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Research article

Reducing carbon footprints in grassland-dominated milk production by rewetting of organic soils and intensified forage productivity on mineral soils

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ABSTRACT

Peatland rewetting is crucial for Germany to achieve net greenhouse gas (GHG) neutrality by 2045 as it can help to drastically reduce emissions in the LULUCF sector. This study combines farm-level Life Cycle Assessment with the biogeochemical model LandscapeDNDC to evaluate three different Bavarian dairy farm systems with varying peatland shares, quantifying GHG mitigation potential of rewetting and associated trade-offs in forage production.

Rewetting reduces peatland emissions by about 84%, lowering total product carbon footprint by 14-53%. However, a biophysical compensation failure threshold (X_{crit}) is identified at a peatland share of 21.8 %. Farms below this threshold can maintain forage production by intensifying mineral soils, while those exceeding it, such as high peat share farms (40% peatland), face structural shortfalls and can realistically rewet only half of their peatland area without production losses.

At regional scale, a circular solution appears biophysically feasible. Aggregated results for the Ammer region indicate that the potential forage surplus from intensification on mineral soils exceeds deficits associated with peatland rewetting by nearly two-fold, while additional emissions from intensified production and increased transport remain small relative to mitigation gains. Practical implementation, however, needs to manage increased nitrogen losses on intensified mineral soils and account for site-specific socio-economic constraints. Realizing this transformation requires EU Common Agricultural Policy payments to incentivize regional cooperation and address associated socio-economic implications of transitioning away from drained peatland use, providing the necessary framework for integrating alternative land-use and restoration goals.

1. Introduction

The agricultural sector, accounting for approximately 12% of global anthropogenic greenhouse gas (GHG) emissions, is under mounting pressure to reduce its contribution (Tubiello et al., 2021). Within this context, drained peatlands represent a critical but often overlooked emission source (Müller et al., 2025). Despite only covering about 3% of the global land area, peatlands function as vital carbon (C) reservoirs, storing around one third of the world's soil C (Tanneberger et al., 2020; Leifeld et al., 2018). However, extensive drainage for agricultural land use (LU) has transformed these ecosystems into significant anthropogenic GHG sources.

Drainage lowers the water table (WT) and aerates the peat soil, thereby accelerating aerobic decomposition and the subsequent release of substantial GHG quantities into the atmosphere (Joosten et al., 2016; Jurasinski et al., 2020).

These dynamics are particularly relevant to Germany, where approximately 95% of peatlands have been drained (Tanneberger et al.,

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2017; Wichmann et al., 2024a), contributing nearly 7% of total national GHG emissions and representing the largest source of these emissions within Europe (Jurasinski et al., 2020; Tanneberger et al., 2017).

In Germany, peatland drainage is critically linked to the dairy sector, as the majority of these areas are used as grasslands for cattle fodder production (Buschmann et al., 2020). This becomes particularly evident in Bavaria, which hosts one of the largest extents of peatlands among the German federal states, comprising an area of approximately 220,000 ha (Gosch et al., 2024; Nitsch et al., 2021). The Bavarian pre-alpine region is characterized by intensive milk production and a high structural dependency on grassland-based LU (Schucknecht et al., 2020). This results in a large proportion of organic soils being used by dairy farms (Krimly et al., 2016; Röder et al., 2012). Currently, 95% of Bavarian peatlands are drained, with approximately 52% utilized as grasslands (Klatt et al., 2019; Bundesministerium für Umwelt, 2022). Depending on management intensity, these areas emit between 24.2 and 34.8 t CO_2-eq ha^{-1} yr^{-1} (Klatt et al., 2019). Consequently, the carbon footprint (CF) of milk produced on drained organic soils is estimated to be three to six times higher than that produced on mineral soils (Müller et al., 2025, 2026).

Beyond GHG emissions, drainage-induced subsidence threatens long-term land viability (Joosten et al., 2016; Jurasinski et al., 2020); recent projections indicate that 40% of Bavarian agricultural peatlands will reach the limit of manageability within the next 30 years (Klatt et al., 2019). To achieve the federal target of reducing peatland emissions by 5 million t CO_2-eq yr^{-1} by 2030 (Bundesministerium für Umwelt, 2022), and the state-level goal of converting 20,000 ha to peat-preserving management (Staatsregierung et al., 2020), scalable GHG mitigation scenarios are essential.

The Ammer region serves as a representative case study for this pre-alpine hotspot where dairy production and high-emitting peatlands converge. While peatland rewetting is recognized as the most effective GHG mitigation measure (Gosch et al., 2024; Bockermann et al., 2024), it necessitates the withdrawal of productive land required for high-quality forage to sustain the region's lactating dairy herd (Bayerische Landesanstalt für Landwirtschaft, 2025). Therefore, effective GHG mitigation must be integrated with compensatory production strategies.

To address these multi-dimensional challenges, this study employs a Life Cycle Assessment (LCA) to quantify the environmental trade-offs of coupled GHG mitigation and compensation scenarios. Advancing beyond previous farm-level analyses ((Müller et al., 2026)), we implement a regional, cluster-based LCA to model three representative farm systems with varying peatland shares, ensuring the scalability required for evidence-based policymaking.

The objectives of the study are (i) to establish an LCA baseline for the CF of milk production across distinct farm systems, (ii) to quantify the environmental and production-related efficacy of rewetting when coupled with the intensification of remaining mineral grasslands, and (iii) to derive transferable management insights regarding GHG mitigation potentials and required compensation ratios.

2. Methods

In this study the environmental performance of grass-based dairy systems was evaluated by applying an LCA approach. The LCA was conducted within an attributional framework to model environmental burdens to the product system under two distinct scenarios: (1) the baseline (status quo) and (2) the mitigation and compensation scenario (rewetting and intensification). This approach is suitable as it allows for the quantification of physical trade-offs resulting from changes in land management and input use within the defined regional farm systems.

2.1. *Scope of the study*

2.1.1. *Study area*

The study focuses on the Ammer region in the Southern Germany pre-alpine region (e.g., TERENO Pre-Alpine Observatory), which is characterized by a temperate oceanic climate (Kottek et al., 2006; Kiese et al., 2018). The regional agricultural structure is defined by a strong reliance on grassland-based systems, with permanent grasslands exceeding 90% of the utilized agricultural area (UAA) (Fig. 1).

These areas are predominantly used for cattle forage production to support the regional dairy sector with an average annual productivity of 7,433 kg milk per dairy cow ((LfL) and B.L.f.L., 2020).

2.1.2. *System boundaries and functional unit*

The functional unit (FU) is defined as 1 kg of fat and protein corrected milk (FPCM), standardized to 4.0% fat and 3.3% protein in accordance with FAO (2016) guidelines.

The assessment follows a “cradle-to-gate” perspective, encompassing all life cycle stages from resource extraction to the point where raw milk leaves the farm gate. The temporal boundary is set at 12 months for the year 2019. The system boundary includes both off-farm activities (e.g., fuel, energy, and forage production, including transport to the farm) and on-farm activities (e.g., forage production, animal husbandry, manure management, emissions from drained peatlands) (Fig. 2). Processes related to medicines, equipment, machinery, and buildings were excluded due to their minor contribution to the overall impact.

2.1.3. *Allocation of co-products*

Dairy systems are multifunctional, yielding meat (calves and culled cows) as secondary outputs alongside the primary product, milk. To accurately determine the environmental impact of milk production, the overall system impacts are partitioned using biophysical allocation, following the methodological guidelines recommended by FAO (2016) (Fig. 2).

2.2. *Farm modeling and management*

The conceptual data workflow of the integrated modeling framework, including the coupling of data streams and model components are visualized in the Supplementary Material (Fig. S1), while farm-specific farm inventory parameters are provided in Table 1.

