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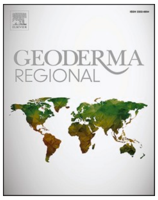

Optimizing soil multifunctionality of coastal peat grasslands

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ABSTRACT

Soils have the capacity to provide a wide range of soil functions that can help address socio-environmental challenges, such as climate change and biodiversity loss. Here, we apply the Functional Land Management framework aimed at optimally balancing supply and demand of soil functions at a landscape-scale to drained coastal peat (*Histosols*) in Friesland, The Netherlands. We focus on the supply side by assessing the capacity of grassland peat soils with different topsoil types to provide five soil functions: climate regulation, habitat provision, nutrient cycling, water storage, and primary productivity. A field campaign was conducted in March 2022 to collect data on soil, water, vegetation, and management from 30 grasslands mapped as peat on the national soil map (Basisregistratie Ondergrond). Results revealed significant differences in above and belowground field conditions between peat with different topsoil types. Peat soils with a mineral cover are predominantly used as grasslands for dairy farming, with a clear differentiation in functioning between fields managed by organic and conventional farmers. Peat soils without a mineral cover are generally owned by nature organizations and managed as semi-natural grasslands aimed at optimizing aboveground habitat provision. Our results show that conventional agricultural management, including deep drainage and high fertilizer inputs, results in moderate to high nutrient cycling and primary productivity, along with low climate regulation, water storage and habitat provision. Extensification results in a decrease in primary productivity and nutrient cycling along with a strong increase in climate regulation, water storage, and habitat provision. To optimize landscape-scale provision of soil functions, we recommend promoting soil multifunctionality while maintaining moderately high yields on peat with a mineral cover. To benefit from the unique and yet unmet potential of peat soil for climate regulation and water storage, we recommend tailoring management of peat soils without a mineral cover to fully restore natural peatlands.

1. Introduction

The anthropogenic impact on the environment has increased exponentially over the last century, driven by a growing global population and high-consumption lifestyles (Hurni et al., 2015; FAO, 2015; FAO, 2020). Reversing trends in climate change, biodiversity loss, and soil degradation while ensuring food security for a growing population is among the greatest challenges of our time (Bos et al., 2013; Rojas et al., 2016; Kraamwinkel et al., 2021; Löbmann et al., 2022). Healthy soils are central to these efforts, providing five key functions: Climate Regulation (CR), Habitat Provision (HP), Nutrient Cycling (NC), Primary Productivity (PP), and Water Regulation (WR) (Schulte et al., 2014; Amundson et al., 2015; EASAC, 2018; Vogel et al., 2018). Historically, agricultural soils have been managed primarily to maximize PP, often at the expense of other functions (Schulte et al., 2014; Creamer et al., 2022).

Increased awareness and international agendas on climate, soil health, and biodiversity are shifting the focus toward soil multifunctionality (Schulte et al., 2014; Veerman et al., 2020; Montanarella and Panagos, 2021; Faber et al., 2022). The Functional Land Management (FLM) framework was developed to optimize soil functioning by optimally balancing the demand for and potential supply of soil functions at a landscape scale, considering factors such as soil type, land use, and climate conditions (Schulte et al., 2014; Schulte et al., 2015). The FLM framework has yielded a multitude of publications and inspired the creation of an open-access tool (Soil Navigator) to assess and promote soil functions on mineral crop- and grasslands in Europe (Debeljak et al.,

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2019). However, organic (peat) soils remain underrepresented, with to the best of our knowledge only one FLM study, a review by Coyle (2016), addressing this soil type. The unique and complex hydrological and soil properties of peat (Weil and Brady, 2017), which depend strongly on drainage state (Joosten and Clarke, 2002), as well as their relatively limited global distribution (Parish et al., 2008), may explain this underrepresentation. This study aims to address this gap by extending the relevance of the FLM framework to include peat soils, advancing efforts to optimize soil multifunctionality beyond mineral soils.

Peat soils form through the incomplete decomposition of plant material under waterlogged, acidic, or cold conditions, leading to a buildup of organic carbon (Weil and Brady, 2017). Though they cover just 3 % of global land area, peat soils store 30 % of global soil organic carbon, provide habitats for specialized species, and regulate water storage and filtration (Parish et al., 2008; Kreyling et al., 2021; Verhoeven and Setter, 2010). However, widespread drainage is rapidly degrading peat soils (Schothorst, 1977; Schils et al., 2008). While drainage improves aeration and load-bearing capacity, boosting PP (Janssen et al., 2023), it also accelerates organic matter oxidation, causing subsidence, high CO_2 emissions, reduced water retention, and habitat loss (Weil and Brady, 2017; Verhagen et al., 2009; Kreyling et al., 2021). Prolonged oxidation transforms organic soils into mineral soils within decades to centuries (Rienks et al., 2002; de Vries et al., 2014). In coastal areas like The Netherlands, drainage-induced subsidence has triggered flooding and mineral sediment deposition atop the peat layer (Polak, 1929; Pierik et al., 2017; Joosten et al., 2017). These processes have created diverse peat types, with and without a mineral cover, impacting soil characteristics and functioning.

The Frisian peat region in Friesland is one of the most deeply drained peat areas in The Netherlands. Approximately 70 % of this region is used for conventional production grasslands in dairy farming. Deep drainage (90–120 cm below ground) has caused soil subsidence rates of ~1 cm/year and annual CO_2 emissions of ~25 tons/ha (Van den Akker et al., 2018; Agrimatie, 2022). The region currently lies 1–3 m below sea level (Fryslân, 2021). This creates natural drainage from higher-lying mineral soils into the peat meadows, reducing drought resilience across Friesland and increasing salinization risks in coastal areas (Wetterskip Fryslân, 2021; Hendriks et al., 2023). Deep drainage and high nutrient inputs have also decreased biodiversity and negatively affected water quality (Hendriks et al., 2023). A minority of production grasslands in Friesland are managed by organic farmers (CBS, 2023). These fields have lower nitrogen inputs and are less deeply drained compared to conventional grasslands (Agrimatie, 2022). Around 15 % of the Frisian peat meadow area is managed as semi-natural grasslands by nature organizations (Klaassen et al., 2018; Van den Akker et al., 2018). Dutch semi-natural grasslands typically feature low fertilizer inputs, low mowing frequencies, and shallow drainage (Deru et al., 2018).

In the context of FLM, the Frisian peat region faces significant local and global demands for soil functions. Local demands include improved water storage to enhance drought resilience and reduce salinization, a balanced nutrient cycle to minimize nitrogen losses, and high primary productivity (Wetterskip Fryslân, 2021; Klaassen et al., 2018). Global demands include high climate regulation to mitigate climate change and habitat provision to combat biodiversity loss (Kreyling et al., 2021; Verhagen et al., 2009; FAO, 2020). The capacity of drained Frisian peat soils to meet these demands remains poorly understood due to the variability in drainage conditions and soil properties shaped by natural and anthropogenic influences. This study seeks to fill this knowledge gap by applying the FLM framework to the Frisian peat meadow area and addressing two key research questions:

1. What is the capacity of drained coastal peat soils in Friesland, with varying topsoil types (peat, clay, and loam) and management strategies (semi-natural grassland, organic, and conventional dairy farming), to perform five key soil functions?
2. Which soil functions should be prioritized on these peat soils to optimize landscape-scale provision in Friesland?

We hypothesize that drained peat soils with and without a mineral cover will perform differently due to inherent differences in their soil characteristics. Peat without a mineral cover is expected to have lower climate regulation, as it is more prone to oxidation, but higher nutrient cycling and water storage capacity compared to mineral-covered peat. Both are anticipated to perform similarly in primary productivity and habitat provision. Furthermore, we expect management tailored to peat soils without a mineral cover will need to focus on enhancing their unique potential for climate regulation and water storage to optimize landscape-scale soil functions.

