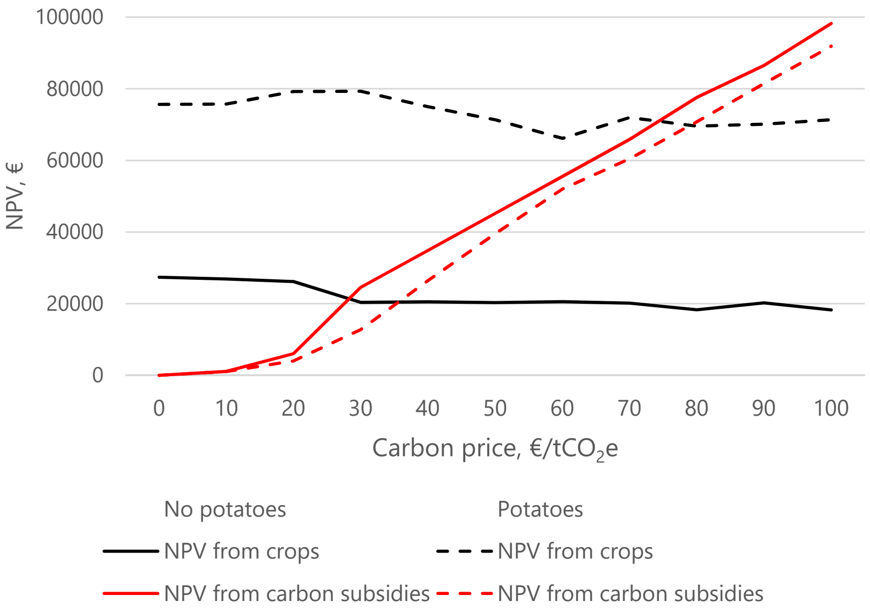

Fig. 3. Net present value (NPV) from crops (incl. agricultural subsidies) and carbon subsidies (incl. investments, costs, and subsidies from drainage), over 10 parcels and 30-year time horizon with 6 % interest rate.

Subsurface drainage with irrigation (Irri) may imply some yield gains compared to regional average yields, so to assess the impact on drainage options, we conducted a sensitivity analysis on the potential crop yield effects resulting from irrigation. Optimal drainage with different levels of irrigation yield gains, with 20€/tCO$_2$e and 50€/tCO$_2$e carbon price is presented in Table 6. As previously observed, with no yield gains, irrigation is never optimal. A 2 % yield gain from irrigation has no effect on farm with no potatoes, but for farm with potatoes, three closest parcels to the farm center turn to irrigation, and two furthermost to adjustable drainage. While Irri does not provide additional carbon subsidies over AD (Table 4), the extra investments to irrigation pay off quickly as potatoes are highly profitable. With 4 % yield gain, irrigation is utilized also on farm with no potatoes. On farm with potatoes the furthermost parcels utilize dams. This happens as NMF is focused more heavily to the furthermost peatland parcels, thus it's not optimal to invest in more expensive drainage options. With 6 % yield gains, irrigation becomes more widespread on both farms (Table 6), with 3 closest parcels utilizing irrigation and rest with dams on farm with no potatoes, and for farm with potatoes, irrigation is installed on all parcels. On farm with no potatoes, even 30 % yield gain is not sufficient to have irrigation on all peatland parcels; the lack of highly profitable crop means that it's not optimal to install irrigation on the furthest parcels, and instead focus NMF there.

Depending on whether potatoes are available or not has strong effect on optimal crop rotation. On farm where potatoes are not available, crop rotation focuses on spring wheat and oilseed, with some barley and NMF as break crops (Fig. 1). Carbon price has little effect on diversity of optimal crop rotation. Main change is that NMF is focused on peatland parcels due to their low emissions and thus high carbon subsidies (Fig. 4).

On Farm type 2, cultivation naturally focuses on the highly profitable potatoes. Since oats have an excellent pre-crop value for potatoes, it's most commonly cultivated right before potatoes (Fig. 2). The effects of increasing carbon price are similar to those observed for farm without potatoes: with higher carbon prices, NMF is focused on the peatland parcels (Fig. 5).

