MODELLING DISSOLVED ORGANIC CARBON (DOC) EXPORT FOR GREENHOUSE GAS (GHG) ACCOUNTING IN DRAINED ORGANIC FOREST SOILS

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Abstract. Dissolved organic carbon (DOC) export from drained organic forest soils represents a substantial but still insufficiently operationalised pathway of carbon loss in greenhouse gas (GHG) accounting frameworks. Although DOC-derived downstream CO_2 emissions are acknowledged in international guidelines, their routine inclusion in national inventories is constrained by data intensity and model complexity. This study presents a pragmatic, inventory-oriented modelling workflow designed to quantify DOC export and associated nutrient losses from drained organic soils using widely available meteorological, hydrological and spatial datasets. The approach combines Penman-Monteith based estimation of reference evapotranspiration with a simplified water-balance framework to derive monthly and annual run-off at the catchment or a field scale. DOC and nutrient exports can be calculated by coupling modelled run-off with measured monthly concentrations, allowing rapid updating as new water-quality data become available. The workflow was parametrised and tested using multi-year field datasets from hemiboreal drained peatland sites in Latvia, including forest stands, agricultural land and abandoned peat extraction areas monitored within the scope of LIFE OrgBalt and other projects. Results demonstrate pronounced differences in DOC export among land-use types, driven jointly by evapotranspiration control on run-off and land-use-specific DOC concentration. Annual DOC exports in drained organic forest soils were generally below the default emission factor from the 2013 IPCC Wetlands Supplement (0.31 t $C \cdot ha^{-1} \cdot yr^{-1}$), with the nationally derived factor for forest land (0.22 t $C \cdot ha^{-1} \cdot yr^{-1}$) approximately 30% lower. The method additionally yields nutrient export estimates relevant to water quality assessment: mean annual total nitrogen export across study sites was 15.52 ± 9.47 $kg \cdot ha^{-1} \cdot yr^{-1}$, indicating substantial losses from drained organic soils under forest land use. By deliberately avoiding data-intensive process-based carbon models, the proposed workflow fills the gap between detailed site studies and operational GHG accounting. It provides an implementable basis for integration DOC-related C losses and nutrient export into national inventories and drainage maintenance planning, thereby supporting both climate-mitigation reporting and evidence-based land and water management in drained organic soils.

Keywords: dissolved organic carbon, drained organic soils, greenhouse gas accounting, hydrological modelling, nutrient export.

Introduction

Greenhouse gas (GHG) inventories and management oriented carbon accounting in drained organic soils risk systematic underestimation when they focus solely on vertical gaseous exchanges while omitting lateral aquatic carbon pathways. Organic (peat) soils contain large soil organic carbon stocks, and drainage for timber production or farming creates persistent hydrological alterations – lowering the water table, increasing aeration, and strengthening hydraulic connectivity between the soil profile and the ditch – stream network. These shifts accelerate peat decomposition and change the partitioning of carbon losses between soil-to-atmosphere fluxes and hydrologically mediated exports, making it necessary to treat carbon loss as a coupled terrestrial – aquatic process rather than a strictly "on-site" phenomenon [1; 2].

Dissolved organic carbon (DOC) export is climate relevant carbon transfer because DOC in inland waters is reactive and is widely assumed to be progressively mineralised, meaning that a large share is ultimately converted to gaseous CO_2 and released to the atmosphere downstream. Waterborne carbon can form a substantial fraction of the organic-soil carbon budget and, under some conditions, may even exceed the net CO_2 exchange inferred from soil – atmosphere measurements. This conceptualisation implies that excluding DOC can bias GHG accounting towards underestimation of total carbon losses from drained peat soils, particularly where hydrological connectivity is high and solute residence times are sufficient for substantial processing, and therefore DOC-derived CO_2 is increasingly treated as "good practice" to include in comprehensive accounting frameworks [3; 4].

The IPCC 2013 Wetlands Supplement [5] provides an implementable Tier 1 methodology to estimate CO_2 emissions associated with DOC export from drained organic soils. In this framework, the annual DOC related CO_2 emission is expressed as carbon mass ($CO_2 - C_{DOC}$) and calculated as the product of the area of drained organic soils and an emission factor (EF_{DOC}): $CO_2 - C_{DOC} = A \times EF_{DOC}$.