2.2.1. *Peatland-based farm systems*

To account for the high variability in peatland distribution across regional dairy systems, three representative peatland-based farm systems were defined. This categorization is necessitated by the fact that peatland emissions have been identified as the primary emission source of the milk CF in peatland-rich landscapes (Müller et al., 2026). As the focus of this study lies on the impact of peatland management, the groups were defined primarily by this structural criterion rather than by management intensity or farming system. The representative farm systems were derived from an empirical dataset of 1,732 farm records (InVeKoS data (2019)). To determine the share of organic soils for each farm, the dataset was spatially intersected with the updated map of organic soils in Germany provided by the Thünen Institute (Wittnebel et al., 2023). Based on this structural criterion of cultivated peatland area, the farm records were clustered into terciles: Low Peat Share (LPS ($n = 577$)), Medium Peat Share (MPS ($n = 577$)), and High Peat Share (HPS ($n = 578$)).

Based on the median peatland share of each cluster, the representative conditions for the typologies were defined at 5% (LPS), 17% (MPS), and 40% (HPS). Key structural parameters, including herd size and UAA, were calculated as the median of the aggregated data within each cluster to ensure representative model inputs.

2.2.2. *Baseline farm management*

Key characteristics of the analyzed farms are summarized in Table 1. Farm structures, including grassland area and cattle numbers, were parametrized using InVeKoS data (2019) (Annuth et al., 2025). Based on these data, total grassland area was differentiated into mown grassland

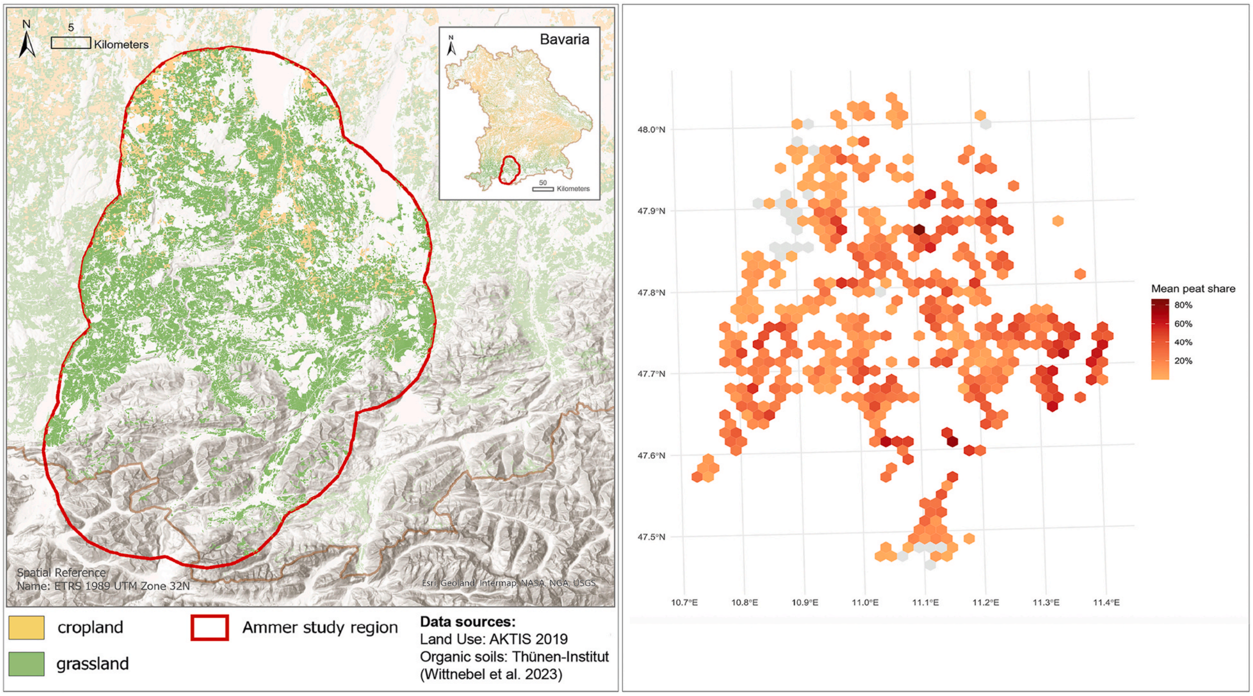

Fig. 1. Spatial distribution of land use in the Ammer region (left) and mean peatland share per 5 km^2 hexagon for dairy farms (right). Although organic soils account for only 7% of the total regional area, they account for 18.9% of the grassland extent. Localized clusters with peatland shares exceeding 60% underscore the high spatial heterogeneity and the concentrated pressure on specific farm groups. To ensure data privacy, hexagons are displayed only if they represent at least three individual farms.

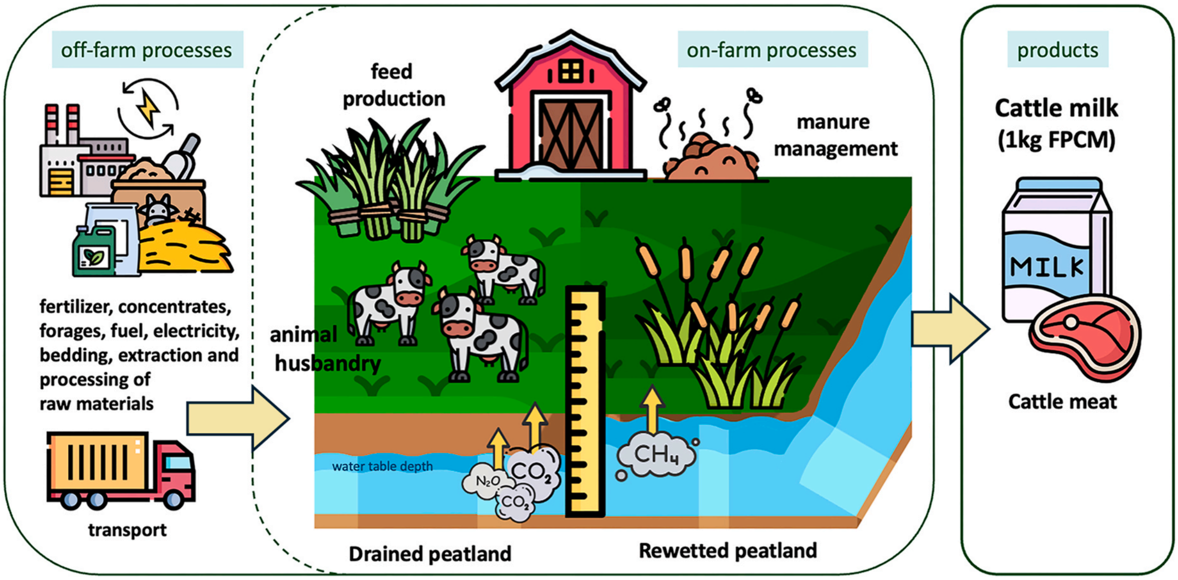

Fig. 2. System boundaries for cattle milk production and main emission sources at on- and off-farm level including emissions from different peatland scenarios (drained vs. rewetted). The main output considered is milk with meat as a co-product.

(primary forage source and subject to intensification) and ‘static’ secondary areas (pastures and extensive meadows) (Table 1). The latter remain at constant management intensity across all scenarios due to site-specific or conservation constraints. While the peatland share is calculated relative to the total grassland area (UAA), operational flexibility for intensification is restricted exclusively to the mown grassland portions. To ensure comparability, milk yields were standardized to the regional average of 7,433 kg milk cow^{-1}yr^{-1}) across all farm system clusters.

Grassland management for the baseline scenario reflects regional common practice. Forage yields were simulated using the terrestrial ecosystem model LandscapeDNDC (LDNDC) (Haas et al., 2013), assuming a management intensity of three mowing events (3 cuts) per year. This regime was selected as it represents the most common practice (60.2%) identified in regional empirical field data (Boos et al., 2024). Details regarding model configuration and validation are provided in section 2.2.3.

2.2.3. *Grassland yield modeling*

Grassland yields for the baseline (3 cuts) and intensified

Table 1
Key characteristics of the analyzed peatland-based farm systems and main input and output flows.