2. Methods

2.1. Field selection

We selected 30 permanent peat grasslands in Friesland, The Netherlands (Fig. 1), from national soil (BRO, 2022) and land use (BRP, 2022) maps to evaluate their ability to perform five key functions. To capture the diversity of peat types and water management strategies, fields were selected based on the following sub criteria: 1) classification as one of the main Frisian peat types (Vlierveen, Weideveen, Koopveen, or Waardveen), 2) varying grassland management (semi-natural, organic agriculture, or conventional agriculture), and 3) different drainage intensities (low, medium, high). Drainage classes are based on the average target ditchwater level (cm bgl) during the growing season and the water management infrastructure present on the field (drainage pipes, ditches and/or gullies). Fields with a low (high) drainage intensity are subject to shallow (deep) drainage. For a full description of peat types, management strategies, and drainage classes, see Supplementary Materials 1.

2.2. Variable selection

Soil functions cannot be directly measured in the field (Creamer et al., 2022). Instead, they are assessed by measuring and evaluating variables that play a central role in, or act as indicators of (part of) the function (Bünemann et al., 2018; Creamer et al., 2022). To include all variables central to the five soil functions, we selected the input variables required to run the Soil Navigator, a tool developed to assess soil functioning on agricultural soils (Debeljak et al., 2019; Creamer et al., 2019). Variables include chemical, physical, and biological soil characteristics, hydrological conditions, vegetation characteristics, and detailed accounts of past and present management practices covering fertilizer use, water management, grazing, mowing, plowing, and liming (Supplementary Materials 2 and 3). In addition, indicator variables were selected based on their ability to represent the provision of a specific function. CO_2 emission and topsoil SOM were selected as indicators for CR. CO_2 emission was selected, despite its high spatial and temporal variability, as it is currently the main form of carbon losses from Dutch drained grassland peat (van den Pol-van Dasselaar et al., 1999; Verhagen et al., 2009; Van den Akker et al., 2018). In addition, closed chamber CO_2 measurements are in good agreement with soil subsidence rates on Dutch peat soils (Van den Akker et al., 2010), suggesting that CO_2 emissions accurately represent carbon losses from these fields. Total nitrogen input, soil nitrogen content, and nitrogen content of English ryegrass blades were selected as indicators of NC, to determine how much of the nitrogen applied to the soil is cycled and taken up by the plants (Schröder et al., 2016). Abundance and diversity of dicotyledons were selected as indicators for aboveground HP on peat grasslands (Deru et al., 2018). The combined Shannon Index of earthworms, enchytraeids, and nematodes was chosen as an indicator for belowground HP, reflecting the diversity of species within the aforementioned faunal groups (Shannon, 1948; Vazquez et al., 2021). Groundwater depth (cm

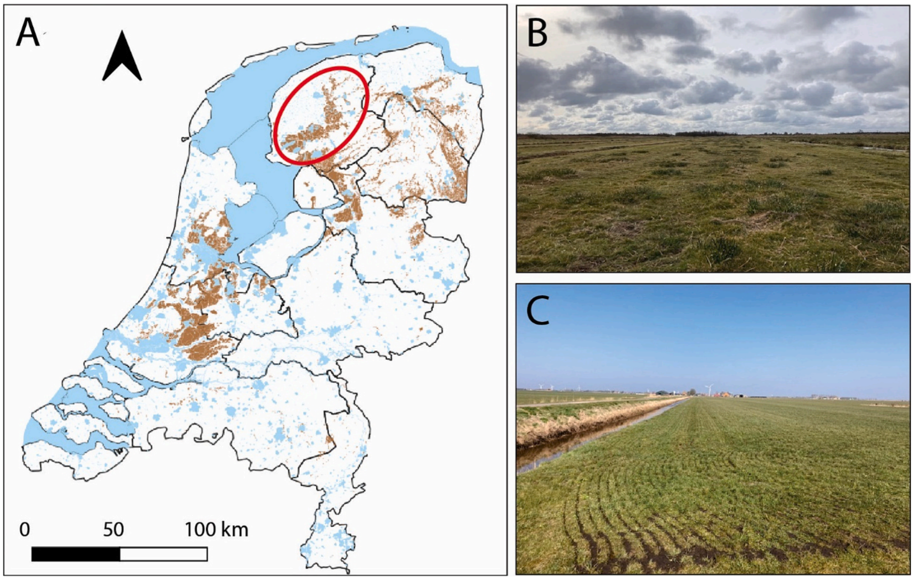

Fig. 1. A) Map of the Netherlands showing peat areas (brown) and the study area in Friesland (red circle). B) Semi-natural grassland on peat. C) High-production grassland on peat. Map: pdok.nl. Photos: C. T. Kraamwinkel.

b.g.l.) and soil moisture (%) of the top 10 cm were selected as indicators for WS. Despite being sensitive to (water) management practices and local weather conditions, these indicators are direct measures of soil water storage (Weil and Brady, 2017). Average yearly yield in ton DM/ha was selected as a proxy for PP, following studies by Sandén et al. (2019) and Vazquez et al. (2021).

2.3. Data collection

Fieldwork was conducted in March 2022 to minimize the seasonal effect and influence of spring-time management practices. Most semi-natural and organic production grasslands were sampled early in the month, before the breeding season, due to meadow bird protection measures. This timing introduced a slight seasonal and fertilizer bias, which was checked and accounted for (Supplementary Materials 4). Only groundwater depth (slight seasonal effect on all fields) and ryegrass nutrient content (fertilizer effect on 4/30 fields) were affected and are discussed with caution throughout this paper.

Measurements were performed on two sites in the field: one at the edge at ~5 m from the ditch and one in the middle. A hand auger and measuring rod were used to construct a soil profile to a depth of 135 cm bgl, and measure the groundwater and rooting depth at both sites. Percentage dicotyledonous ground cover and number of dicotyledon species were examined in two squares of 0.25m^2. CO_2 emission was measured once at both sites, using a closed chamber and a Vaisala handheld CO_2 meter version GM70. The measuring time was set at 15 min and the sampling interval at 10 s. Infiltration rate was measured during a 30 min timespan using a double ring infiltrometer. The highly heterogeneous variables soil moisture, vegetation height, and penetration resistance were measured on a 20 m transect (10 measuring points) from the ditch toward the middle of the field. Soil and grass samples were collected from each site separately and combined into a composite sample prior to analysis in the lab. Soil samples were taken from the top 10 cm of the soil, since this is the most important layer for grassland vegetation and soil life such as nematodes, enchytraeids, micro-arthropods, and epigeic earthworms (FAO, 2020). Earthworms were sampled on a total of six sites on the field to a depth of 20 cm b.g.l., to allow for the inclusion of deep dwelling endogeic earthworms (Onrust, 2017). English ryegrass blades were dried, ground and analysed on an Elemental Analyser for total C and N. Soil samples were analysed in the lab to determine the dry-bulk-density (dbd), grain size distribution, pH, salinity, CEC, SOM, total C and N, and plant available Fe, Mg, and K. Earthworms and Enchytraeids were counted and identified to species level, nematodes to genus level. Phospholipid Fatty Acid Analysis (PFLA) was performed to determine the total bacterial and fungal biomass. For a detailed account of all methods used during the field and lab campaign and an overview of variables, see Supplementary Materials 2 and 3.

2.4. Soil classification

Peat soils are notorious for being poorly mapped on (inter)national soil maps due to their high spatial and temporal heterogeneity following drainage-induced peat oxidation and flooding (de Vries et al., 2014; Tanneberger et al., 2017). An FLM assessment requires accurately identifying the (top)soil types in a region, as they significantly influence both current and potential functioning. Preliminary data exploration revealed substantial variation in mineral cover thickness, grain size distribution, and SOM content in the topsoil across the 30 sampled fields (Supplementary Materials 5), highlighting the need for a soil classification prior to analysis. Soils were classified according to the classification tree developed and outlined in Fig. 2, based on the definition of peat soil (de Bakker and Schelling, 1989), used in the Dutch soil classification system (Basis Registratie Ondergrond BRO, 2022), and the USDA textural triangle (USDA, 2017).