How the total NPV is divided between NPV from farming and from carbon subsidies is depicted in Fig. 3. On both farm types, as carbon price is increased, the NPV from carbon subsidies increases. For farm with no potatoes, since the total NPV is lower, the NPV from carbon subsidies exceeds that of NPV of crops already around carbon price of 30€/tCO$_2$e (Fig. 3). Above this price, the farmer obtains higher income from carbon subsidies than crops, and focuses more and more efforts in "carbon farming", i.e. installing dams on peatland parcels (Table 5) regardless of obtaining yield penalties due to the high water table (Table 4). For the farm with potatoes, since potatoes are very profitable, also the NPV from crops is very high. With this farm type, the NPV from carbon subsidies exceeds that of crops only at 80 €/tCO$_2$e (Fig. 3), and even after that, the farmer does not forgo crop cultivation (Table 5).

Total GHG emissions were calculated over 30 years for both farm types and across different prices of carbon subsidies ranging from 0 to 100 € €/tCO$_2$e (Fig. 6). The most significant result is that increasing the carbon subsidy price to 30€/tCO$_2$e results in obtaining most of the reductions in emissions (Fig. 6). After this level, increasing carbon price has little effect on total emission reduction.

4. Discussion

The results on farm level production, income (represented by NPV), and GHG emissions show how agriculture in the region (northern Ostrobothnia) could change due to carbon subsidy pricing. In accordance with Stachowicz et al. (2022), open diches (OD) is the cheapest rewetting option, hence preferred by farmers when the carbon price is zero. Farmers with no access to the production contracts of high valued crops such as food potatoes will most likely invest in low-cost damming (Dams) of open ditches if carbon payments are higher than €30/t CO$_2$e. Still, even if only part of the rewetted peatland stayed rewetted in the long-term, the carbon payment level necessary for profitable rewetting is relatively low compared to the prices of CO2e permits in the EU (€80–100/t CO2 eq. in recent years (Ember, 2025)).

The results suggest that low-cost damming of open ditches is likely to happen despite a large 40 % yield loss of annual crops due to high water tables, because the value of carbon payments per ha exceeds the value of lost yield per hectare. This specific practice can be viewed as a form of "carbon farming", where farmers prioritize payments from carbon subsidies over crop productivity. If farmers prioritize carbon subsidies over crop productivity across many farms in the region, it may cause significant challenge for the food and feed industry, as well as for suppliers of agricultural inputs. On the other hand, buyers of carbon credits and suppliers of ditch damming or subsurface drainage constructions will benefit from this. Farmers with access to production contracts for high valued crops may reach higher crop yields due to adjustable subsurface drainage and irrigation systems (Peltonen-Sainio et al., 2021). Thus, they would not decrease but rather increase agricultural production. However, it is worth to note that if this "carbon farming" practice is adopted on wider scale in a region, it would change the market balance, thus also affecting unit prices, and thus the optimality of each drainage alternative.

Incentivising farmers to adopt climate-smart water management strategies on peatlands may arise regulatory challenges. For example, neighbouring farms that rely on intensive production on drained peatlands may be negatively affected if adjacent farms invest in low-cost dams which imply increased water tables on several other field parcels. Thus, creating strong incentives such as carbon payments may lead to actions affecting the production and aims of other farms. If low-cost dams become popular due to carbon pricing, as the results suggest, given the relatively small number of farms producing high-valued crops in the region, it could trigger disputes between farmers and other landowners at a local level due to impacts of rising water table on neighbouring parcels. These issues could also create tension between farmers,

Table 6
Optimal drainage in each peatland parcel with different levels of irrigation yield gains. Carbon prices 20€/tCO$_2$e and 50€/tCO$_2$e. OD = Open ditches, AD = Adjustable subsurface drainage, Dams = Dams in open ditches, Irri = Adjustable subsurface drainage with irrigation.