Farm structure	LPS	MPS	HPS
Main Parameters			
Total grassland area (ha)	38	32	35
Peatland area (ha)	2 (5%)	5.5 (17%)	14 (40%)
Pastures (ha)	2	2	3
Extensive meadows (ha)	1	2	4
Dairy herd size	42	33	35
Replacement rate (%)	17%	21%	18%
Milk yield (kg/milk/cow/yr)	7,433	7,433	7,433
Inputs			
Concentrates (t DM/cow/yr)	2.75	2.81	2.75
Electricity (kWh/yr)	21,000	16,500	17,500
Diesel (liter/yr)	6,174	4,850	5,145
Bedding (kg/yr)	6,726	5,313	3,635
Outputs			
Milk (kg FPCM/yr)	317,636	249,571	264,696
Meat (kg liveweight/yr)	7,440	5,589	6,124

compensation scenarios (4 and 5 cuts) were simulated using LDNDC (revision 10786). The model integrates coupled C, nitrogen (N) and water fluxes along with plant growth via the PlaMo^x physiology module for grassland community growth (Kraus et al., 2015). Harvested biomass from each cut equals the standing biomass on the day of cut minus the remaining above ground biomass (Kraus et al., 2015).

The simulations were parametrized using high-resolution regional data (Boos et al., 2024), including LU type and cutting dates (Reinermann et al., 2023). The observed cutting frequency ranged from one to six cuts per year. For the baseline scenario, all fields cut three times in 2019 were evaluated ($n = 11{,}163$). For the two compensation scenarios, fields cut four or five times were used ($n = 6{,}428$ and $n = 953$, respectively). To ensure the representativeness of the smaller number of fields that were actually cut four or five times, two additional simulations were performed, assuming that all fields in the catchment were cut four or five times in 2019.

Climate inputs were derived from the ClimEx project virtual climate stations, and soil properties were derived from the Bavarian State Office of the Environment (LfU) (Boos et al., 2024). Critically, yield simulation was restricted to mineral soils (organic C < 10%), thereby excluding peatland areas from the LDNDC-based productivity modeling (Boos et al., 2024). This restriction was applied because LDNDC currently lacks a validated standard parametrization for regional organic soil dynamics. Consequently, mineral soil yields were used as a conservative baseline proxy for forage production across all soil types. The implications of this potential bias and its impact on the regional results are further addressed in the discussion (section 4).

Management intensity was defined by a variable annual manure N-application rate proportional to the cutting frequency: 98 kg N ha^{-1} yr^{-1} for 3 cuts, 171 kg N ha^{-1} yr^{-1} for 4 cuts, and 244 kg N ha^{-1}yr^{-1} for 5 cuts. These rates reflect regional agricultural practice and expert consensus, ensuring that the simulated yield response aligns with the biophysical conditions of the study area (Boos et al., 2024).

The model configuration was calibrated and validated against long-term lysimeters measurements from the TERENO pre-alpine observatory (2012-2021) (Boos et al., 2024). Yields from individual mowing events were captured with an $r^2 = 0.61$ and RMSE = 0.94 t ha^{-1} (Annuth et al., 2025; Boos et al., 2024). Simulated gross dry matter (DM) yields were utilized directly in the LCA. For subsequent LCA calculations, the metabolizable energy (ME) content of grass silage was standardized to 10.7 MJ kg^{-1} DM based on the Gruber Tables (2021) for regional cattle nutrition ((LfL) and B.L.f.L., 2021).

While mown grassland yields were dynamically simulated using LDNDC, the productivity of the 'static' secondary grassland areas was derived from regional average values (Müller et al., 2026). Specifically, pastures and extensive meadows were assigned constant annual yields of 5.0 and 2.0 t DM ha^{-1} yr^{-1}, respectively, across all scenarios.

The simulated yields for the mown grasslands and N-related emissions for each cutting frequency are summarized in Table 2. These values provide the biophysical foundation for both the baseline (3 cuts) and intensification (4 or 5 cuts) scenarios on mineral soils, reflecting the inherent trade-off between enhanced biomass productivity and increased nitrous oxide (N_2O) emissions.

2.3. Scenario definition

This section details the two distinct scenarios applied for each farm system to quantify the GHG mitigation potential of peatland rewetting within the framework of regional compensation strategies.

2.3.1. Baseline scenario (status quo)

The baseline scenario represents the current dairy farming practices in the study region (status quo). In this reference, all grassland is maintained under the prevailing management regime of three annual mowing events for forage production. The gross DM yield for this regime was parametrized via LDNDC at 7.89 ± 0.93 t ha^{-1} yr^{-1} (Table 2) (Boos et al., 2024). GHG emissions from drained organic soils are calculated using site-specific annual emission factors (EFs) (section 2.4.3.) This scenario establishes the CF benchmark (kg CO_2-eq/FPCM) against which mitigation efforts are evaluated.

2.3.2. Mitigation and compensation scenario

The mitigation and compensation scenario models the combined effect of LUC and farm management adjustments. The aim is to achieve substantial reductions in peatland-derived emissions while maintaining milk production at the baseline level. This scenario integrates two coupled strategies.

1. Mitigation (GHG reduction):

The entire drained peatland area within each farm system cluster (5%, 17% and 40% of UAA) is assumed to undergo rewetting. Consequently, these areas are withdrawn from high-quality forage production. GHG fluxes of these sites are modeled to reflect a near-natural state with a target water table depth (WTD) of −0.100 m (section 2.4.3.) (Drösler, 2024).

2. Compensation (forage self-sufficiency):

To sustain baseline milk production levels, the forage deficit resulting from rewetting is compensated by intensifying management on the remaining mineral mown grasslands. This intensification is modeled by increasing the mowing frequency from three to four or five cuts per year on the available mineral soils. The objective is to maintain a total farm-level forage supply that meets or exceeds baseline requirements, thereby ensuring self-sufficiency.

The yields for these intensified regimes, as derived from LDNDC, are 9.62 ± 0.92 t DM ha^{-1} yr^{-1} (4 cuts) and 10.09 ± 0.98 t DM ha^{-1}yr^{-1} (5 cuts) (Table 2). The LCA accounts for the associated increase in N inputs and N_2O emissions. Beyond the GHG inventory, the process-based simulation was used to quantify additional N-related losses associated

Table 2
Modeled annual mean productivity and associated nitrogen dynamics for mown grasslands at baseline (3 cuts) and intensification levels (4 and 5 cuts) in the Ammer catchment derived by LDNDC.

Number of cuts	Yields (t DM/ha)	N input (kg N/ha)	N_2O emissions (kg N-N_2O/ha)
3 (baseline)	7.89 ± 0.93	98	0.76 ± 0.21
4	9.62 ± 0.92	171	0.99 ± 0.47
5	10.09 ± 0.98	244	1.42 ± 0.69

with mineral soil intensification. Corresponding rates of NH_3 volatilization and NO_3^- leaching were extracted for each scenario to assess non-climate environmental trade-offs (Supplementary Material Table S1).

For each farm system, the lowest intensification level (mowing frequency) required to bridge the forage deficit was selected to optimize the trade-off between environmental impact and production maintenance.

2.3.3. *Assessment of operational forage feasibility*

To evaluate the practical viability of the combined mitigation and compensation strategy, an operational forage balance was calculated for each farm system. This assessment determines whether the total net forage production (P_{net}) is sufficient to meet the respective annual DM requirements of the dairy herd. P_{net} was calculated as the sum of net yields from all grassland areas: the mown grassland area (subject to dynamic LDNDC-simulated yields; Table 2) and the 'static' secondary grassland (pastures and extensive meadows; constant yields as defined in Section 2.2.3). To account for realistic farming conditions, a standardized 15% loss factor was applied to the gross yields to represent conservation and forageing losses (Borreani et al., 2018; Teagasc, 2016).

A scenario was categorized as 'operationally feasible' if the resulting P_{net} met or exceeded the dairy herd's forage demand. This approach distinguishes between the theoretical biophysical compensation potential and the actual structural constraints of individual farm systems.