2.5. Statistical analysis

Fields were clustered into three groups based on outcomes of the soil classification: 1) peat - no cover ($n = 10$), 2) peat - clay cover ($n = 11$), and 3) peat - loam cover ($n = 9$). These groups reflect the main peat types in the Frisian peat meadow and will be used to assess the supply of soil functions in the region. Since (water) management significantly impacts current functioning (Schulte et al., 2014; Coyle et al., 2016), frequency histograms were created to show the number of fields within each peat group under specific (water) management regimes. For each measured variable, we tested for statistical significance between the three peat groups using the nonparametric Wilcoxon rank sum test, suitable for non-normally distributed, unpaired data as well as small or uneven sample sizes (Weaver et al., 2017; Boslaugh and Watters, 2008). To explore interrelations among soil, water, and vegetation characteristics in the Frisian peat meadow, Non-metric Multi-Dimensional Scaling

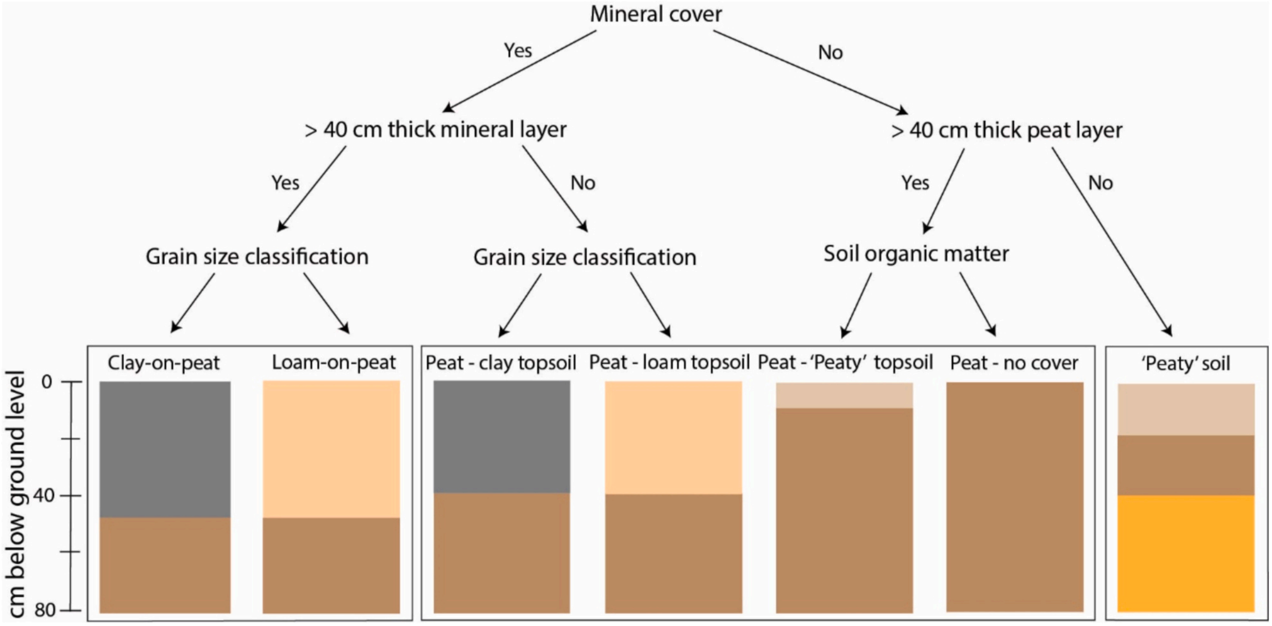

Fig. 2. Decision tree for classifying Dutch coastal peat soils, based on de Bakker (1989) and the USDA texture triangle (2017). Boxes from left to right: mineral soils on top of a peat layer, peat soils with/without a mineral cover, and peaty soil. Grey: clay, beige: loam, brown: peat, yellow: sand.

(NMDS) analysis was performed using the VEGAN package for R Software (Oksanen et al., 2022; R Core Team, 2022). Before the NMDS analysis, variables with a wide range of values, such as infiltration rate and thickness of the mineral cover, were square root transformed. Next, all variables were Hellinger transformed to normalize the data and reduce the effect of extreme values. NMDS ordination was calculated in three dimensions using physical, chemical, and biological soil properties, vegetation characteristics, and hydrological conditions. The fit of the NMDS analysis was evaluated and expressed as a stress level, where a stress <0.1 indicates a good fit and a stress >0.2 a poor fit (Dexter et al., 2018). To visualize how the distribution of variables relates to the three peat groups, ellipses with a circumference equal to the standard deviation of the three peat groups were added to the plot. Permanova was used to test the level of significance between the peat groups (Oksanen et al., 2022). Finally, management variables were passively fitted to the ordination plot.

Table 1
Categories and threshold values defined for all indicator variables in the context of Dutch peat soils, predominantly based on previous studies (see Supplementary Materials 7).

Function	Variable	Unit	Categories
CR	CO_2 emission	tons/ha*year	<15 = low 15–25 = moderate >25 = high
CR	SOM	%	<25 = low 25–40 = moderate >40 = high
PP	Yield	tons/ha*year	<8 = low 8–9.5 = moderate >9.5 = high
NC	N input	kg/ha*year	<100 = low 100–250 = moderate >250 = high
NC	N soil	%	<1.3 = low 1.3–1.5 = moderate >1.5 = high
NC	N grass	%	< 3.5 = low 3.5–4.0 = moderate >4.0 = high
HP	Dicotyledonous cover	%	< 10 = low 10–20 = moderate >20 = high
HP	Dicotyledon species	species/0.25m^2	<2 = low 2–4 = moderate >4 = high
HP	H soil fauna	–	<2.3 = low 2.3–2.5 = moderate >2.5 = high
WS	Soil moisture	%	<55 = low 55–75 = moderate >75 = high
WS	Groundwater depth	cm below ground level	<50 = low 50–90 = moderate >90 = high

2.6. *Present-day soil functioning*

Indicator variables were used to estimate the present-day capacity of the different peat groups to perform the five soil functions. First, to account for variation in management between the fields, the peat groups were divided into sub-groups of management: semi-natural grasslands, organic agriculture, and conventional agriculture. Only groups containing more than 2 fields were selected for further analysis, resulting in 5 peat groups: 1) no cover - semi-natural ($n = 7$), 2) clay cover - organic ($n = 5$), 3) clay cover - conventional (n = 5), loam cover - semi-natural ($n = 3$), and 5) loam cover - conventional ($n = 6$). Next, median values of indicator variables were normalized into scores (low, medium, high) based on thresholds set for Dutch peat grasslands (Table 1). Most thresholds were derived from literature (Supplementary Materials 7), except for dicotyledon species and soil moisture, that have thresholds based on data from this study. For dicotyledon species, because it was measured in species/0.25m^2, a unit that has not previously been used in studies on Dutch grasslands. For soil moisture, because it is too dependent on seasonality and weather conditions to determine meaningful thresholds at a national level (Weil and Brady, 2017). The context of Dutch peat grasslands was selected due to its distinctive soil characteristics and (water) management strategies. As a result, scores are assigned specifically within the narrow framework of production grasslands on drained coastal peat. Different scores would apply if these fields were evaluated alongside natural peat ecosystems.

Scores of indicator variables were integrated into end scores for each soil function using weight factors (Supplementary Materials 8 and 9). CO_2 emissions and SOM contributed 75 % and 25 % to CR, yield accounted for 100 % of PP, soil moisture (75 %) and groundwater depth (25 %) contributed to WS, and biodiversity indicators equally contributed to HP. For NC, nitrogen content of ryegrass blades contributed 50 %, while soil nitrogen and nitrogen input contributed 25 % each. Groundwater depth, while a direct WS measure, had a smaller weight due to seasonal effects (Supplementary Materials 4). Soil moisture was strongly positively correlated with management and drainage intensity (Supplementary Materials 4) and consequently deemed a more suitable proxy for WS. The relatively small contribution of SOM (%) toward the end score of CR, is due to the fact that topsoil SOM varies strongly among peat with no cover and peat with a mineral cover, independent of CR. In addition, no seasonal or fertilizer effect was observed for CO_2 emissions (Supplementary Materials 4), making it a suitable indicator of carbon losses on these fields. Present-day soil functioning was visualized in radar plots for each peat group separately.