	Carbon price 20€/tCO$_2$e								
	No potatoes					Potatoes			
Irrigation yield gain	0 %	2 %	4 %	6 %	30 %	0 %	2 %	4 %	6 %
Parcel 2	OD	OD	OD	Irri	Irri	AD	Irri	Irri	Irri
Parcel 4	OD	OD	OD	Irri	Irri	AD	Irri	Irri	Irri
Parcel 6	OD	OD	OD	OD	Irri	AD	Irri	Irri	Irri
Parcel 8	OD	OD	OD	OD	Irri	AD	Irri	Irri	Irri
Parcel 10	Dams	Dams	Dams	Dams	Irri	AD	Irri	Irri	Irri
	Carbon price 50€/tCO$_2$e								
	No potatoes					Potatoes			
Irrigation yield gain	0 %	2 %	4 %	6 %	30 %	0 %	2 %	4 %	6 %
Parcel 2	AD	AD	Irri	Irri	Irri	AD	Irri	Irri	Irri
Parcel 4	Dams	Dams	Dams	Irri	Irri	AD	Irri	Irri	Irri
Parcel 6	Dams	Dams	Dams	Irri	Irri	AD	Irri	Irri	Irri
Parcel 8	Dams	Dams	Dams	Dams	Irri	AD	AD	Dams	Irri
Parcel 10	Dams	Dams	Dams	Dams	Dams	Dams	AD	Dams	Irri

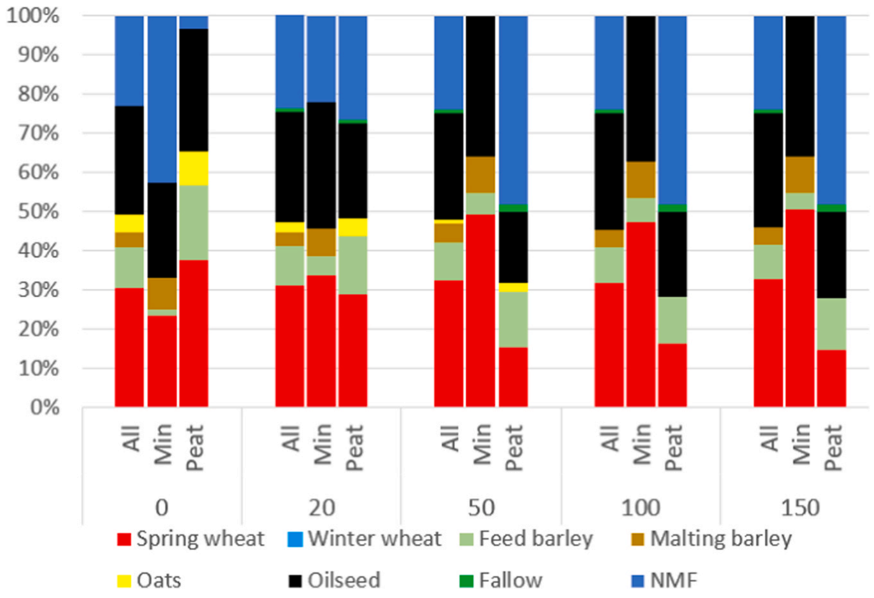

Fig. 4. Average share of each crop of total farm area (All), on mineral (Min) and peatlands (Peat) parcels on a farm with no potatoes, with carbon prices 0, 20, 50, 100, and 150 €/tCO_2e.