To establish a baseline for this comparison, we first modeled the theoretical maximum compensation capacity by assuming that the entire remaining mineral soil area of a farm's UAA is available for intensification. This defines a biophysical limit (X_{crit}) independent of farm-specific management. Subsequently, we calculated the operational forage balance for the specific LPS, MPS, and HPS models. This second step incorporates the structural constraints of each farm system, specifically the restriction of intensification to mown grassland, and accounts for pre-existing forage buffers (baseline surplus).

2.4. *Life cycle inventory (LCI) and GHG emission factors*

2.4.1. *Farm inputs and outputs*

To establish a detailed farm inventory, three representative peatland-based farm systems (LPS, MPS, HPS) were defined based on the structural clustering of 1,732 farm records. Key parameters, such as herd size and composition as well as UAA, reflect the medians of each group. For inventory parameters not available in the primary records, including manure management, concentrate composition, bedding consumption and energy use, data were complemented by regional averages and established models from previous work (Müller et al., 2026). Primary outputs were defined as Fat and Protein Corrected Milk (FPCM) and meat (liveweight) as a co-product. Table 1 summarizes the main input and output parameters for the three modeled peatland-based farm systems.

2.4.2. *Estimation of emissions*

Off-farm emissions associated with purchased inputs (e.g., concentrates, grains, and bedding) were assessed across their full life cycle, from agricultural production to processing and transportation. These emissions were quantified using the Agri-footprint v5.0 database (Blonk Agri-footprint BV, 2020). Land use change (LUC) emissions for external forage inputs were integrated using Agri-footprint datasets, supported by the PAS 2050–1 Land Use Change Assessment Tool and FAOSTAT historical data. On-farm emissions from fuel and electricity consumption were derived from the Ecoinvent 3.3 database (Ecoinvent, 2016).

Methane (CH_4) emissions from enteric fermentation were calculated using the IPCC 2019 Tier 2 approach. Farm-specific data on diet composition were used to determine gross energy intake based on estimated animal energy requirements and dietary digestibility. Enteric CH_4 emissions were subsequently calculated using a methane conversion factor (MCF; Y_m) of 6%, reflecting the specific forage regimes and productivity levels of the dairy cows. Emissions from manure management (solid storage and liquid slurry) were likewise estimated according to IPCC (2019) guidelines. For warm temperate moist climate, MCFs of 2% for solid storage and 24% for liquid slurry (based on an average storage duration of 3 months) were applied.

N_2O emissions were derived from the N-excretion rates using IPCC (2019) methodology. Direct N_2O emission factors (EF) were set at 1% for solid storage and 0.5% for liquid slurry. In contrast, all soil-related N losses from the mineral grassland scenarios including direct N_2O emissions as well as ammonia (NH_3) volatilization and nitrate (NO_3^-) leaching, were derived from site-specific, process-based modeling using LDNDC (see Section 2.3.2.b). This approach replaces standard Tier 1 default EFs to capture the non-linear emission responses across the different intensification levels (3, 4 and 5 cuts). The modeled NH_3 and NO_3^- fluxes were subsequently used to calculate indirect N_2O emissions from atmospheric N deposition and N losses from managed soils via leaching and runoff, following the IPCC (2019) methodology.

2.4.3. *Emissions from peatlands*

Drained peatlands used for agriculture are significant sources of GHG emissions, primarily CO_2, N_2O and CH_4 (Tanneberger et al., 2020). These emissions result from lowering the water table depth (WTD), soil aeration, and subsequent aerobic decomposition of organic matter, as well as anaerobic decomposition of organic matter in drainage ditches (Tiemeyer et al., 2024). In contrast, rewetting these peatland areas, as assumed in the GHG mitigation scenarios, substantially reduces CO_2 and N_2O emissions, while CH_4 emissions typically increase due to the restoration of anerobic conditions in the soil (Gunther et al., 2020).

In this study, peatland emissions are treated as a continuous land management change (LMC) (Müller et al., 2025) rather than applying the conventional 20-year LUC amortization. Given that drained peatlands undergo persistent oxidation, standard amortization is considered scientifically inadequate for capturing long-term C loss dynamics. Consequently, GHG emissions were treated as annual flux rates and fully integrated into the LCI of the respective reporting year. This approach ensures that the substantial climate impact of peatland-based dairy production, that is identified as dominant emission driver, is accurately represented (Müller et al., 2026). The resulting annual impact was allocated to the FU (FPCM) using biophysical allocation.

The selection of the GHG EFs for peatlands was based on a prior comprehensive evaluation of three methodologies Müller et al., 2026: IPPC Tier 1 EFs (Hiraishi et al., 2014), national implied EFs (Tiemeyer et al., 2020a), and WTD-specific response functions (Tiemeyer et al., 2020a). Previous results demonstrated that WTD-specific EFs offer the highest accuracy and regional specificity (Müller et al., 2026). Accordingly, this LCA utilizes EFs derived from non-linear response functions linking regional WTD to CO_2 and CH_4 fluxes. This method utilized available annual mean WTD data for the year 2020 (Friedrich, 2025) across the Ammer region.

The annual mean WTD was obtained from a high spatial resolution modeling approach developed by Friedrich (2025), which employs Gradient Boosting Regression to regionalize point-based WTD measurements across Bavarian peatlands (Friedrich, 2025). This value served as the primary input for the WTD-dependent response functions (applied Gompertz and exponential functions) to calculate site-specific EFs for CO_2 and CH_4 (Supplementary Material S3 Table S2). For N_2O, average EFs based on observed fluxes were used, as no significant correlation with WTD was identified (Tiemeyer et al., 2020a).

2.4.3.1. Scenario application. The WTD-specific methodology was employed to determine GHG fluxes for both the agricultural baseline and the rewetting-based mitigation scenarios.

Baseline scenario (drained peatlands): GHG emissions from peatlands were calculated using the WTD-specific functions, based on a modeled regional mean annual WTD of −0.381 m for the reference year 2020

(Friedrich, 2025). This value was applied across all three farm systems (Table S3). In accordance with previous findings (Müller et al., 2026), natural baseline emissions (i.e., GHG fluxes from intact, near-natural peatlands) were not subtracted from the drained baseline CF, as the resulting difference in the final CF was found to be negligible (Müller et al., 2026).

Mitigation scenario (rewetted peatlands): The EFs for rewetted peatland areas were determined by modeling a near-natural reference state. Using the same WTD-response functions, a mean annual WTD of −0.100 m was assumed (Drösler, 2024). These EFs were subsequently applied to the rewetted areas within the mitigation scenario to quantify emissions resulting from LMC (Table S3).

The resulting site-specific EFs for CO_2, CH_4 and N_2O for both baseline and mitigation scenarios are detailed in the Supplementary Material (Table S3).

2.5. Impact assessment and characterization

To evaluate the climate change impact, the IPCC 2021 methodology was applied, utilizing GWP factors for a 100-year time horizon (GWP100) (Intergovernmental Panel on Climate and C., 2023). Emissions of CO_2, CH_4, and N_2O were converted into CO_2-equivalents (CO_2-eq) using the following conversion factors: 1 for 1 kg of CO_2, 27.2 for 1 kg of biogenic CH_4, and 273 for 1 kg of N_2O. The calculations were performed using SimaPro 9.1 LCA software.

3. Results

3.1. Net GHG mitigation and environmental effectiveness of the compensation strategy

The full rewetting of peatland area (100%), coupled with the intensification strategy, results in a significant net reduction of the absolute CFs across all farm systems. This decline is primarily driven by the mitigation of peatland-derived emissions (Fig. 3). While rewetting reduces the specific peatland-related emission component by an average of 83.5% across the three farm systems (Table S4), the resulting impact on the total product CF varies by farm system. To maintain forage security under peatland rewetting, on-farm management was adjusted according to the specific operational requirements: LPS retains three cuts/year (utilizing pre-existing yield surpluses), while MPS and HPS systems intensify to four and five cuts, respectively. Crucially, the intensification level of five cuts represents the maximum biophysical capacity in this study and serves as the boundary condition for determining the compensation failure threshold (X_{crit}), as detailed in Section 3.2.