3. Results

3.1. Soil types

Of the 30 fields mapped as peat (Basis Registratie Ondergrond BRO, 2022), 7 are mineral soils: 5 clay-on-peat and 2 loam-on-peat. Among the 23 fields accurately mapped as peat, 10 lack a mineral cover, while 6 (7) have a clay (loam) cover <40 cm. Since the clay or loam cover on mineral soils is only ~5 cm too thick to classify as peat (Supplementary Materials 5), and given their high spatial heterogeneity, they were included as peat with a clay or loam cover. This results in three groups: 1) peat - no cover (10 fields), 2) peat - clay cover (11 fields), and 3) peat - loam cover (9 fields).

3.2. General characteristics

In addition to soil type, grassland peat characteristics are shaped by land management practices and drainage (Van den Akker et al., 2018; Deru, 2021). Fig. 3 illustrates the uneven distribution of fields within each peat group along land management types and drainage intensities. Fields without a cover are mainly managed as semi-natural grasslands with low drainage intensity to maintain shallow groundwater during the growing season. Fields with a clay cover mainly function as production grasslands for dairy farming, either under the management of organic farmers (5 fields) subject to shallow drainage (low intensity) or conventional farmers (5 fields) subject to deep drainage (high intensity). Fields with a loam cover are managed either as production grasslands by conventional dairy farmers subject to deep drainage (6 fields), or as semi-natural grasslands (3 fields) subject to low or medium drainage intensities. For a detailed description drainage classes, see Supplementary Materials 1.

Table 2 and Fig. 4 highlight the similarities and differences in soil, plant, and hydrological traits among peat groups. Though not all variables directly assess soil functions, they provide context for interpreting functionality. The outcome of the NMDS analysis (Fig. 4) reveals how the variables are distributed within a dissimilarity matrix along two (NMDS 1 and 2) of the three axes. NMDS 1 and 2 seem strongly affected by 1) soil type (bottom left - top right), as indicated by 'clay', 'sand', and 'SOM', and 2) management (top left - bottom right) as indicated by the type and amount of nitrogen inputs. Pairwise comparisons revealed significant differences (p adj. = 0.003) among groups. Peat soils without mineral cover have significantly higher soil carbon, soil nitrogen and plant-available Fe, higher soil moisture, and significantly lower yield and dry-bulk-density (dbd) as opposed to soils with a mineral cover (Table 2, Fig. 4). Peat soils with a clay cover are associated with high plant-available K and have a significantly higher plant-available Mg, earthworm abundance, and earthworm diversity (Shannon (H) Index) (Table 2, Fig. 4). Peat soils with a topsoil of loam are associated with high yield, vegetation height, penetration resistance, dbd, CO_2 emission, infiltration rate, and plant-available P, and negatively correlated with dicotyledonous cover and number of dicotyledon species (Table 2, Fig. 4).

3.3. Present-day soil functioning

3.3.1. Climate regulation

The capacity for CR varied across peat types. Peat without cover, managed as semi-natural grassland, and clay-covered peat managed by organic farmers scored high due to low CO_2 emissions and high SOM, indicating low carbon losses (Fig. 5A, Fig. 6). Loam-covered peat soils managed as semi-natural grassland had a moderately low score, and clay- or loam-covered peat grasslands managed as production grassland by conventional farmers had low scores due to high CO_2 emissions and low topsoil SOM, indicating high carbon losses from these fields (Fig. 5A, Fig. 6).

3.3.2. Primary productivity

Peat with a clay cover managed as conventional production grassland received a high score for PP (Fig. 6) due to a median yearly yield of 9.6 ton DM/ha (Fig. 5B). Conventional grasslands with a loam cover and organic grasslands with a clay cover, median yearly yields of 9.3 and 9.0 ton DM/ha respectively, both received moderate scores for PP (Fig. 5B, Fig. 6). Semi-natural grasslands had a low median yield of 6.5 ton DM/ha*year (Fig. 5B) corresponding to low scores for PP (Fig. 6).

3.3.3. Nutrient cycling

Conventional grasslands on mineral-covered peat scored moderate (loam) to high (clay) due to high nitrogen inputs (495–610 kg N/ha), low soil nitrogen, and moderate to high ryegrass nitrogen content, indicating rapid nitrogen cycling (Fig. 5C, Fig. 6). Scores for clay-covered conventional grasslands might be slightly overestimated as fertilizer was applied on 3/5 fields shortly before sampling (Supplementary Materials 4). Organic grasslands scored moderate due to moderate nitrogen levels. Semi-natural grasslands on peat with no cover scored low, with high soil nitrogen but low nitrogen input and grass nitrogen content, indicating slow cycling (Fig. 5C, Fig. 6).

3.3.4. Habitat provision

Conventional grasslands on clay- and loam-covered peat scored moderately low and low, respectively, due to low biodiversity (Fig. 5D).

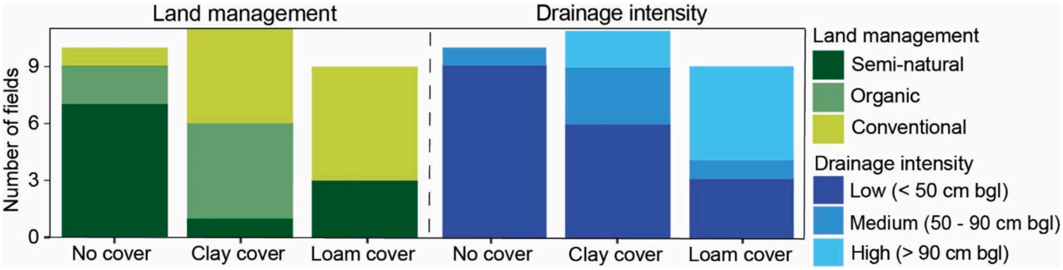

Fig. 3. Distribution of grassland management types and drainage intensities over the three main peat groups. Drainage intensity is based on target ditchwater depth (cm below ground level) and water infrastructure present. Peat with no cover is predominantly managed as semi-natural grassland ($n = 7$) subject to shallow drainage. Peat with a clay cover is either managed as conventional grassland with deep drainage ($n = 5$) or as organic grassland with shallow drainage ($n = 6$). Peat with a cover of loam is either managed as conventional grassland (n = 6) subject to deep drainage or as semi-natural grassland subject to low to medium drainage ($n = 3$). For a detailed description of land management types and drainage intensities, see Supplementary Materials 1.

Table 2
The mean and standard deviation of all measured variables calculated for each of the peat groups (no cover, clay cover, and loam cover) separately, along with p-values derived through between-group comparison (Wilcoxon rank sum test). *P*-values in bold signify a significant difference.