The Wetlands Supplement further defines the calculation principle for EF_{DOC} by decomposing it into three interpretable parameters: a baseline DOC flux from naturally wet (undrained) organic soils ($DOC_{NATURAL}$), the proportional change in DOC flux caused by drainage ($\Delta DOC_{DRAINAGE}$), and the fraction of exported DOC that is ultimately oxidised to CO_2 after export ($Frac_{DOC-CO_2}$). Operationally, this structure is commonly implemented as $EF_{DOC} = DOC_{NATURAL} \times (1 + \Delta DOC_{DRAINAGE}) \times Frac_{DOC-CO_2}$, allowing inventories to separate assumptions about background fluxes, drainage impact, and downstream oxidation in a transparent way [5].

For temperate regions the Supplement provides default values that make the calculation transparent and enable uncertainty propagation: $DOC_{NATURAL} = 0.21$ t C·ha^{-1}·yr^{-1} (range 0.17-0.26), $\Delta DOC_{DRAINAGE} = 0.60$ (0.43-0.78), and $Frac_{DOC-CO_2} = 0.9 \pm 0.1$, obtaining a default EF_{DOC} for drained organic soils of 0.31 t C·ha^{-1}·yr^{-1} (0.19-0.46). In applications where results are reported as CO_2 mass rather than carbon mass, the conversion is performed with the molar ratio 44/12 [5]. These defaults provide a consistent baseline for inventories that do not yet have national factors, and they clarify which process components should be targeted when moving towards Tier 2 (i.e. improved national estimates of run-off, DOC concentrations and the drainage induced change relative to undrained reference conditions).

Evidence from hemiboreal conditions indicates that national parametrisation can be warranted, consistent with the 2019 Refinement principle of improving representativeness when data permit [6]. DOC related carbon losses from drained organic forest soils have not been routinely included for drained sites. A national DOC emission factor developed for forest land (pine and birch stands) was estimated at 0.22 t C·ha^{-1}·yr^{-1}, which is markedly lower than the IPCC default of 0.31 t C·ha^{-1}·yr^{-1}, and the report highlights that the national factor development relied on the IPCC default assumption for DOC export from undrained organic soils (0.21 t C·ha^{-1}·yr^{-1}). This dependency implies that further refinement should include empirical DOC export estimates from naturally wet reference sites to reduce structural uncertainty in $\Delta DOC_{DRAINAGE}$ and to strengthen national reporting robustness [6; 7].

A further motivation for a practical modelling workflow is the strong land-use dependence of DOC concentrations and associated export potential. Published data from hemiboreal drained organic soils demonstrate marked contrasts between forest stand types, with substantially higher DOC concentrations in pine stands (113.7 mg·L^{-1}) than in birch stands (51.9 mg·L^{-1}) [7]. These contrasts reflect a mechanistic framework in which vegetation type, peat chemistry, and redox regime govern DOC production and mobilisation, while run-off determines the realised export. DOC export is therefore determined by the interaction of hydrological fluxes and solute concentrations, both of which exhibit strong seasonality and event-scale variability. High-flow periods can dominate annual loads, while concentrations respond to water-table dynamics, temperature, and hydrogeochemical conditions. This complicates direct upscaling from sparse sampling and motivates a modelling strategy in which run-off is simulated continuously and concentrations are characterised at a frequency sufficient to capture seasonal dynamics [7].

Operationalising DOC estimates are also synergistic with water protection objectives because the same framework can deliver dissolved nutrient exports. Such co-transported nutrients (N, P, K) are directly relevant to eutrophication risk and to evaluating trade-offs of drainage maintenance and restoration, implying that DOC-oriented monitoring and modelling can deliver climate-accounting and water-quality co-benefits [8].

In view of (i) the documented importance of DOC as a component of the organic-soil carbon budget, (ii) the current under-implementation of DOC for drained organic soils in inventory practice, and (iii) the sensitivity of national estimates to default-factor assumptions, the aim of this study is to develop and test a practical, inventory-oriented modelling workflow that links meteorology-driven run-off estimation with monthly water quality observations to quantify catchment-scale DOC export and associated biogenic element (N, P, K) export in drained organic forest soils. By explicitly aligning the workflow with the IPCC Wetlands Supplement calculation principle and benchmarking outputs against default and emerging national factors, the study aims to support implementable Tier 2 development and to strengthen decision support for drainage maintenance and restoration planning.