The environmental effectiveness of the compensation strategy is reflected in the shifting composition of the CF between the baseline and rewetting scenarios. Under baseline conditions, the CF is dominated by enteric fermentation in the LPS, whereas peatland emissions constitute the primary emission source for MPS and HPS. Due to its high proportion of peatland area, the HPS model exhibits the highest baseline CF at 2.60 kg CO_2-eq/kg FPCM (Fig. 3).

Consequently, rewetting leads to significant GHG mitigation across all farm systems. The HPS model demonstrates both the largest absolute mitigation potential of 1.38 kg CO_2-eq/kg FPCM (Table S4) and the highest relative reduction, amounting to over 50% of the total CF (Fig. 3). The MPS model reduces its CF by approximately 34% (absolute reduction of 0.57kg CO_2-eq/kg FPCM), while the LPS model achieves the lowest overall CF in the rewetted scenario, with a reduction of approximately 14% (reduction of 0.16 kg CO_2-eq/kg FPCM. Detailed absolute and relative changes for both the peatland emissions component and the total product system are provided in the Supplementary Material (Table S4).

The observed GHG mitigation is rooted in the strong decline of peatland emissions, which transition from the dominant emission driver to a minor contributor to the total CF. Although the intensification of grassland management slightly increases GHG contributions from internal food production, these increments remain negligible relative to the magnitude of GHG savings achieved through peatland restoration. However, the full realization of this GHG mitigation potential remains contingent upon required compensatory effort and the biophysical limits of the farms to offset forage yields.

Beyond the GHG balance, the intensification of mineral grasslands (4 and 5 cuts) led to an increase in reactive N losses from 4.29 kg N

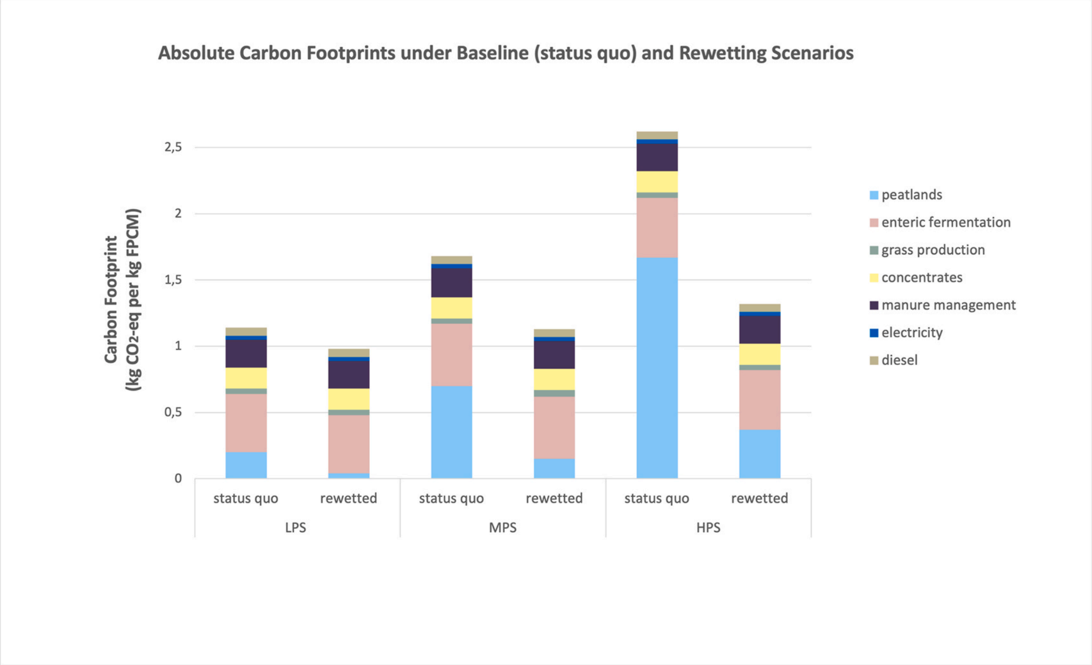

Fig. 3. Composition of absolute Carbon Footprints (CF) under baseline (status quo) and rewetting scenarios. The stacked bars quantify the absolute CFs (kg CO_2-eq/kg FPCM) for the three farm systems (LPS, MPS, HPS) under the current management (3 cuts) and the rewetting scenario (LPS: 3 cuts, MPS: 4 cuts, HPS: 5 cuts).

$ha^{-1}yr^{-1}$ (3 cuts) to 25.34 kg N ha^{-1} yr^{-1} (5 cuts). While NH_3 volatilization showed a non-linear increase at the highest intensification level, NO_3^- leaching remained consistently low across all cutting scenarios. Detailed disaggregated values for each pathway are provided in the Supplementary Material (Table S1).

3.2. *Derivation of biophysical compensation limits and the compensation failure threshold*

While the previous results (Fig. 3) demonstrate a substantial GHG mitigation potential through rewetting, the analysis of forage production reveals significant practical constraints at the farm level. To quantify the limitations of intensification as a compensatory strategy, a generalized biophysical model was developed to correlate a farm's peatland share with the relative change in forage production (Fig. 4).

This model identifies a critical compensation failure threshold (X_{crit}) at a peatland share of 21.8 %. This value represents the theoretical biophysical limit beyond which even maximum management intensification (5 cuts/year) on the entire remaining mineral grassland area cannot offset the production losses incurred by peatland rewetting.

In this context, X_{crit} is derived from the intersection where the maximum potential yield increment on mineral soils is exactly offset by the production losses incurred from peatland rewetting. At this specific peatland share, the net change in total forage production under a 5-cut regime is zero. As a theoretical benchmark, this threshold is independent of specific farm structures. Importantly, this theoretical limit assumes that the entire remaining mineral soil area of a farm's UAA is fully available for intensification. The representative farm systems (LPS, MPS, and HPS) in Fig. 4 are subsequently used to illustrate this threshold at specific peatland shares (5%, 17%, and 40%), and do not account for individual operational structures (e.g., animal forage demand, non-intensifiable land area).

In contrast, Table 3 reflects the actual operational forage balances of the LPS, MPS and HPS farm systems. These balances integrate farm-specific structural constraints that are not captured in the generic biophysical curves of Fig. 4, specifically individual livestock forage demands and the presence of non-intensifiable grassland areas (e.g., pastures and meadows). These areas are assumed to maintain static productivity, meaning they cannot directly contribute to the compensatory yield increases required on mineral soils to offset peatland losses.

The LPS model (5% peatland) illustrates the distinction between relative production change (Fig. 4) and absolute forage security (Table 3). As shown in Fig. 4, rewetting under the baseline regime (3 cuts) results in a minor biophysical production decline of approximately 5% relative to the status quo. However, Table 3 clarifies that this does not lead to an operational deficit, as the farm maintains a substantial absolute forage surplus of +28.0 t DM/yr. This is due to the high proportion of productive mineral soils (95 %) and a baseline supply that already exceeds dietary requirements. Since livestock density and associated forage demand remain constant, the yield loss on the small peatland fraction merely reduces the pre-existing operational buffer (from +41.7 to +28.0 t DM/yr) without causing a supply gap.