Variable	Unit	No cover		Clay cover		Loam cover			*P* values	
		Mean	stdev	Mean	stdev	Mean	stdev	No cover – clay	No cover - loam	Clay -loam
Vegetation height	(cm)	6.8	3.3	6.9	5.7	9.9	3.5	0.512	**0.042**	**0.042**
Nitrogen grass	(%)	3.4	0.7	4.1	0.6	3.6	0.5	**0.040**	0.604	0.143
Carbon grass	(%)	42.3	1.3	42.4	1.4	42.5	1.5	0.970	0.970	0.970
Grass cover	(%)	74.0	10.4	74.0	12.4	84.1	11.5	1.000	0.110	0.110
Dicot cover	(%)	20.1	9.3	19.4	12.0	6.5	5.9	0.833	**0.011**	**0.018**
Dicot species	(%)	4.0	1.8	2.9	1.4	1.9	1.8	0.200	0.120	0.190
Rooting depth	cm b.g.l.	17.7	5.4	16.5	3.4	17.9	2.6	1.000	1.000	1.000
Groundwater depth	cm b.g.l.	88.2	27.7	86.5	33.4	102.1	21.8	0.970	0.420	0.540
Infiltration rate	cm/h	3.6	8.9	52.5	111.7	2.0	3.2	0.680	0.680	0.680
Soil moisture	%	78.7	11.9	65.8	16.2	66.2	13.8	0.098	0.098	0.882
Dry-Bulk-Density	(g/cm^3)	0.4	0.9	0.6	0.9	0.6	0.9	**0.002**	**0.001**	0.370
pH		5.2	0.4	5.6	0.3	5.7	0.5	0.087	0.087	0.565
Soil Organic Matter	%	37.3	9.7	27.8	5.2	22.7	5.3	**0.030**	**0.004**	0.067
Salinity	(μS/cm)	633.5	179.6	535.5	85.7	517.4	124.5	0.230	0.230	0.590
Nitrogen soil	%	1.5	0.4	1.1	0.2	0.9	0.2	**0.007**	**0.004**	**0.038**
Carbon soil	%	20.2	4.4	13.5	2.9	10.9	2.9	**0.002**	**0.000**	0.112
CEC	(cmol+/kg)	39.6	11.2	38.1	2.6	33.8	8.0	0.860	0.430	0.430
Ammonium	(mg/kg)	674.4	209.6	553.7	101.9	423.7	75.6	0.173	**0.011**	**0.011**
Phosphate	(mg/kg)	83.8	20.7	91.4	12.0	121.4	114.4	0.970	0.970	0.970
Plant-available K	(mg/kg)	172.0	66.8	434.5	157.0	293.0	203.2	**0.000**	0.400	0.228
Plant-available Mg	(mg/kg)	389.9	138.0	606.9	73.5	435.1	84.5	**0.001**	0.549	**0.000**
Plant-available Fe	(mg/kg)	4.4	2.1	2.5	1.9	2.0	0.6	**0.007**	**0.007**	0.703
CO2 emission	(ton/ha*year)	14.2	16.9	30.6	26.0	41.3	22.9	0.377	0.052	0.456
Earthworm abundance	(ind./6 spades)	91.1	54.1	180.3	37.2	147.2	44.3	**0.002**	0.067	0.067
Earthworm richness	(sp./6 spades)	5.9	1.8	7.2	1.3	6.9	0.9	0.220	0.220	0.400
Enchytraeid abundance	(ind./232 cm^3)	32.9	10.5	45.5	33.3	49.9	25.3	0.550	0.460	0.510
Enchytraeid richness	(sp./232 cm^3)	5.5	2.1	5.8	1.2	6.0	1.7	0.640	0.680	0.850
Nematode abundance	(ind./100 g)	8211.8	4602.4	13,278.2	6538.5	9482.1	5706.5	0.250	0.500	0.300
Nematode richness	(gen./100 ind.)	14.0	2.2	12.5	2.4	12.8	2.4	0.300	0.300	0.850
Fungal biomass	(nM/g)	11.4	2.8	12.2	2.2	10.3	2.3	0.600	0.600	0.290
Bacterial biomass	(nM/g)	187.6	34.6	179.0	27.1	136.8	31.0	0.512	**0.009**	**0.009**
Land use intensity[1]		1.4	0.7	2.4	0.7	2.3	1.0	**0.024**	0.068	0.067
13,278.2Livestock density	(LU/ha)	8.8	8.4	27.8	23.7	7.5	8.6	**0.033**	0.775	**0.033**
Harvested via grazing	(%)	46.6	25.4	70.0	16.1	31.1	25.1	0.052	0.201	**0.007**
Mowing frequency	(no. /year)	1.8	0.4	2.9	1.1	2.9	1.5	**0.031**	0.150	0.938
Nitrogen solid	(kg N/ha*year)	29.7	29.5	9.7	22.1	16.2	26.8	0.270	0.340	0.550
Nitrogen slurry	(kg N/ha*year)	18.0	38.2	244.0	173.9	240.5	217.8	**0.006**	**0.024**	0.969
Nitrogen artificial	(kg N/ha*year)	5.4	17.1	77.6	97.1	117.0	91.6	0.086	**0.023**	0.261
Nitrogen total	(kg N/ha *year)	53.2	45.4	331.3	240.0	373.7	273.5	**0.005**	**0.035**	1.000
Expected yield[2]		1.2	0.4	2.0	0.4	2.2	1.0	**0.005**	**0.028**	0.432
Drainage intensity[3]		1.1	0.3	1.6	0.8	2.2	1.0	0.114	**0.026**	0.176

Despite an above-average dicotyledonous cover, organic production grasslands have moderate scores for HP (Fig. 6) due to average below- and aboveground diversity (Fig. 5D). Semi-natural grasslands without a mineral cover, received the highest scores for HP (Fig. 6) due to high above- and belowground diversity Fig. 5D).

3.3.5. *Water storage*

Organic grasslands with a clay cover and semi-natural grasslands without mineral cover on top of the peat, have the highest scores for WS (Fig. 6) due to high soil moisture and shallow groundwater depth (Fig. 5E). In contrast, conventional production grasslands with a clay (loam) cover score low (moderately low) for WS (Fig. 6) due to a relatively low soil moisture and high groundwater depth (Fig. 5E).

4. Discussion

The Functional Land Management (FLM) framework aims to create sustainable landscapes by optimally balancing the demand for and supply of soil functions in a specific region (Schulte et al., 2014). As outlined in the introduction, the demand of soil functions in the Frisian peat meadow region includes 1) carbon storage to mitigate climate change, 2) water storage to increase drought resilience and prevent salinization, 3) above- and belowground biodiversity to mitigate biodiversity loss, 4) a balanced nutrient cycle to reduce nitrogen losses to the environment, and 5) sufficiently high yields to provide profitable incomes for farmers. To reach an optimal balance between demand and supply and effectively use peat soils to balance functioning at a landscape level requires 1) accurate classification of the peat types present, 2) assessment of the present-day functioning, and 3) comparison between present-day and potential functioning, in order to determine which peat types are most suited to provide a specific function and where there is most room for improvement.

4.1. *Soil classification*

Classification of the 30 fields mapped as peat revealed that 7 were misclassified as organic (peat) soils. Misclassification of peat soils within the BRO has previously been reported by de Vries et al. (2014), who found that continued drainage-induced peat oxidation had significantly reduced peat layer thickness since initial mapping (1960–1995) (de Vries et al., 2014). In 12 % of the cases, this reduction resulted in a shift from an organic to a mineral soil (de Vries et al., 2014). Besides a high temporal heterogeneity, Frisian peat soils also exhibit a high spatial heterogeneity following natural and anthropogenic influences on the soil (van Mourik and Ligtendag, 2015; Vos et al., 2020). Such influences include widespread peat mining, recurrent flooding events, and the application of “toemaak” to the land (van Mourik and Ligtendag, 2015; Brouns et al., 2015). Accurate classification is challenging not only in Friesland but also across the Netherlands (de Vries et al., 2014) and Europe (Tanneberger et al., 2017; Martin and Couwenberg, 2021).

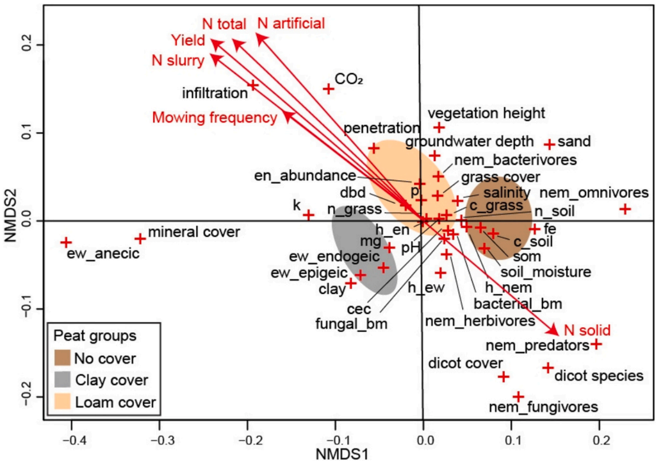

Fig. 4. Dissimilarity matrix showing associations in the data. The stress level (0.096) indicates a good model fit. Management variables showing significant associations were passively fitted to the plot. Ellipses represent the three main (top)soil types. Abbreviations: infiltration = infiltration rate (cm/h), penetration = penetration resistance (N/cm^2), dbd = dry-bulk-density (g/cm^3), cec = cation-exchange-capacity (cmol+/kg), n_soil = soil N (%), c_soil = soil C (%), n_grass = ryegrass blade N (%), c_grass = ryegrass blade C (%), en_abundance = enchytraeid abundance (individuals/232cm^3), ew_anecic = anecic earthworms, ew_endogeic = endogeic earthworms, ew_epigeic = epigeic earthworms, H_en = Shannon Index enchytraeids, H_ew = Shannon Index earthworms, H_nem = Shannon Index nematodes, fungal_bm = fungal biomass (nM/g), bacterial_bm = bacterial biomass (nM/g). Units of remaining variables: Supplementary Materials 3.