Materials and methods

The workflow quantifies catchment-scale run-off and couples it with monthly water-quality measurements to derive DOC and co-exported biogenic elements (N, P, K). DOC and nutrient concentrations are taken from monthly ditch run-off and soil-water chemistry datasets compiled in the LIFE OrgBalt and other project study sites, with subsequent verification against an independent run-off monitoring dataset from the Aģe River catchment (9 ha drained organic forest site; run-off monitoring 2016-2019). The approach is designed to minimise additional field effort by using routinely available meteorological observations and standard spatial layers (land cover and vegetation).

Catchments (and sub-catchments where relevant) are delineated from high-resolution terrain data in a GIS environment (QGIS/GRASS). Where physically justified, drainage-network features and culverts are considered because they can modify effective flow paths and run-off connectivity in low-relief drained landscapes.

Daily meteorological drivers are obtained from Latvian Geology, Meteorology and Environment agency: daily maximum/mean/minimum air temperature, maximum/mean/minimum relative humidity, and mean wind speed, prepared in spreadsheet format and imported to the FAO ETo Calculator (EToCalc). Reference evapotranspiration is computed with the FAO-56 Penman–Monteith formulation [9], producing daily evapotranspiration ET_0 values that are aggregated to monthly sums for the run-off balance.

$$ET_0 = \frac{0.408\Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)}, \tag{1}$$

where ET_0 – reference evapotranspiration, mm day^{-1};
R_n– total solar radiation, MJ m^{-2}, d;
G – soil heat flux, MJ m^{-2}, d;
T – daily mean air temperature at 2 m height from ground, °C;
u_2 – wind speed, 2 m height, m s^{-1};
e_s – saturated vapor pressure, kPa;
e_a – water vapor pressure, kPa;
$e_s - e_a$ – saturated vapor pressure deficit, kPa;
Δ – vapor pressure curve, kPa °C^{-1};
γ – psychometric constant, kPa °C^{-1}.

To translate ET_0 to land-cover-specific evapotranspiration, FAO-style crop cover coefficients K_c are applied by dominant management or cover type. K_c is structured as $K_{c_{ini}}$, $K_{c_{mid}}$and $K_{c_{end}}$, and interpolated across the season: values increase linearly from $K_{c_{ini}}$to$K_{c_{mid}}$ at the start of the active growing period, remain at $K_{c_{mid}}$ during the peak season, and decrease linearly to $K_{c_{end}}$ towards the season end, then transition back to $K_{c_{ini}}$ under negative mean daily temperatures (Table 1).

$$ET_c = K_c \cdot ET_0 \tag{2}$$

where ET_c – the land-cover-specific (actual) evapotranspiration, mm·day^{-1};
K_c – the dimensionless crop cover coefficient, varying by cover type and growth stage;
ET_0 – the reference evapotranspiration, mm·day^{-1}.

Table 1

Land-cover coefficients (K_c) used for ET adjustment

Land cover/management type	$K_{c_{ini}}$	$K_{c_{mid}}$	$K_{c_{end}}$
Pine forest	1.00	1.00	1.00
Birch forest	0.50	1.20	0.95
Bare peat soil (no vegetation)	0.55	0.55	0.55

To support spatial consistency of ET patterns, remote sensing products can be used to characterise vegetation activity (e.g., Sentinel-2 NDVI for LAI estimation) and soil wetness constraints (soil moisture map), which inform expected contrasts in transpiration among forest types and wetness classes.

Run-off is computed at monthly resolution within each catchment using an empirical water-balance approach, subtracting evapotranspiration from precipitation, consistent with a simplified basin water balance:

$$Q = P - ET - V, \tag{3}$$

where Q – monthly run-off, mm;
P – precipitation, mm;
ET – actual evapotranspiration, mm;
V – change in subsurface water storage, mm.

For operational monthly run-off, storage change is treated as a lumped residual; in the parsimonious implementation, monthly run-off is constrained to non-negative values.

Where higher process detail is required, the workflow remains compatible with hydrological model outputs (e.g., TOPMODEL, HYPE) for sensitivity checks; however, parameter availability and transferability can be limiting for full DOC-process models, motivating the simplified runoff-first approach for inventory use.