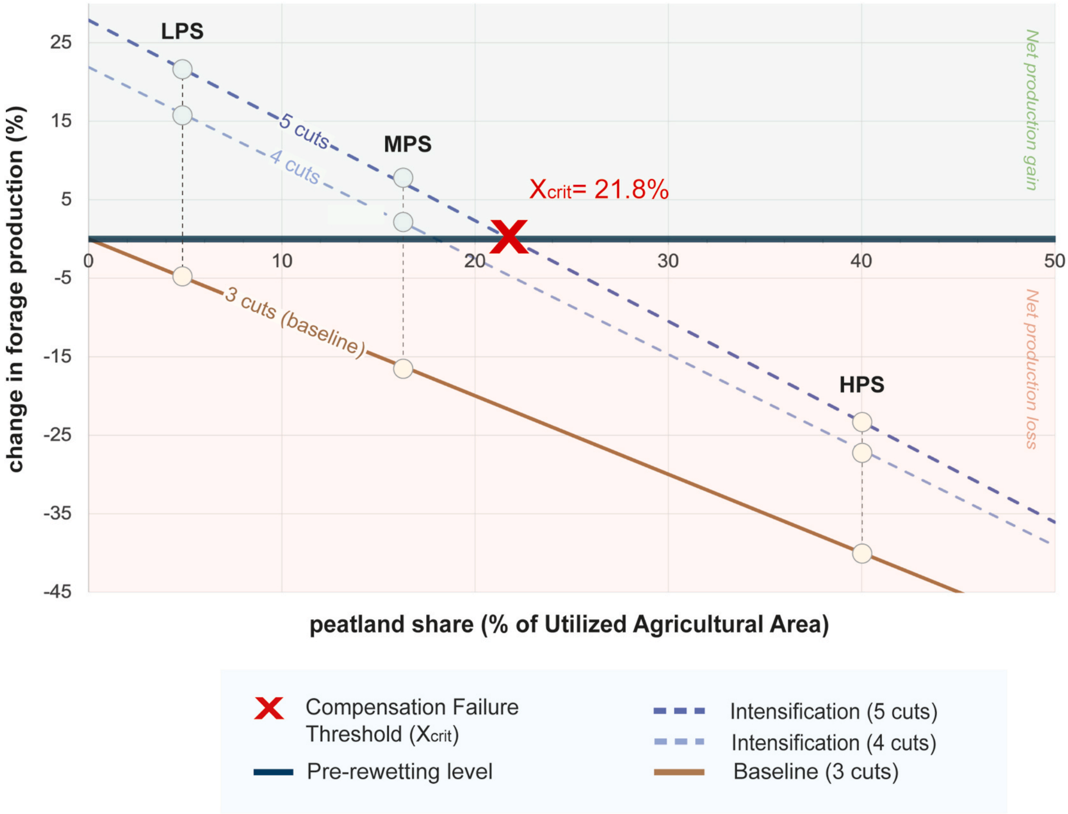

Fig. 4. Relative change in forage production in relation to a farm's peatland share. The horizontal line ($y = 0$) represents the biophysical status quo of the land prior to rewetting. The solid brown line represents the baseline regime (3 cuts), while dashed lines indicate intensification levels (4 and 5 cuts). Open circles mark the potential production levels at the specific peatland shares of the analyzed farm systems: LPS (5%), MPS (17%), and HPS (40%) with vertical dashed lines highlighting their positions. The threshold $X_{crit} = 21.8$ % marks the biophysical limit beyond which even maximum intensification (5 cuts) cannot compensate for production losses incurred by rewetting. Note: Peatland share is expressed as percentage of the total utilized agricultural area. The intensification curves represent a theoretical biophysical maximum, assuming that all remaining non-peatland area can be fully intensified. In contrast, actual farm-scale operational feasibility (Table 3) accounts for structural constraints, such as secondary grasslands (pastures and meadows) with static productivity that cannot be intensified and specific livestock forage demand. Thus, the operational tipping point for an individual farm may occur at a lower peatland share than the theoretical X_{crit} (e.g., if the available intensifiable area is limited).

Table 3

Total net forage production yields and forage balance under the 100% peatland rewetting scenario and different management intensities (t DM/yr).

	pre-rewetting (3 cuts)		3 cuts		4 cuts		5 cuts	
	P_{net}	bal.	P_{net}	bal.	P_{net}	bal.	P_{net}	bal.
LPS	245.2	+41.7	231.5	+28.0	-	-	-	-
MPS	199.9	+32.0	162.8	−5.1	195.9	+28.0	-	-
HPS	207.3	+37.2	113.4	−56.7	134.0	−36.1	139.6	−30.5

Note: LPS (Low Peat Share), MPS (Medium Peat Share), HPS (High Peat Share). Balance (bal.) = total net forage production (P_{net}) minus total forage demand. Positive (+) = surplus; negative (−) = deficit.

Consequently, the LPS farm system can achieve full rewetting (100 % of peatland area) without the need for management intensification.

In contrast, the MPS model (17 % peatland) exhibits higher sensitivity to rewetting. Under the 3-cut baseline regime, the production decline (Fig. 4), leads to an immediate operational deficit (−5.1 t DM/yr). This is a direct consequence of the higher peat share, and a smaller initial forage buffer compared to the LPS model. However, by transitioning the intensifiable mown grassland area to a 4-cut regime, the farm recovers its operational stability, achieving a surplus of +28.0 t DM/yr (Table 3).

The HPS model (40 % peatland) falls significantly into the compensation failure zone, as its peatland share is nearly double the theoretically derived X_{crit} (Fig. 4). The steep decline of the production curves in Fig. 4 at this share highlights that the yield increase required on the remaining mineral soils far exceeds the biophysical potential, even when the management is intensified to five cuts.

Furthermore, these curves show the diminishing effectiveness of intensification after the fourth cut, as indicated by the narrow gap between the 4-cut and 5-cut lines (Fig. 4).

This biophysical ceiling is also reflected in the operational results (Table 3). Even under maximum intensification (5 cuts), the HPS farm remains the only model facing an operational deficit of −30.5 t DM/yr (Table 3). The transition from 4 to 5 cuts on the intensifiable mineral grassland yields only a minor increase in total forage production (from 134.0 to 139.6 t DM/yr). This minimal gain confirms that for farms with such high peatland shares, the limited area of remaining mineral soil area combined with farm-specific constraints makes operational self-sufficiency unattainable.

The practical consequences for regional rewetting are that while LPS and MPS farms can feasibly maintain their forage balance through existing buffers or moderate intensification, thus making 100% rewetting of their peatland area achievable, the HPS model reaches its operational limit at approximately 50% rewetting of its peatland area, even under maximum intensification. When accounting for additional structural constraints like static pastures (Table 3), this operational tipping point may occur even earlier as the area available for intensification is further restricted.

To assess the broader impact on the Ammer area, these farm-scale forage balances were aggregated to the regional level. This aggregation represents a total peatland area of 12,420 ha being set aside for rewetting, while a total mineral soil area of 48,201 ha is available across all farm clusters. Of the mineral soil, 40,116 ha (83%) consist of intensifiable mown grassland, while the remaining mineral soil area (8,085 ha) consists of pastures and meadows with static productivity. The total regional forage surplus, calculated by multiplying the surpluses of the LPS (at 3 cuts; n = 577) and MPS (at 4 cuts; n = 577) models, yields a cumulative surplus of 32,312 t DM/yr. In contrast, the regional deficit derived from the HPS cluster (n = 578, at 5 cuts) amounts to 17,599 t DM/yr.

While individual HPS farms face a structural inability to maintain forage self-sufficiency through internal resources, the cumulative regional surplus exceeds the total regional deficit by a factor of nearly 1.8.

These findings provide the biophysical basis for evaluating regional forage distribution strategies and management trade-offs, which are further addressed in the discussion.

4. Discussion

The results of this study provide critical quantitative insight into the substantial GHG mitigation potential of peatland rewetting, alongside the inevitable trade-offs in farm management and forage self-sufficiency. Our findings confirm that peatland emissions exert a dominant influence on the CF of dairy farming (Müller et al., 2025; Müller et al., 2026) in regions characterized by grassland dominance and a high prevalence of organic soils. This effect is particularly pronounced in MPS and HPS farm systems, where peatland emissions constitute nearly half or more of the total CF. While a full regional CF up-scaling exceeds the scope of this study, the observed average reduction of ∼84 % in peatland-derived GHG emissions through their rewetting underlines the strategic importance of this measure and represents its potential to contribute to the achievement of regional and national climate targets (Reise et al., 2024) by minimizing high emission sources.