Misclassification has severe implications, as (national) soil maps are continuously used by policymakers, planners, and scientists (de Vries et al., 2014). In FLM, accurate soil type information is crucial, as it strongly affects both potential and present-day functioning.

4.2. Present-day soil functioning

4.2.1. Peat - no cover

Around 70 % of the peat grasslands with no mineral cover sampled are managed by nature organizations as semi-natural grasslands, with management focused on optimizing aboveground HP rather than PP (Fig. 3). This is surprisingly high, considering only 15 % of Frisian peat soils are managed by nature organizations (Van den Akker et al., 2018; Klaassen et al., 2018). A possible explanation is that these soils are wetter, have lower load-bearing capacity, are more acidic, and contain more plant-available iron than mineral-covered peat, making them less attractive for agriculture (Schothorst, 1982; Osman, 2018; Deru, 2021). This aligns with our findings (Table 2, Fig. 4).

In terms of soil functioning, these semi-natural grasslands have low PP and NC, moderately high HP, and high WS and CR (Fig. 6A). The high CR score is surprising, as these peat soils lack a mineral cover to protect them from oxidation (Supplementary Materials S.5). However, it should be noted that the CR score is mainly based on the heterogeneous variable CO_2 emission, sensitive to groundwater depth, soil moisture content, and (soil) temperature (Van den Akker et al., 2018; Weil and Brady, 2017). The current score thus reflects CR in March 2022, under relatively wet and cold conditions. CR scores are expected to decrease in summer as the soil dries (Schothorst, 1982) and CO_2 emissions increase (Brouns, 2016; Evans et al., 2021). This would align our results more closely with the findings of van den Akker et al. (2018), showing higher CO_2 emissions on Frisian peat with no cover, relative to peat with a mineral cover.

4.2.2. Peat - clay cover

Almost all clay-covered peat soils assessed are managed as production grasslands by either conventional or organic farmers (Fig. 3). Clear differences in characteristics (Table 2, Fig. 4) and functioning (Fig. 5, Fig. 6B) exist between fields managed by conventional or organic farmers. Conventional fields have high PP and NC, and relatively low HP, WS, and CR, while organic fields have moderate PP, NC, and HP, along with high WS and CR (Fig. 6B). The low CR score on conventional grasslands is mainly due to high CO_2 emissions, with a median of around 60 tons/ha*year (Fig. 5A). This is two- to threefold higher than the

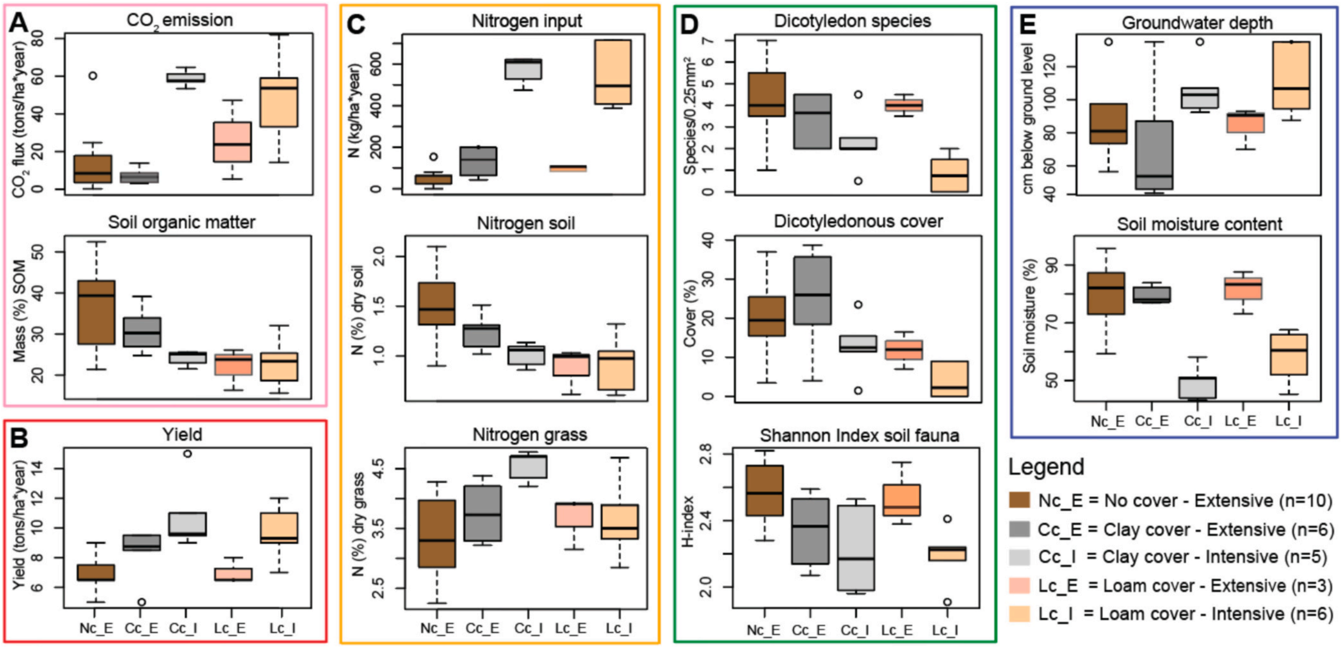

Fig. 5. Boxplots of indicators per peat and management type for soil functions: A) CR (pink box): CO₂ emission (tons/ha*year) and SOM (%); B) PP (red box): yield (ton DM/ha*year); C) NC (orange box): nitrogen input (kg N/ha*year), soil N (%), and ryegrass blade N (%); D) HP (green box): dicot species, cover (%), and Shannon Index; E) WS (blue box): groundwater depth (cm b.g.l.) and soil moisture (%). See Supplementary Materials 6 for *p*-values.

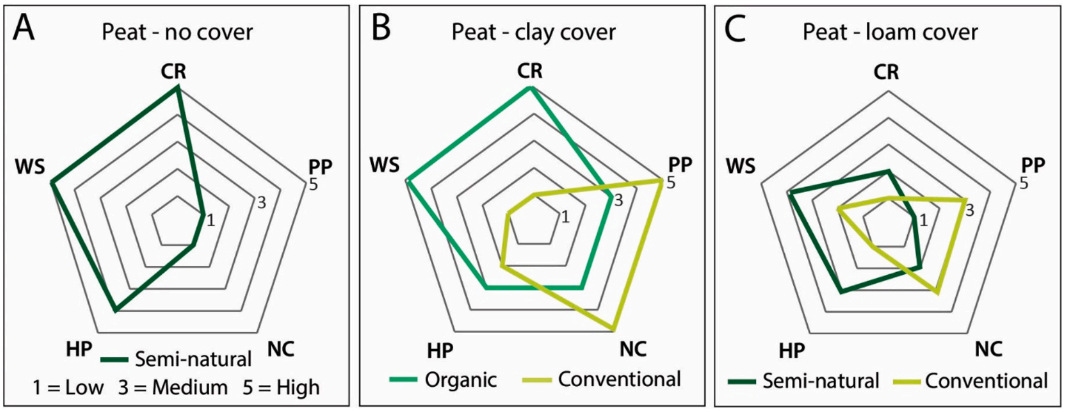

Fig. 6. Radar plots of the present-day capacity of peat types to perform five soil functions: Climate Regulation (CR), Primary Productivity (PP), Nutrient Cycling (NC), Habitat Provision (HP), and Water Storage (WS). A) Peat with no cover, managed as semi-natural grassland (n = 7). B) Peat with a clay cover, managed as organic (n = 5) or conventional (n = 5) production grassland. C) Peat with a loam cover, managed as semi-natural (n = 3) or conventional (n = 6) grassland.