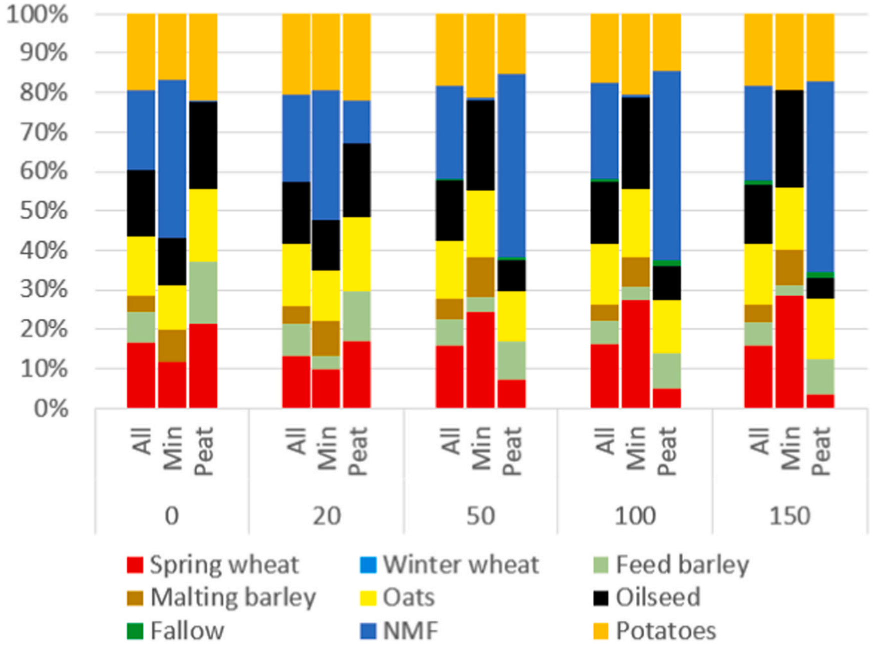

Fig. 5. Average share of each crop of total farm area (All), on mineral (Min) and peatland (Peat) parcels on a farm with potatoes, with carbon prices 0, 20, 50, 100, and 150 €/tCO_2e.

especially in small communities where cooperation is essential for agricultural viability. One could say that carbon pricing as such may not yet imply coordinated actions to find suitable field parcels and areas of several peatland parcels to be rewetted using the options studied in the paper.

One of the limitations of this study is that we did not consider dynamic soil organic carbon (SOC) changes due to crop rotations. In this part of Finland mineral soils in agriculture typically have SOC levels surpassing the capacity of soil particles to retain organic carbon in the soil (Kostensalo et al., 2024). This means that even if crop rotations could increase SOC, that increase is likely to be temporary. In crop rotations, only temporary perennial grasslands can lead to an increase in SOC (Kostensalo et al., 2024), and on crop farms forage grasslands with high yields are typically not cultivated because of no feed demand, although Nature Management Fields (NMF) with little to no crop yield and relatively low SOC accumulation is often part of rotation at individual field plots. In addition, SOC loss is appr. 10 times larger from peatlands than from mineral soils due to decomposing peat, and changes in SOC due to crop rotations are relatively minor (Kostensalo et al., 2024). Finally, it is difficult to measure changes in SOC, thus subsidizing this change is problematic compared to reduced C and N_2O emissions from peatlands which can be decreased effectively and more reliably. Hence, in this study it is assumed that GHG emissions can be reduced by increasing water tables by various means on peatlands, and by cultivated perennial grasses through NMF, which decreases GHG emissions from both mineral and peat soils.

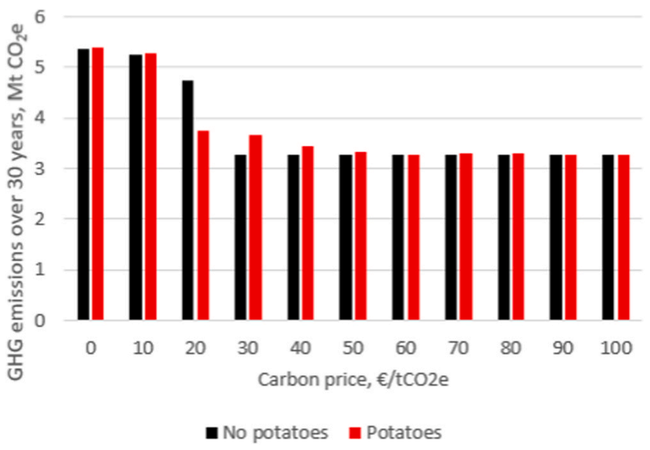

Fig. 6. Total cumulative GHG emissions for both farm cases over 10 parcels and 30-year time horizon with carbon prices from 0 to 100 €/tCO_2e.

Another important aspect of agricultural water management is nutrient leaching. Studies suggest that improved subsurface drainage may lead to increased nitrogen leaching (Jokinen et al., 2024), emphasizing the importance of water management on impacts to watercourses. In this study we focused on carbon payments and GHG emissions, and did not cover effects of drainage on biodiversity. Further studies with sufficient data material are needed for that.

The results compare fairly well with previous studies on agricultural peatland rewetting in various countries, at least in terms of the costs per rewetting action (Stachowicz et al., 2022) costs per ton of reduced GHG emissions (Röder et al., 2015), and in terms of the required carbon payments (Grossmann and Dietrich, 2012; Röder et al., 2015) necessary for making different rewetting options profitable. However, it is worth noting that the current study focused on widely utilized crops in the Northern Ostrobothnia region and did not consider e.g. cultivation of paludiculture crops. Incorporating these crops in the analysis would produce interesting and important information on impacts of rewetting on profitability and GHG emissions.