Crucially, the compensation strategy was shown to be feasible for LPS and MPS farm systems. As illustrated by the relative change in production (Fig. 4), LPS farms can maintain their operational status quo without intensification (retaining 3 cuts), as their minor theoretical production decline (∼5%) is fully buffered by existing yield surpluses. In contrast, for MPS farms, the transition to a 4-cut regime offsets the initial production loss and results in a net increase in forage availability, enhancing operational resilience. This illustrates that for MPS farm systems, moderate intensification acts as a primary mechanism for achieving stability and even increasing forage safety margins. While emissions from intensified grass production increase for MPS farms, this rise is proportionally small compared to the magnitude of the GHG savings achieved through rewetting.

This strategic coupling of peatland rewetting with the intensification of production on mineral soils reflects the ‘land sparing’ concept (Lamb et al., 2016). By concentrating high-intensity production on resilient mineral soils to ‘spare’ organic soils for maximum ecological restoration, the farm system optimizes the trade-off between food production and GHG mitigation (Lamb et al., 2016). This contrasts with a ‘land sharing’ approach (Lamb et al., 2016), which would involve moderate, extensive use across all soil types. Our results suggest that land sparing might be the superior strategy for peatland regions, as it allows for a near-complete reduction of peatland-derived CO_2 emissions, that could not be achieved through medium-intensity drainage.

Despite the theoretical advantages of land sparing, the application of this strategy reveals a clear biophysical limit for the HPS model. As its peatland share (40%) significantly exceeds the critical compensation failure threshold (X_{crit}) of 21.8%, the relative production decline at the baseline management exceeds the farm's compensatory capacity.

It is critical to distinguish between the theoretical biophysical potential of the land (Fig. 4) and the operational reality of the farm (Table 3). While X_{crit} identifies a theoretical compensation limit where rewetting 100% of the peatland area is balanced by intensification on the remaining area, the actual operational tipping point might occur at even lower peatland shares than the 21.8% due to farm-specific constraints (e.g., non-intensifiable land, high livestock forage demand).

Consequently, individual farm structures may require even more conservative restoration targets to maintain forage self-sufficiency than the generic X_{crit} suggests.

Ultimately, even under maximum intensification, the HPS model faces a structural deficit, restricting its feasible rewetting extent to approximately 50% of its peatland area if internal forage self-sufficiency must be maintained. The marginal yield gains observed when transitioning from 4 to 5 cuts further confirm a biophysical yield ceiling on mineral soil productivity that renders full rewetting unfeasible for the HPS model. This finding underscores the argument by Girkin et al. (2023) that peatland management is strongly context-dependent (Girkin et al., 2023). While 'land sparing' remains biophysically viable for farms with lower peat share, the thresholds reached in the HPS model demonstrate that biophysical and structural constraints necessitate site-specific compromises over a uniform transition strategy (Girkin et al., 2023).

To evaluate the broader scalability of these findings, the identified X_{crit} must be contextualized within the regional farm structure. In the Ammer catchment, the average peatland share per farm is approximately 24%, already exceeding the biophysical limit for internal compensation. Moreover, approximately 39% of all dairy farms in the Ammer catchment lie above this threshold, meaning the 'land-sparing' approach cannot be realized within their individual farm boundaries.

Despite the farm-level constraints, regional aggregation reveals a significant divergence between individual limits and systemic resource availability. The cumulative forage surplus from the LPS and MPS clusters (32,312 t DM/yr) is theoretically sufficient to cover the total structural deficit of the HPS cluster (17,599 t DM/yr). This regional cooperation, underpinned by a regional surplus-to-deficit ratio of 1.8, could even enable HPS farms to achieve 100 % rewetting by utilizing the surplus of neighboring farms, thereby realizing the high regional GHG mitigation potential inherent to HPS model. However, this regional aggregation represents a simplified farm model-based scaling. While the aggregated regional peatland share of 20.5% (12,420 ha) aligns closely with GIS-based catchment average of 18.9% for the total regional grassland extent (Fig. 1), the calculation assumes these models accurately reflect average regional conditions and does not fully account for the spatial heterogeneity of real-world farms. Furthermore, the theoretical nature of this regional concept must be noted, as its realization depends on logistical coordination and the willingness of farms to implement this strategy.

Nevertheless, a supplementary inventory analysis (Supplementary Material section S6) confirms that the GHG burden associated with forage redistribution and transport remains negligible (0.009 kg CO_2-eq/kg FPCM for the 30 km long distance scenario; Table S5) compared to the GHG mitigation achieved through rewetting (Table S4). Thus, while this regional aggregation identifies a systemic opportunity for compensation, these findings serve as a strategic framework requiring site-specific validation at the individual farm level.

Beyond these aggregational simplifications, the robustness of the regional outlook is further linked to the inherent uncertainties of the LDNDC simulations of grassland yields and N_2O fluxes. While LDNDC is robustly calibrated and validated (Boos et al., 2024), such models necessarily simplify complex ecological processes and may not capture the full spatio-temporal variability driven by microclimates or soil heterogeneity. This uncertainty, reflected in the Root Mean Square Error (RMSE) of 0.94 t ha^{-1} yr^{-1} (Boos et al., 2024), directly propagates into the calculated X_{crit} and resulting forage balances.

Furthermore, while LDNDC has demonstrated its capability in site-specific studies of organic soils (Kajasilta et al., 2025), the framework currently lacks a validated standard parametrization for organic soil dynamics suitable for broader regional applications. This limitation, combined with the absence of high-resolution WT data for the study area, necessitated the use of mineral soil yields as a baseline proxy for all forage calculations. Consequently, the model potentially underestimates baseline production on peatlands and, thus, the magnitude of forage losses related to rewetting. This directly affects the X_{crit} threshold; if the actual productivity on peatlands is higher than on mineral soils, the forage gap per rewetted unit would be larger, meaning X_{crit} would be reached at a lower peatland share than 21.8%.

To verify that yield simulations for the intensification scenarios (e.g., 4 and 5 cuts) were representative for the entire study area, additional test simulations were conducted. In these simulations, 4-cut and 5-cut regimes were applied to all grassland fields in the catchment, regardless of their observed management. The resulting yields (9.97 t DM ha^{-1} yr^{-1} for 4 cuts; 10.1 t DM ha^{-1} yr^{-1} for 5 cuts) showed only marginal differences compared to the yields derived from the specific field subsets (9.62 t DM ha^{-1} yr^{-1} for 4 cuts; 10.09 t DM ha^{-1} yr^{-1} for 5 cuts). This consistency confirms that the subsets used in our scenarios are representative of the regional yield potential and do not introduce a selection bias.

The use of LDNDC represents a significant advancement over standard IPCC Tier 1 approaches, because it captures non-linear N_2O dynamics, which is crucial under high intensification. Since high N-inputs and frequent harvesting cycles disproportionally alter soil N dynamics, accounting for these non-linearities is essential for a robust assessment.

While any model-based estimation carries risk of overestimating yields or underestimating N_2O fluxes (Scheer et al., 2025), our approach provides an improved site-specific representation of the trade-offs involved. For instance, the marginal yield gains of a fifth cut for HPS farms (increasing only from 134.0 to 139.6 t DM/yr) suggest that the ecological and economic costs of the fifth harvest may outweigh its benefits. Specifically, the transition from 4 to 5 cuts resulted in a nearly threefold increase in NH_3 volatilization (from 8.91 to 23.21 kg N ha^{-1} yr^{-1}), significantly increasing risks of eutrophication and acidification (Table S1) (Galloway et al., 2003). Furthermore, a 5-cut regime increases operational risks by reducing farm resilience against increasing climate-driven weather anomalies, such as droughts or extreme wet events (Chomel et al., 2022; Chang et al., 2021). Given the marginal yield increases alongside the substantial regional surplus, a 4-cut regime represents a more resource-efficient and resilient strategy, avoiding the disproportionately higher N_2O fluxes and reactive N losses associated with extreme intensification (Shcherbak et al., 2014).

