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RESEARCH

Classifying the productivity of drained peatland forests for precision management

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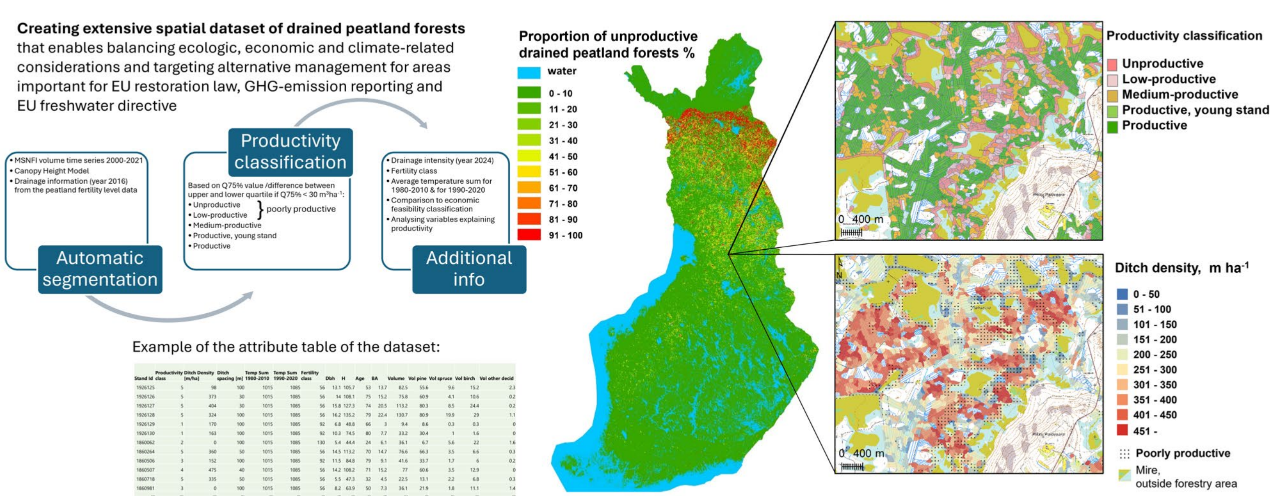
Abstract

Utilizing advancements in peatland mapping, spatial analysis of drainage intensity, and automated segmentation of forest resource data, we produced an openly available dataset to classify drained peatland forests in Finland based on productivity. Five classes were separated: unproductive, low-productive, medium-productive, and productive, the latest including a separate class for young stands. Productivity was assessed through tree stand volume development, using consecutive Multi-Source National Forest Inventory (MSNFI) data from 2000 to 2021. Our results show that approximately 83% of forestry-drained peatlands were productive or medium-productive. The identified poorly productive areas (unproductive i.e. volume < 30 m^3ha^{-1} excluding young stands, and low-productive i.e. volume < 45 m^3ha^{-1}) covered an area of 782 000 ha (17% of all forestry-drained peatlands). Earlier classification of economic feasibility for timber production, based on temperature sum and site fertility class, yielded larger poorly productive areas, but increasing temperature sums seems to decrease their area. Besides temperature sum, drainage intensity and fertility class explained the lowest and highest classes of productivity. Poorly productive drained peatland forests were primarily located in the northernmost regions. The produced dataset includes stand boundaries, most recent stand information from MSNFI, stand productivity classification (1–5), ditch density and spacing, and site fertility class, and supports targeted decision-making for the management of drained peatland forests, greenhouse gas emission reduction, the restoration law, and the freshwater directive of the European Union.

Graphical Abstract



Keywords Peatland management · Boreal · Climate change · Ditch density · Spatial dataset · Restoration

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Introduction

Peatlands occur in all continents and climate zones but are especially abundant in northern Eurasia (Tanneberger et al. 2017; Greifswald Mire Centre 2022; Tegetmeyer et al. 2024). In northern Europe, especially in the Nordic and Baltic countries, peatlands have commonly been used for forestry and for that purpose, peatlands have been drained by ditching (Holden et al. 2006; Siiskonen 2007). For instance, in Finland, peatlands cover approximately one third of the land area, and more than a half of the peatland area has been drained for forestry (henceforward "forestry-drained"; Kulju et al. 2023; Korhonen et al. 2024). Draining peatlands have transformed landscapes so that they offer less variation between forested and open habitats, with significant species turnover (Laine et al. 1995; Lõhmus et al. 2015). While the drained peatland forests are regionally important timber resources (Hökkä et al. 2017), they also act as sources of greenhouse gases (GHG) to the atmosphere (Turunen and Valpola 2020; Alm et al. 2023; Jauhiainen et al. 2023) and of nutrients and carbon to watercourses (Laurén et al. 2021; Finér et al. 2021). Thus, their future management should be carefully designed to retain economic pros while reducing environmental cons. Restoration will be one of the future management options as guided by EU Regulation 2024/1991.