Monthly DOC export is calculated by combining modelled monthly run-off with measured monthly concentrations. Concentrations vary strongly by land use (e.g., higher DOC in pine stands and peat extraction fields; lower in croplands/grasslands), supporting the need for land-use-stratified calculation rather than a single national mean concentration.

Monthly areal loads are computed with a unit-consistent conversion using run-off depth (mm) and concentration (mg·L^{-1}). As 1 mm over 1 ha equals 10,000 L, the conversion factor to kg ha^{-1} is 0.01. Monthly load (generic solute; DOC, N, P, K) can be calculated using following equation:

$$L_{x,m} = 0.01 \cdot Q_m \cdot C_{x,m}, \tag{4}$$

where $L_{x,m}$ – monthly areal load of solute x, kg·ha^{-1}·month^{-1};
Q_m – monthly run-off depth, mm;
$C_{x,m}$ – measured monthly concentration of solute x, mg·L^{-1};
0.01 – unit-conversion factor.

Annual areal load of each solute is obtained by summing the twelve monthly loads calculated from Equation 4.

DOC export is linked to downstream CO₂ emissions following the IPCC Wetlands Supplement structure, where annual carbon emissions associated with DOC export from drained organic soils are computed as the product of area and an emission factor EF_{DOC} expressed in t C·ha^{-1}·yr^{-1} using following equation:

$$CO_2 - C_{DOC} = \sum_{c,n} A_n \cdot EF_{DOCn}, \tag{5}$$

where $CO_2 - C_{DOC}$ – annual carbon emission associated with DOC export from drained organic soils, t C·yr^{-1};
A_n – area of drained organic soils in a land use type n, ha;
EF_{DOCn} – DOC emission factor for the corresponding land use type, t C·ha^{-1}·yr^{-1}.

In the default-factor formulation, the DOC emission factor is parametrised as the product of (i) natural DOC flux, (ii) proportional change due to drainage, and (iii) the fraction of exported DOC that is ultimately oxidised to CO₂ in downstream systems ($Frac_{DOC-CO_2}$). The report provides temperate-zone defaults and uncertainty ranges (where $CO_{2,DOC}$ – annual CO₂ emission attributable to DOC export, t CO₂·yr^{-1};
$CO_2 - C_{DOC}$ – carbon mass from Equation 7, t C·yr^{-1};
44/12 – molar mass ratio of CO₂ to C used to convert carbon mass to CO₂ mass.

Table 2), enabling benchmarking of modelled national factors against IPCC defaults according to default-factor parametrisation (carbon units) equation:

$$EF_{DOC} = DOC_{NATURAL} \cdot (1 + \Delta DOC_{DRAINAGE}) \cdot Frac_{DOC-CO_2}, \tag{6}$$

where EF_{DOC} – DOC emission factor, t C·ha^{-1}·yr^{-1};
$DOC_{NATURAL}$ – baseline DOC flux from naturally wet undrained organic soils, t C·ha^{-1}·yr^{-1};
$\Delta DOC_{DRAINAGE}$ – proportional increase in DOC flux caused by drainage, dimensonless;
$Frac_{DOC-CO_2}$ – fraction of exported DOC ultimately oxidised to CO₂ in downstream water bodies, dimensionless.

To report in CO₂ mass units (t CO₂·yr^{-1}), carbon emissions are converted using the molecular-weight ratio 44/12:

$$CO_{2,DOC} = (CO_2 - C_{DOC}) \cdot \frac{44}{12} \ , \tag{7}$$

where $CO_{2,DOC}$ – annual CO₂ emission attributable to DOC export, t CO₂·yr^{-1};
$CO_2 - C_{DOC}$ – carbon mass from Equation 7, t C·yr^{-1};
44/12 – molar mass ratio of CO₂ to C used to convert carbon mass to CO₂ mass.