The precision of such GHG assessments remains closely linked to the temporal resolution of the environmental drivers. A crucial limitation is the reliance on a single mean annual WTD. Given that GHG fluxes are non-linearly driven by hydrological fluctuations, using a single annual mean WTD can lead to averaging errors (Tiemeyer et al., 2020b). Future refinements should prioritize monthly or seasonal WTD data. Additionally, the temporal discrepancy between the LCA reference year (2019) and the WTD data (2020) must be noted, although 2020 was a representative hydrological year for the pre-alpine region (Friedrich, 2025). Nevertheless, years with higher or lower precipitation totals and differing patterns of evapotranspiration, could alter the emission estimates (Friedrich, 2025).

Furthermore, peatland rewetting involves a management choice between avoiding CO_2 emissions from drainage while potentially increasing CH_4 emissions (Günther et al., 2020). However, considering the radiative forcing and atmospheric lifetimes, the warming effect of CH_4 as strong but short-lived GHG, does not undermine the long-term climate benefits of rewetting, as postponing action only increases the warming effect of continued CO_2 emissions (Bockermann et al., 2024; Günther et al., 2020).

While our model assumes rewetted peatland as non-productive, paludiculture could provide biomass for insulation or energy production, offering a socio-economic alternative (Joosten et al., 2015; Tanneberger et al., 2022). However, its net impact remains uncertain, as the lack of disaggregated EFs for varying management intensities suggests a potentially lower GHG mitigation potential compared to full peatland restoration (Bianchi et al., 2021).

Additionally, moisture-adapted forage production on wet grasslands (WTD = −0.200 m) represents a direct compensation pathway. Practical experience in Bavaria confirms the feasibility of stable stands using specific seed mixtures (e.g., the BQSM®-W-1M mixture in Bavaria) based on species like reed fescue (*Festuca arundinacea*) and reed canary (*Phalaris arundinacea*) under wet conditions (Landwirtschaft, 2025). While DM yield and protein content may decline by 15 % (N-yield by 30 %) compared to moderately moist grassland, these yields are multi-annually stable and provide valuable structural supplementation for young stock and dry cows (Bayerische Landesanstalt für Landwirtschaft, 2025). Although moisture-adapted forage production ('land sharing') significantly reduces emissions compared to drained conditions, its mitigation potential remains lower compared to full restoration ('land sparing'), where agricultural management and associated inputs are absent (Tiemeyer et al., 2020b; Bianchi et al., 2021)

Notably, even if occurring forage deficits would be covered entirely by external imports instead of implementing internal compensation measures (e.g., moisture-adapted forage production), the overall CF would remain substantially below the baseline CF (e.g., without rewetting) (Table S5). This reinforces the robust GHG reduction potential of rewetting, particularly at HPS farms.

Beyond GHG mitigation, rewetting offers substantial co-benefits for biodiversity, aligning with the targets of the European Biodiversity Strategy 2030 and the EU Nature Restoration Plan as central pillar of the Europea Green Deal. Revitalizing these ecosystems leads to an increase in habitat specialists and overall species richness, evidenced by the return of endangered and previously lost bird species (e.g., *Zapornia pusilla, Crex crex, Gallinago gallinago*) (Tanneberger et al., 2022; Renou-Wilson et al., 2019).

However, large-scale implementation is dependent on overcoming complex hydrological, legal, and economic hurdles (Wichmann et al., 2024b). First, the success of restoration is fundamentally bound to local water availability. In the context of increasing climatic variability and summer droughts, the technical challenge of redirecting and maintaining high WTs is significant (Wichmann et al., 2024a). Furthermore, large fragmented land ownership commonly found in Bavaria, necessitates the promotion of mechanisms like voluntary land consolidation and area exchange (which is already offered in Bavaria) (Gosch et al., 2024).

The transition also depends on economic viability (Tanneberger et al., 2021), requiring long-term net income for farmers from biomass sales and adapted EU Common Agricultural (CAP) funding (Jurasinski et al., 2020; Tanneberger et al., 2021; Wichtmann et al., 2016). Specifically, funding criteria must prioritize the activity of rewetting and subsequent management over specific plant species (Tanneberger et al., 2022). However, developing paludiculture value chains is a long-term process, and the organizational burden of adopting entirely new production systems remains a major barrier for farmers (Wichmann et al., 2024a).

While our regional peatland-based farm systems provide a strong preliminary framework for regional climate policy planning by offering quantitative insights beyond individual farm analyses, practical implementation requires a refined, farm-specific approach (Wichmann et al., 2024b). This also necessitates moving beyond the binary "full rewetting vs. no rewetting" perspective towards a spectrum of diversified restoration intensities. Such site-specific management needs to account for the unique hydrological and socio-economic constraints of individual farmers to ensure a feasible transition.

Importantly, this study assumes that milk production must be maintained at current high levels, which necessitates the identified compensation requirements. However, this premise could be fundamentally questioned. A broader societal discussion regarding climate neutrality in the agricultural sector should consider whether a reduction in milk consumption might be necessary to allow for lower production volumes. This could simplify the achievement of climate goals and reduce pressure on intensification and resource use, while avoiding the risk of carbon leakage to other regions.

5. Conclusion

Our study demonstrates that regional rewetting of agricultural peatlands is a powerful lever for significantly reducing carbon footprints of peatland-based dairy farming. Our study shows that reconciling climate targets with dairy production can be biophysically feasible when managed strategically. By identifying the critical compensation failure threshold ($X_{crit} = 21.8\%$), we provide a first quantitative benchmark that generically defines individual farm-level limits while demonstrating that regional forage surpluses can theoretically fully offset local deficits through inter-farm cooperation.

To bridge the gap between these model-based benchmarks and on-farm reality, a shift from uniform strategies to flexible, site-specific management is required. By acknowledging water availability and socio-economic hurdles, the X_{crit} framework can help in political decision-making to prioritize restoration where regional cooperation is possible, ensuring that peatland restoration and agricultural production remain regionally compatible.

Future research should investigate an even broader spectrum of restoration intensities and water levels to meet practical implementation. Assessing the multi-functional trade-offs between agricultural productivity, GHG mitigation, and biodiversity recovery will be essential to develop holistic management strategies that not only optimize ecological resilience and regional food security but also meet farmers' reality.

CRediT authorship contribution statement

Anna-Lena Müller: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Guillermo Pardo:** Conceptualization, Data curation, Formal analysis, Methodology, Resources, Writing – review & editing. **Sylvia Helena Annuth:** Data curation, Visualization, Writing – review & editing. **Sebastian Friedrich:** Resources, Writing – review & editing. **Carolin Boos:** Methodology, Software, Writing – review & editing. **David Kraus:** Data curation, Resources, Software, Writing – review & editing. **Ralf Kiese:** Conceptualization, Supervision, Writing – review & editing. **Clemens Scheer:** Conceptualization, Project administration, Supervision, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.130028.

Abbreviation list

C	Carbon
CAP	Common Agricultural Policy
CF	Carbon Footprint
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-eq	CO_2-equivalents
DM	Dry Matter
EF	Emission Factor
FAO	Food and Agriculture Organization
FPCM	Fat and Protein Corrected Milk
FU	Functional unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HPS	High Peatland Share
InVeKoS	Integriertes Verwaltungs-und Kontrollsystem
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDNDC	LandscapeDNDC
LfL	Bayerische Landesanstalt für Landwirtschaft
LMC	Land Management Change
LPS	Low Peatland Share
LU	Land Use
LUC	Land Use Change
LULUCF	Land Use, Land-Use Change and Forestry
ME	Metabolizable Energy
MPS	Medium Peatland Share
N	Nitrogen
NH_3	Ammonia
NO_3^-	Nitrate
N_2O	Nitrous Oxide
RMSE	Root Mean Square Error
UAA	Utilized Agricultural Area
TERENO	Terrestrial Environmental Observatories
WT	Water Table
WTD	Water Table Depth
X_{crit}	Compensation Failure Threshold

Data availability

Data will be made available on request.

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