yearly Dutch (~19 tons/ha) and Frisian (~25 tons/ha) averages for peat soil (Van den Akker et al., 2010, 2018). The high CO_2 emission is surprising, as the peat layer is covered by a 40 cm clay layer (Supplementary Materials 5), and even a thin (1–2 cm) clay layer on peat can reduce CO_2 emissions (van Agtmaal and Keuskamp, 2023). This high emission may indicate a strong positive soil priming effect, with rapid turnover of organic matter driven by frequent and high fertilizer inputs (Bastida et al., 2019), though more research is needed to test this hypothesis. Although suitable for comparing emissions between fields, the median values from this study are based on March 2022 measurements and do not reflect yearly emissions. Future research across seasons is needed to calculate a more representative yearly average and detect intra-annual CO2 variability. Our findings suggest that organic management, with moderate nutrient inputs and low groundwater depth (<50 cm bgl), can improve CR and WS without severely compromising PP (Fig. 5B, Fig. 6B).

4.2.3. Peat - loam cover

Around 70 % of the loam-covered peat grasslands in this study are managed by conventional farmers (Fig. 3), with high nutrient inputs and groundwater depths of >90 cm below field level (Fig. 5). Production grasslands on loam-covered peat received moderate scores for NC and PP, and relatively low scores for WS, HP, and CR (Fig. 6C). A possible reason for the reduced soil (multi)functionality on these fields could be the long history of intensive management aimed at optimizing PP, which is associated with soil degradation and a gradual decline in soil functioning, eventually undermining PP capacity (Stavi et al., 2016; EASAC, 2018). Another reason could be that three of the six fields have an anthropogenic topsoil (‘toemaak’) composed of canal slurry, solid manure, city waste, and ‘terpaarde’, sand from an outcrop deposited during the last ice age (Weichselian) (Schothorst, 1982; van de Ven, 1993). Peat fields with an anthropogenic cover are relatively common in The Netherlands (Dinoloket, 2013) and associated with high heavy metal concentrations (Rutgers et al., 2009). Concentrations are expected to increase further as heavy metals remain at the surface when SOM is lost under continued oxidation (Rutgers et al., 2009). Loam-covered peat soils managed as semi-natural grasslands have higher HP, WS, and CR, and lower NC and PP compared to conventional fields (Fig. 6C). However, since this group is small (*n* = 3), more studies are needed to confirm these results.

4.3. Potential soil functioning

The potential capacity to perform the five soil functions varies between peat types and (historical) management regimes (see conceptual Fig. 7 A-E). A natural peat ecosystem, where organic matter is actively stored under waterlogged conditions (Joosten et al., 2017), has a high potential for WS and CR (Weil and Brady, 2017). It provides a specific peatland habitat for flora and fauna (Kreyling et al., 2021) but has a low potential for PP (grass production) and NC (Coyle et al., 2016; Tanneberger et al., 2020). Peatland drainage (resulting in *peat - no cover*) inevitably leads to a loss of WS, initially only present-day WS as the groundwater depth increases and the soil moisture content drops (Weil and Brady, 2017). Over time, the potential for WS also decreases, as drainage-induced structural changes in the soil render the peat hydrophobic (Dekker and Ritsema, 2000). In addition, drainage causes peat oxidation and accelerates decomposition rates, resulting in low CR and high NC and PP (Joosten et al., 2017; Weil and Brady, 2017). Clay and loam-covered peat soils are no longer naturally functioning peat ecosystems (Joosten et al., 2017). These soils have high potential for PP, combining the benefits of mineral and organic soils (Weil and Brady, 2017). The mineral cover protects the underlying peat from oxidation (Van den Akker et al., 2018), but prevents active peat buildup, reducing CR potential compared to uncovered peat. Additionally, WS potential is slightly lower due to the reduced topsoil content of the mineral cover (Weil and Brady, 2017). However, these mineral-covered peat soils have high potential for both HP and NC, as the peat layer adds nutrients to the soil (Brouns, 2016). Overall, these sediment-covered peat soils have high multifunctionality potential.

4.4. Recommendations for functional land management

4.4.1. Peat - no cover

To fully realize the unique potential of peat soils with no mineral cover for CR and WS (Fig. 7A and E), management should focus on restoring natural peat ecosystems to promote active buildup of the peat layer and re-appearance of specialized peatland species - thereby increasing landscape-scale diversity (Kreyling et al., 2021; Tanneberger et al., 2020; Maes et al., 2021). At present, only 5.5 % of the Dutch peat soil shows active buildup of the peat layer (Joosten et al., 2017). Although similar percentages are found in surrounding countries with heavily drained coastal peat, such as Germany and Denmark, it is low compared to the European average of ~54 % (Tanneberger et al., 2020). Around 62 % (36,342 ha) of the Frisian peat soils do not have a mineral cover (van den Akker et al., 2018) and could, in theory, be restored to natural peatlands. However, this process is complex and requires fully raising the groundwater table to ground level, eliminating external nutrient inputs, inoculating with native mire species (e.g., Sphagnum spp.), and time (Joosten et al., 2017; Tanneberger and Wichtmann, 2011). Since raising the groundwater table in one field affects neighboring fields, this requires a collective approach among all land managers in the area (Tanneberger et al., 2020). Successfully eliminating