Table 2

IPCC Wetlands Supplement temperate-zone default parameters (drained organic soils)

Parameter	Default	Uncertainty range
$DOC_{NATURAL}$, t C·ha^{-1}·yr^{-1}	0.21	0.14-0.29
$\Delta DOC_{DRAINAGE}$	0.60	0.47-0.73
$Frac_{DOC-CO_2}$	0.90	0.85-0.95
EF_{DOC}, t C·ha^{-1}·yr^{-1}	0.31	0.22-0.41

CO₂ from DOC oxidation is calculated using following equation:

$$E_{CO_2,DOC} = L_{DOC,yr} \cdot Frac_{DOC-CO_2} \cdot \frac{44}{12} \ , \tag{8}$$

where $E_{CO_2,DOC}$ – site-level annual CO₂ emission from DOC oxidation, kg CO₂·ha^{-1}·yr^{-1};
$L_{DOC,yr}$ – annual DOC load from Equation 6, kg C·ha^{-1}·yr^{-1};
$Frac_{DOC-CO_2}$ – oxidation fraction from Equation 8 (default 0.9), dimensionless;
44/12 – C-to-CO₂ molar mass conversion.

Uncertainty is quantified by propagating (i) run-off uncertainty (stemming from meteorological station variability and ET reparametrisation) and (ii) analytical/temporal uncertainty in concentrations from monthly sampling. For annual loads, uncertainty is summarised as mean ± standard deviation across sites and land uses (e.g., the report demonstrates strong spatial variability in annual nitrogen export), and can be extended to confidence intervals via bootstrap resampling of monthly concentration–run-off pairs within each land-use stratum.

Results and discussion

Modelled run-off showed pronounced seasonality, with the largest run-off and export potential occurring during wet and low-evapotranspiration periods and a marked decline during the vegetation period when evapotranspiration increases. This seasonality directly propagated into DOC and nutrient loads because monthly loads were computed as the product of the modelled run-off and measured monthly concentrations.

DOC concentration differed strongly among land-use types on drained organic soils. The highest mean concentration occurred in Scots pine forests (113.7 ± 4.4 mg·L^{-1}) and in abandoned extraction areas without vegetation (109.7 ± 14.1 mg·L^{-1}), followed by Silver birch forests (51.8 ± 4.4 mg·L^{-1}) (Table 3).

Table 3

Mean DOC concentration by land-use type (drained organic soils)

Land-use type	DOC (mg·L^{-1})
Bare peat soil (no vegetation)	91.8 ± 6.1
Pine forest (afforested extraction area)	113.7 ± 3.3
Birch forest	51.9 ± 1.4

Annual DOC export (expressed as DOC-C) spanned nearly an order of magnitude across land uses. Among the studied forest stands, Scots pine recorded the highest export at 0.328 ± 0.023 t C·ha^{-1}·yr^{-1}, while Silver birch showed considerably lower values of 0.154 ± 0.011 t C·ha^{-1}·yr^{-1}. The highest export overall was observed at abandoned peat extraction sites with bare peat at 0.414 ± 0.030 t C·ha^{-1}·yr^{-1}, reflecting the combined effect of elevated DOC concentrations and high runoff from sparsely vegetated surfaces [7].

To translate DOC export into an indicative downstream CO_2 emission component, DOC-C loads were multiplied by the IPCC oxidation fraction and stoichiometric factor. Using the default oxidation fraction ($Frac_{DOC-CO_2}$ = 0.9) and the molar mass ratio (44/12), the conversion factor equals 3.3 kg CO_2 per kg DOC-C. This implies that bare peat conditions (0.413 t C·ha^{-1}·yr^{-1}) correspond to approximately 1.37 t CO_2·ha^{-1}·yr^{-1}, Scots pine to approximately 1.08 t CO_2·ha^{-1}·yr^{-1}, and Silver birch to approximately 0.51 t CO_2·ha^{-1}·yr^{-1} attributable to DOC oxidation(Table 4).

Table 4

Annual DOC export and implied CO_2 from DOC oxidation (assuming $Frac_{DOC-CO_2}$= 0.9)

Land-use type	DOC export, t C·ha^{-1}·yr^{-1}	CO_2 from DOC, t CO_2·ha^{-1}·yr^{-1}
Bare peat soil (no vegetation)	0.413 ± 0.030	1.37 ± 0.109
Pine stand	0.328 ± 0.023	1.08 ± 0.083
Birch stand	0.153 ± 0.011	0.51 ± 0.063