5. Conclusions

Climate, water protection and biodiversity targets impose requirements for the use of peatlands in agriculture. This study analysed economic profitability of drainage options on peatlands in Finland from farm level perspective. The set up of this study considered very typical cases in Northern Ostrobothnia region Finland: farms which can cultivate a limited number of relatively low-valued crops, and farms which have access to production contracts of high-valued crops as well.

The results suggest that those farms which have limited or no possibility (i.e. no chance for production contracts with food industry) for cultivation of higher valued crops may, if they are incentivised using carbon subsidies, allocate their agricultural peatlands to low-cost rewetting which leads to permanently higher water table. Carbon payments of 30–40 €/tCO_2e already trigger drainage options with increased water tables and reduced GHG emissions. This means that rewetting agricultural peatlands can provide relatively low-priced GHG emission abatement for those who are willing to pay for them. However, rewetting drained agricultural peatlands may not lead to permanent CO_2e reductions since rewetted peatlands can be drained again, if carbon payments decrease or cease in the future. If the farm has access to production contracts and value chains of high-valued crops such as food potatoes, even low carbon payments such as 20€/tCO_2e would trigger advanced water management such as subsurface irrigation on these farms. However, the long-term nature of water management requires that carbon markets or other ways to realise carbon payments provide long-term avenues for farmers to develop and re-orient their activities.

CRediT authorship contribution statement

Rämö Janne: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tzemi Domna:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **Miettinen Antti:** Data curation. **Wejberg Henrik:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Lehtonen Heikki:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition.

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.

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Appendix A

The impact of nitrogen fertilization on yields are calculated using nitrogen response functions. Either mitscherlich (Eq. A.1) (Spring and winter wheat, feed and malting barley, oats) or quadratic (Eq. A.2) (oilseed) function is used.

$$M_i = \left(\widehat{Y}_i + \frac{p_N}{p_i + \beta_i} - \frac{p_N e^{-\beta_i \widehat{N}_i}}{p_i + \beta_i}\right) e^{-\beta_{3i}} N_{itp} \tag{A.1}$$

$$Q_i = \widehat{Y}_i - \frac{\widehat{N}_i}{2}\left(\theta_i + \frac{p_N}{p_i}\right) + \theta_i N_{itp} - \frac{1}{2\widehat{N}_i}\left(\theta_i + \frac{p_N}{p_i}\right) {N_{itp}}^2 \tag{A.2}$$

where M_i and Q_i are the yields of crop i after fertilization in mitscherlich and quadratic forms. $\widehat{Y}_i$ is the baseline yield level based on statistics and $\widehat{N}_i$ the baseline fertilization amounts for crop i. p_N and p_i refer to prices of nitrogen fertilization and crop $_i$, respectively. N_{itp} is the optimized fertilization amounts of crop i at time t on parcel p. Parameter values for equations A1 and A2 are given in Table A1.

Table A.1
Parameter values for nitrogen response functions Source: Purola et al. (2018)

Crop	θ	β	$\widehat{Y}$	$\widehat{N}$
Winter wheat	-	0.0105	4385	140
Feed barley	-	0.0168	3848	90
Malting barley	-	0.0168	3851	90
Oats	-	0.0197	3893	90
Oilseed	9.82	-	1654	100

Data availability

Data will be made available on request.

References

Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R., 2016. Peatland restoration and ecosystem services: science, policy and practice. Cambridge University Press.

Buschmann, C., Röder, N., Berglund, K., Berglund, Ö., Lærke, P.E., Maddison, M., Mander, Ü., Myllys, M., Osterburg, B., van den Akker, J.J.H., 2020. Perspectives on agriculturally used drained peat soils: comparison of the socioeconomic and ecological business environments of six European regions. Land Use Policy 90, 104181. https://doi.org/10.1016/j.landusepol.2019.104181.

Ember, 2025. European Electricity Prices and costs. ⟨https://ember-energy.org/data/european-electricity-prices-and-costs/⟩. Accessed 18 March 2025.

FAO, 2020. Peatland mapping and monitoring-Recommendations and technical overview. Report to FAO.

Finnish Food Authority, 2024. Tuet: Maatalous (https://www.ruokavirasto.fi/tuet/maatalous/) (https://www.ruokavirasto.fi/tuet/maatalous/).

Finnish Forest Research Institute, 2014. Finnish Statistical Yearbooks of Forestry (1979–2014). Finnish Forest Research Institute, Helsinki.