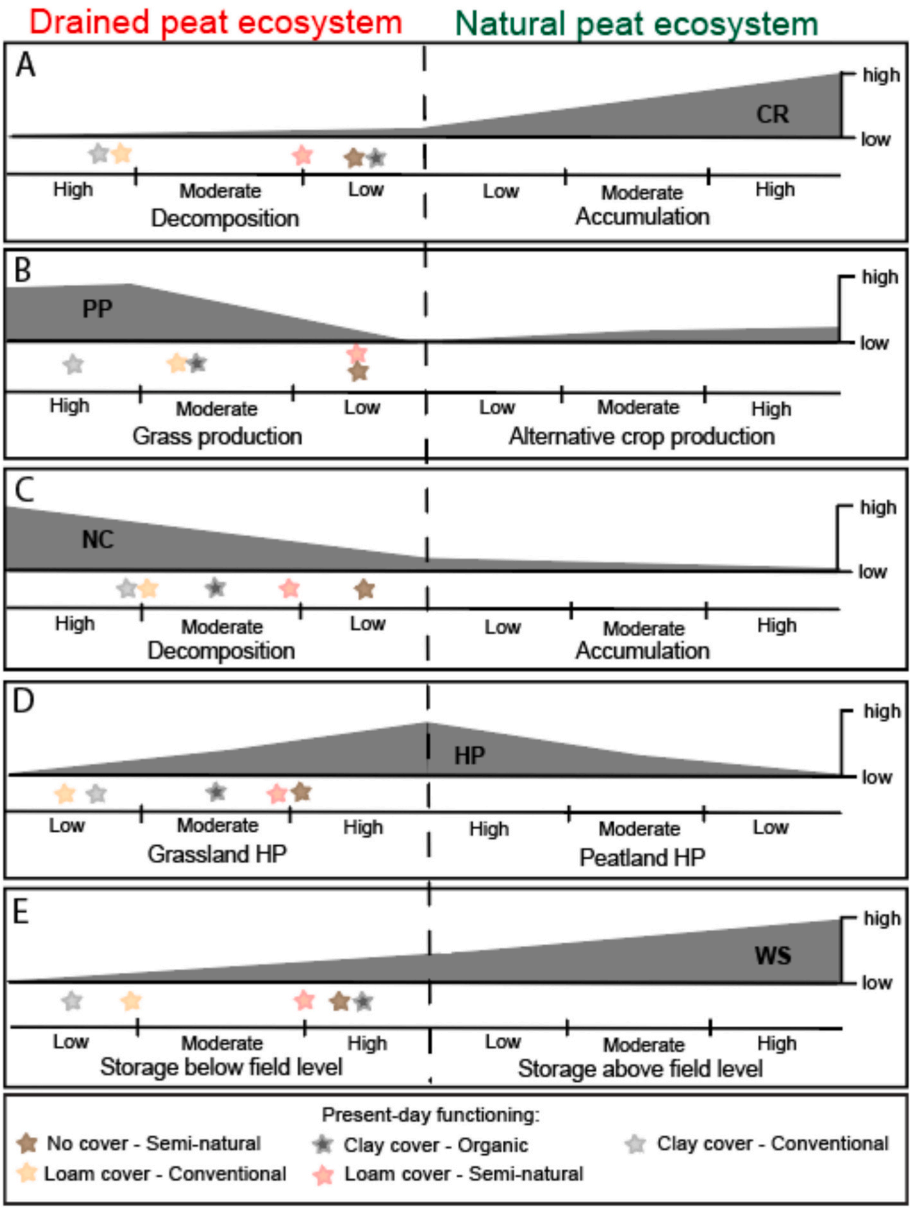

Fig. 7. Conceptual representation of peatland functioning on a scale from severely drained peat (far left) to pristine peatland conditions (far right). Subplots show the soil functions: A) Climate Regulation (CR), B) Primary Productivity (PP), C) Nutrient Cycling (NC), D) Habitat Provision (HP), and E) Water Storage (WS). Clear trade-offs exist between CR and WS on the one hand, and PP and NC on the other. Stars represent the present-day functioning of the different peat groups. Peat managed as conventional grassland falls more toward the far left as opposed to organic production grasslands and semi-natural grasslands.

external nitrogen inputs, including the deposition of atmospheric nitrogen (Joosten et al., 2017; Wamelink et al., 2013), is extremely challenging and requires (inter)national efforts (Erisman et al., 2005) along with clear policy measures.

Restoring peatlands would decrease NC and grassland PP, leading to a loss of (traditional) income for farmers. Thus, peat restoration must be accompanied by viable alternative business models (Tanneberger and Wichtmann, 2011; Tanneberger et al., 2020). Inspired by the EU Climate Strategy, the EU Biodiversity Strategy, and the EU Soil Strategy, funding for the development and implementation of alternative business models on peat is slowly becoming available through CAP 2023–2027 and national funds such as the German Federal Action Plan on Nature-based Solutions for Climate and Biodiversity (European Commission, 2018; European Commission, 2021; European Commission, 2022; BMUV, 2022).

Previous studies indicate that restoring natural peatlands is challenging and can temporarily lead to high fluxes of N_2O and CH_4 emissions to the atmosphere (Offermanns et al., 2023), as well as long-lasting changes to pre-drainage vegetation and ecosystem services (Kreyling et al., 2021). However, other studies suggest that while rewetting drained peatlands may initially increase CH_4 emissions, it significantly reduces N_2O, CO_2, and overall CO_2-equivalent GHG emissions over time (Tanneberger et al., 2020; Günther et al., 2020; Liu and Lennartz, 2020). A recent assessment found that rewetting 15 % of agricultural land in the Netherlands could achieve a 34 % reduction in total GHG emissions from agriculture (Martin and Couwenberg, 2021). Peat restoration enhances the provision of CR, WS, and landscape-scale HP (Tanneberger et al., 2020; Weil and Brady, 2017; Kreyling et al., 2021), contributing to global biodiversity conservation and climate mitigation goals. It also addresses local challenges, including reducing soil subsidence (currently 1–2 cm/year; Brouns et al., 2015), improving drought resilience, and mitigating salinization.

4.4.2. *Peat - clay or loam cover*

Peat soils with mineral covers have high potential for grassland PP (Fig. 7B). In conventionally managed grasslands, there is untapped potential for CR, HP, and WS (Fig. 6B and C; Fig. 7). Our results show that organic farmers, using extensive management practices, can significantly improve these functions before severe trade-offs with PP emerge (Fig. 6B). The median grassland yield on organic fields is only 6 % (loam) to 17 % (clay) lower than on conventional fields (Fig. 5). We therefore recommend improving WS, CR, and HP in peat grasslands with a mineral cover while maintaining moderate to high PP. This applies to 38 % (22,197 ha) of the Frisian peat soils and an additional 14,551 ha of mineral soils with a peat layer at 40–80 cm b.g.l. (van den Akker et al., 2018). Raising the groundwater table to ~40 cm b.g.l. on peat with mineral covers would reduce CO_2 equivalent GHG emissions by 66–87 % (van den Akker et al., 2018). For mineral soils with a peat layer within 40–80 cm, the reduction would be 73–100 % (van den Akker et al., 2018). Besides improving CR, maintaining a low groundwater depth would improve WS, reduce soil subsidence, increase drought resilience, and combat coastal salinization by reducing natural drainage from higher-lying mineral soils to the peat region (Wetterskip Fryslân, 2021). In addition, it would support restoration efforts on peat soils with no cover by reducing drainage to deeply drained grasslands. Due to trade-offs between PP, WS, and CR (Fig. 6; Fig. 7), higher prices for farm products and additional income sources, such as carbon credits or biodiversity subsidies, are needed to finance the transition to sustainable land management.

This research suggests that the FLM perspective is a promising framework for studying sustainable land management on peat. We evaluated soil functioning on drained coastal peat soils in Friesland, The Netherlands, but the framework can be applied globally by adjusting indicator variables and thresholds to match specific peat types, land uses, regions, or scales. Many European countries face severely degraded peatlands, contributing to climate change (Verhagen et al., 2009), biodiversity loss (Kreyling et al., 2021), and the loss of essential ecosystem services (Weil and Brady, 2017). Applying the FLM framework to assess the demand for and supply of soil functions at a landscape scale can help map out different peatland futures. This work points to a scenario where peat, through protection and restoration, contributes positively to life within planetary boundaries (Kraamwinkel et al., 2021). Beyond the scope of peat soils, optimally balancing demand and supply of soil functions requires a landscape-scale assessment and should ideally be accompanied by a socio-economic assessment of the region to map out the socio-economic potential. Although a full system change is needed for sustainable land management, the FLM framework can guide the spatial design of sustainable and resilient landscapes.

In addition to a socio-economic assessment, future research on soil functioning in peat soils should prioritize long-term monitoring of soil functions to capture both inter- and intra-annual variability, given the high temporal heterogeneity of peat. As this study measured soil functioning at a single point in time, it reflects conditions in early spring. For the provision of functions assessed using temporally heterogeneous variables (e.g. carbon and water storage), it would be valuable to determine whether the provision changes during later stages of the growing season. To address the spatial heterogeneity of peat soils, we recommend that future research, particularly on coastal peat, focus on assessing within-field variability. In this study, we measured soil functioning at two sites within the field, which limited our ability to capture or account for much of the within-field variability. Therefore, determining and comparing within- and between-field variability of coastal peat soils would be an important step to support future field campaigns and enhance the interpretation of their results.

5. Conclusion

This study highlights the potential for improving CR, WS, and landscape-scale HP in the Frisian peat meadow region. Promoting these functions can help meet local needs, such as improving drought resilience and combating salinization, as well as global goals like climate mitigation and biodiversity restoration. Peat soils with no cover have significant untapped potential for CR and WS, which could be unlocked through management aimed at restoring natural peat ecosystems. Peat soils with a mineral cover have high potential for PP and soil multifunctionality. The difference in WS, CR, and HP between fields subject to organic or conventional management suggests that conventionally managed peat grasslands can strongly improve multifunctionality before severe trade-offs with PP become apparent. Managing soil function demand and supply at a landscape scale offers a promising approach to addressing socio-economic challenges while fostering sustainable, resilient landscapes.

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Declaration of competing interest

The authors have no conflict of interest to declare.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2025.e00929.

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