Nutrient export estimates demonstrated substantial variation with forest type and surface cover. Annual total nitrogen export was 7.75 ± 0.60 kg·ha^{-1}·yr^{-1} in Silver birch stands and 35.78 ± 2.41 kg·ha^{-1}·yr^{-1} at bare peat sites, indicating that nitrogen loss is strongly sensitive to both vegetation cover and runoff volumes. Mean annual phosphorus export at bare peat sites was notably low at 0.05 ± 0.007 kg·ha^{-1}·yr^{-1}, while potassium export ranged from 1.06 kg·ha^{-1}·yr^{-1} in birch stands to 9.16 ± 2.51 kg·ha^{-1}·yr^{-1} at bare peat extraction sites. The observed DOC concentration and export gradients across drained organic-soil land uses align with the conceptual expectation that exposed or weakly vegetated peat surfaces and drainage-enhanced flow paths increase DOC mobilisation and transport. High DOC concentrations in peat extraction and cutover surfaces are consistent with the mechanism that oxidative peat decomposition and hydrological connectivity of ditches promote DOC production and export, while vegetated systems can reduce concentrations through plant uptake, microbial processing, and altered hydrological partitioning. The magnitude 0.08-0.63 t C·ha^{-1}·yr^{-1} depending on land use also overlaps with published evidence that DOC and nutrient exports from drained peatland forests can be substantial and can respond to management events such as harvesting and fertilisation, although direction and magnitude depend on site hydrology, peat properties, and catchment buffering capacity [10].

A key implication for GHG accounting is that the study-derived DOC export factors can deviate from IPCC defaults, particularly for peat extraction-related land uses. The 2013 IPCC Wetlands Supplement derives a default emission factor for DOC export by combining a natural DOC flux with a relative drainage-induced increase $\Delta DOC_{DRAINAGE}$, and it assumes a high fraction of exported DOC is oxidised to CO_2 downstream [5]. In this context, measured annual evidence suggests that national circumstances – especially legacy peat extraction landscapes and highly connected ditch networks – may produce DOC related CO_2 emissions larger than those implied by a single "temperate/boreal default". This supports the practical value of a workflow where updated concentration monitoring can rapidly update export estimates without re-building the hydrological model structure.

The nutrient export results reinforce the co-benefit dimension of integrating DOC accounting with water protection metrics. Nitrogen export (mean 15.52 ± 9.47 kg·ha^{-1}·yr^{-1}) is within the broad range reported for managed organic soils and peatland catchments, where loads can be low under limited discharge but can rise sharply under high discharge conditions or intensive management. Empirical ranges cited in the report indicate that nitrogen exports from drained peat soils can reach 30 $kg \cdot ha^{-1} \cdot yr^{-1}$ in Norway, while phosphorus losses are typically 0.2-0.5 $kg \cdot ha^{-1} \cdot yr^{-1}$ in Finland, and potassium exports frequently fall in the 5-15 $kg \cdot ha^{-1} \cdot yr^{-1}$ range in boreal peatland forestry contexts [11; 12]. Potassium exports frequently fall in the 5-15 $kg \cdot ha^{-1} \cdot yr^{-1}$ range in boreal peatland forestry contexts, emphasising that site hydrology and management determine whether nutrient losses become ecologically relevant. For decision support, presenting DOC together with N, P, and K loads is advantageous because of interventions that reduce duration and eutrophication pressure [13].

Scaling behaviour differed between site-level land-use classes and aggregated land-cover categories. The two-year data means show that mixed land-cover classes can yield intermediate DOC exports even when local "hotspot" land uses (e.g., extraction surfaces) have much higher exports. This suggests that national inventory implementation should treat peat extraction legacies and ditch-network density explicitly in the activity data used for inventory stratification and area estimation, rather than relying exclusively on broad land-cover classes.

Uncertainty is dominated by the multiplicative structure of the load calculation: errors in run-off depth propagate linearly, while concentration uncertainty and sampling frequency influence both mean estimates and the representation of episodic peaks. Because high-flow events can disproportionately contribute to annual export, monthly sampling is operationally attractive but may still under-represent event-driven pulses; therefore, uncertainty reporting should explicitly include sampling design limitations alongside statistical uncertainty. Where physically based hydrological models (e.g., HYPE and SWAT) are applied, the report evidence that parameter sets tuned for other countries may not transfer robustly highlights the need for national calibration before replacing the pragmatic water-balance approach [14].