Flessa, H., Wild, U., Klemisch, M., Pfadenhauer, J., 1998. Nitrous oxide and methane fluxes from organic soils under agriculture. Eur. J. Soil Sci. 49, 327–335.

Greifswald Mire Centre (GMC), Wetlands International, and National University of Ireland, Galway (NUI). 2020. Peatlands in the EU. Common Agricultural Policy (CAP) after 2020. Position Paper, ⟨https://www.greifswaldmoor.de/files/dokumente/Infopapiere_Briefings/202003_CAP%20Policy%20Brief%20Peatlands%20in%20the%20new%20EU%20Version%204.8.pdf⟩.

Grossmann, M., Dietrich, O., 2012. Social benefits and abatement costs of Greenhouse Gas emission reductions from restoring drained fen wetlands: a case study from the Elbe river Basin (Germany). Irrig. Drain. 61, 691–704.

Haddaway, N.R., Burden, A., Evans, C.D., Healey, J.R., Jones, D.L., Dalrymple, S.E., Pullin, A.S., 2014. Evaluating effects of land management on greenhouse gas fluxes and carbon balances in boreo-temperate lowland peatland systems. Environ. Evid. 3, 1–30.

IPCC, 2014. In: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G. (Eds.), 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Published: IPCC, Switzerland.

Jokinen, V., Salo, H., Mäkelä, M., Nurminen, J., Äijö, H., Laine-Kaulio, H., Koivusalo, H., 2024. The effects of improved subsurface drainage on runoff and nitrogen leaching from a clayey field section. Irrig. Drain.

Joosten, H., 2009. The Global Peatland CO2 Picture: peatland status and drainage related emissions in all countries of the world. Glob. Peatl. CO2 Pict. Peatl. Status Drain. Relat. Emiss. All Ctries. World.

Joosten, H., Tapio-Biström, M.-L., Tol, S., 2012. Peatlands: guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Food and Agriculture Organization of the United Nations, Rome.

Kässi, P., Niskanen, O. & Lehtonen, H. 2015. Pellonhankinnan vaihtoehdot, kustannukset ja peltomarkkinoiden toimivuus. Luonnonvara- ja biotalouden tutkimus 30/2015. 37 p. ISBN: 978-952-326-034-4 (Verkkojulkaisu) ISSN 2342-7647 (Verkkojulkaisu). http://urn.fi/URN:ISBN:978-952-326-034-4.

Kekkonen, H., Ojanen, H., Haakana, M., Latukka, A., Regina, K., 2019. Mapping of cultivated organic soils for targeting greenhouse gas mitigation. Carbon Manag. 10, 115–126.

Kostensalo, J., Hyväluoma, J., Jauhiainen, L., Keskinen, R., Nuutinen, V., Peltonen-Sainio, P., Heikkinen, J., 2024. Diversification of crop rotations and soil carbon balance: impact assessment based on national-scale monitoring data. Carbon Manag. 15, 2298373. https://doi.org/10.1080/17583004.2023.2298373.

Krimly, T., Angenendt, E., Bahrs, E., Dabbert, S., 2016. Global warming potential and abatement costs of different peatland management options: a case study for the Pre-alpine Hill and Moorland in Germany. Agric. Syst. 145, 1–12.

Liu, X., Lehtonen, H., Purola, T., Pavlova, Y., Rötter, R., Palosuo, T., 2016. Dynamic economic modelling of crop rotations with farm management practices under future pest pressure. Agric. Syst. 144, 65–76.

Miettinen, A., Saarnio, S., 2024. Cheap greenhouse gas emission reductions from peat fields by damming meltwater and heavy rains. Luomulehti 2, 36–37.

Ministry of Agriculture and Forestry 2022. Suomen CAP-suunnitelma 2023-2027. Valtioneuvosto. 1102 p. Available at: ⟨https://mmm.fi/cap27/cap-suunnitelma⟩.

Myllys, M., 2019. Säätösalaojituksesta hyötyä turvemailla/Turvemaat hyötyvät säätösalaojituksesta. Salaojayhdistys.Finnish Field Drainage Association. In Finnish.

Ovenden, G.N., Swash, A.R., Smallshire, D., 1998. Agri-environment schemes and their contribution to the conservation of biodiversity in England. J. Appl. Ecol. 35, 955–960.

Peltonen-Sainio, P., Juvonen, J., Korhonen, N., Parkkila, P., Sorvali, J., Gregow, H., 2021. Climate change, precipitation shifts and early summer drought: an irrigation tipping point for Finnish farmers? Clim. Risk Manag. 33, 100334.

Peltonen-Sainio, P., Niemi, M., Jauhiainen, L., 2024. Legacy effects of crop sequencing on biomass and their variability on farmers' fields in Finland are shaped by weather, farm conditions and rationales for land use. Agric. Syst. 215, 103850. https://doi.org/10.1016/j.agsy.2023.103850.

Purola, T., Lehtonen, H., 2022. Farm-level effects of emissions tax and adjustable drainage on peatlands. Environ. Manag. 69 (1), 154–168.

Purola, T., Lehtonen, H., Liu, X., Tao, F., Palosuo, T., 2018. Production of cereals in northern marginal areas: an integrated assessment of climate change impacts at the farm level. Agric. Syst. 162, 191–204.

Rämö, J., Tzemi, D., Lehtonen, H., Palosuo, T., Peltonen-Sainio, P., 2024. Improving a dynamic farm level model by coupling empirically estimated pre-crop values with crop rotation optimization. Agric. Food Sci. 33 (3), 223–236. https://doi.org/10.23986/afsci.14474.

Räsänen, T.A., Myllys, M., Kekkonen, H., Tapio, S., Pitkänen, T., Laatikainen, M., Laine-Petäjäkangas, A., Väänänen, T., Palmu, J.-P., Kivimäki, A., Oksanen, J., 2023. Turvepeltolohkojen määrittely ja tunnistaminen: maatalousmaiden turvetieto (MaaTu) -hankkeen raportti. Luonnonvara- ja biotalouden tutkimus 58/2023. Luonnonvarakeskus. Helsinki. 40 s. Finn. Engl. Abstr.

Regina, K., Nykänen, H., Silvola, J., Martikainen, P.J., 1996. Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity. Biogeochemistry 35, 401–418.

Röder, N., Henseler, M., Liebersbach, H., Kreins, P., Osterburg, B., 2015. Evaluation of land use based greenhouse gas abatement measures in Germany. Ecol. Econ. 117, 193–202.

Salaojayhdistys 2024. Salaojitus. SALAOJITUS – salaojayhdistys. ⟨https://www.salaojayhdistys.fi/salaojitus/⟩. Accessed December 5 2024.

Schäffer, S., 2009. Biodiversität und Klimawandel: synergien aus dem Moorschutz. Biodiversität Klima-Verne-.-. der Akteure Dtschl. V 18.

Stachowicz, M., Manton, M., Abramchuk, M., Banaszuk, P., Jarašius, L., Kamocki, A., Povilaitis, A., Samerkhanova, A., Schäfer, A., Sendžikaitė, J., Wichtmann, W., Zableckis, N., Grygoruk, M., 2022. To store or to drain — To lose or to gain? Rewetting drained peatlands as a measure for increasing water storage in the transboundary Neman River Basin. Sci. Total Environ. 829, 154560.

Tanneberger, F., Appulo, L., Ewert, S., Lakner, S., Brolcháin, Ó., Peters, J, N., Wichtmann, W., 2021. The power of nature-based solutions: how peatlands can help us to achieve key EU sustainability objectives. Adv. Sustain. Syst. 5 (1), 2000146.

Turunen, J., 2008. Development of Finnish peatland area and carbon storage 1950–2000. Boreal Environ. Res. 13 (4), 319.

Wejberg, H., Miettinen, A., Lehtonen, H., Mäkelä, M., Häggblom, O., Myllys, M., 2024. Vesienhallinnan taloudelliset edellytykset turvepelloilla. Luonnonvara- ja biotalouden tutkimus 78/2024. Luonnonvarakeskus. Helsinki. 41 pg. http://urn.fi/URN:ISBN:978-952-380-967-3. Includes an English abstract "Economic conditions of water management in peat fields".

Wichtmann, W., Schröder, C., Joosten, H., 2016. Paludiculture-productive use of wet peatlands: climate protection-biodiversity-regional economic benefits. Schweizerbart Science Publishers, Stuttgart, p. 272.