Conclusions

1. The developed workflow operationalises DOC-related carbon losses from drained organic soils for inventory and management use by coupling Penman – Monteith based evapotranspiration, a parsimonious monthly water balance run-off model, and monthly water-quality observations, thereby enabling rapid recalculation of DOC and nutrient loads when new concentration data become available.
2. Empirical results demonstrate strong land-use control on DOC concentrations and exports in drained organic-soil landscapes. DOC concentrations were highest in Scots pine forests (113.7 ± 3.3 $mg \cdot L^{-1}$) and bare peat surfaces (91.8 ± 6.1 $mg \cdot L^{-1}$), and substantially lower in Silver birch forests (51.9 ± 1.4 $mg \cdot L^{-1}$), reflecting the influence of vegetation type, peat chemistry, and redox regime on DOC production and mobilisation.
3. Annual DOC export ranged from 0.154 ± 0.011 t $C \cdot ha^{-1} \cdot yr^{-1}$ in Silver birch stands to 0.413 ± 0.030 t $C \cdot ha^{-1} \cdot yr^{-1}$ at bare peat surfaces, with Scots pine at 0.328 ± 0.023 t $C \cdot ha^{-1} \cdot yr^{-1}$. Under the IPCC default oxidation assumption ($Frac_{DOC-CO_2} = 0.9$), this translates to DOC-derived downstream CO_2 of 0.51 t $CO_2 \cdot ha^{-1} \cdot yr^{-1}$ in birch stands, 1.08 t $CO_2 \cdot ha^{-1} \cdot yr^{-1}$ in pine stands, and 1.37 t $CO_2 \cdot ha^{-1} \cdot yr^{-1}$ at bare peat surfaces.
4. Benchmarking against the IPCC Wetlands Supplement temperate default ($EF_{DOC} = 0.31$ t $C \cdot ha^{-1} \cdot yr^{-1}$, range 0.19-0.46) demonstrates that site-specific exports diverge substantially by forest type. Scots pine (0.328 ± 0.023 t $C \cdot ha^{-1} \cdot yr^{-1}$) falls within the default range with an empirical ΔDOC of 0.56 compared to the IPCC default of 0.60, while Silver birch (0.154 ± 0.011 t $C \cdot ha^{-1} \cdot yr^{-1}$) falls well below it. The resulting nationally derived forest factor (0.22 t $C \cdot ha^{-1} \cdot yr^{-1}$) is approximately 30% below the IPCC default, demonstrating that a single temperate default overestimates DOC-related carbon losses from drained organic forest soils in Latvia and supporting the case for Tier 2 development based on nationally stratified land-use classes.
5. The approach delivers co-benefit indicators for water protection by quantifying nutrient exports alongside DOC. Annual total nitrogen export ranged from 7.75 ± 0.60 $kg \cdot ha^{-1} \cdot yr^{-1}$ in Silver birch stands to 35.78 ± 2.41 $kg \cdot ha^{-1} \cdot yr^{-1}$ at bare peat sites, while potassium export ranged from 1.06 $kg \cdot ha^{-1} \cdot yr^{-1}$ in birch stands to 9.16 ± 2.51 $kg \cdot ha^{-1} \cdot yr^{-1}$ at bare peat sites, highlighting the value

of integrating climate accounting with nutrient-loss assessment for prioritising drainage maintenance and restoration interventions.

6. Remaining uncertainty is driven primarily by the multiplicative run-off concentration structure and by the potential under-capture of event-driven export peaks with monthly sampling. The current workflow lacks an explicit snow accumulation and snowmelt module; in snow-dominated periods, particularly during spring floods, this omission may introduce substantial errors in run-off and export estimates, and its inclusion should be a priority in future development. Future refinement should therefore combine targeted high-flow sampling with improved national baselines for naturally wet reference conditions to better constrain drainage-induced changes in DOC flux.

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Author contributions

Conceptualization, A.L. and R.N.M.; methodology, A.L. and R.N.M.; validation, A.B.; formal analysis, A.B. and R.N.M.; data curation, A.B. and M.V.D.; writing – original draft preparation, A.L. and Z.A.Z.; writing – review and editing, R.N.M. and A.B.; visualization, A.B.; project administration, A.L.; funding acquisition, A.L. All authors have read and agreed to the published version of the manuscript.

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