Throughout the Nordic-Baltic region, both undrained and forestry-drained peatlands have been classified to different site types and fertility classes to describe variation in soil nutrient content and water-level regime (e.g., Laine et al. 2018; Middleton et al. 2023). These two terms are sometimes used synonymously, but fertility class is a more general term, and each fertility class can be divided into several site types (e.g., Middleton et al. 2023). Both site types and fertility classes are recognized based on ground vegetation composition and tree stand characteristics (e.g., Bušs 1981; Lõhmus and Laasimer 1981; Hånell 1988; Laine et al. 2018). The peatland sites that were drained represented several different site types; e.g., in Finland, 31 undrained peatland site types had been subjected to drainage between 1930 and 1978, when the intensity of drainage activities was highest (Keltikangas et al. 1986). Currently, drained peatland forests are generally classified using ground vegetation into five fertility classes ("herb-rich", "*Vaccinium myrtillus*", "*Vaccinium vitis-idaea*", "dwarf shrub" and "*Cladina*" in the order of decreasing nutrient content). In this context, stand productivity refers more directly to the timber production capability of a site. Site productivity often correlates highly with fertility, but it covers also the effects of other elements such as climatic factors, and in peatland sites also moisture conditions.

The classification systems applied for forestry-drained peatlands in the Nordic and Baltic countries are, despite of some specifics and slightly differing terminologies, comparable (e.g., Bušs 1981; Lõhmus and Laasimer 1981; Hånell 1988; Laine et al. 2018). Fertility classes are currently used as a basis for management guidelines (e.g., Äijälä et al. 2019). Forest management is, however, increasingly using the principles of precision forestry (Fardusi et a. 2017), which emphasizes the need for integrating site-specific information, advanced sensing technologies for data-driven decision support systems. It is obvious, that the current fertility classes cover a wide range of variation in soil nutrient status and stand productivity (e.g., Westman and Laiho 2003). Therefore, precision management requires easy access to more precise and spatially explicit information for site productivity assessment than what can be concluded based on mere fertility class.

It has long been recognized that some drained sites were in fact not suitable for production forestry but have remained poorly productive. This may be due to insufficient soil nitrogen (N) availability, a severe imbalance of high N but low phosphorus (P) and/or potassium (K) availability retarding tree growth, or inadequate drainage due to geomorphological constraints (Vasander 1982; Jutras et al. 2007; Ojanen et al. 2019). In Finland, the area of such sites has been estimated to range from 0.5 to 1 million ha, i.e. 10–20% of the ca. 5 million ha forestry-drained peatland area (Laiho et al. 2016; Korhonen et al. 2024). This area requires specific consideration because in their current state they provide no benefits for regional economy or nature.

So far, a detailed spatial description of different stand productivity classes has not been available. Such information would, however, be highly useful for designing the future management, be it ecological restoration or continued silviculture. Forest management is obviously economically viable only at sites with high or at least moderate productivity. Thus, poorly productive drained peatlands may be of special interest for restoration. However, the suitability of a site for restoration, or for continued silviculture, depends on multiple factors, including fertility class, and drainage intensity that affects the soil water-table (WT) regime. Fertility classes may also be used in GHG inventories (Alm et al. 2023), as soil emissions vary significantly among those (e.g., Jauhiainen et al. 2023). The inventories would benefit from the possibility to distinguish between different productivity classes and accounting for the soil WT regime and drainage intensity (Jauhiainen et al. 2023).

Drainage intensity in peatland forests can be explored through ditch density and ditch depth, which give an indication of WT levels, soil moisture, and nutrient dynamics (Laurén et al. 2021). High ditch density generally enhances drainage efficiency and lowers the WT (e.g., Meshechok

1960). The WT in turn affects tree growth directly by controlling water and oxygen supply to roots and indirectly by controlling nutrient release from decomposing organic matter (Laurén et al. 2021). A drop in WT caused by drainage initially enables better tree growth and stand productivity (Heikurainen 1980; Hökkä et al. 2008). However, deep WT also accelerates the loss of carbon stored in peat soils, contributes to GHG emissions, and increases the risk of nutrient and sediment runoff into surrounding water systems (Ojanen and Minkkinen 2019; Nieminen et al. 2022). Furthermore, recent research suggests that trees currently grow better at shallow than deep WT in drained peatlands (Hökkä et al. 2025) contradicting the earlier paradigm (e.g., Heikurainen 1980).

Understanding drainage intensity is essential for balancing forest management goals with environmental impacts, such as carbon retention, restoration, and water quality. Palviainen et al. (2024) found that dissolved organic carbon export can be decreased, and site carbon sink increased by reducing drainage intensity, to which ditch spacing effectively influences. Although ditch spacing can be interpreted from maps, there has not been a directly available national scale data on ditch spacing or density, which could allow exploration of variation in ditch density across the country and apply site-specific ditch spacing e.g. in simulating the dynamics of drained peatland forests.

Recent advancements in spatial data and peatland mapping allow for a comprehensive reassessment of the extent, fertility, and productivity of drained peatlands. Spatial datasets and high-resolution mapping tools currently enable classification of drained peatland forests to a choice of productivity classes, accounting for both their site fertility class and drainage intensity. Identifying forestry-drained areas with different productivity levels is a critical step in optimizing their management, both for restoration and continued silviculture. This study builds on the time series of Multi-Source National Forest Inventory (MSNFI) data (Mäkisara et al. 2016, 2022) spanning 2000–2021, national map data of peatland site types (Middleton et al. 2023), and high-resolution drainage data. Utilizing these data, this study evaluates the productivity of forestry-drained peatlands in Finland. By incorporating attributes such as fertility class, drainage intensity, and ditch spacing, the research provides critical insights for land-use planning and restoration. To our knowledge, this is the first attempt to classify drained peatland forests by combining national-level data sources with the precision and detail relevant to actual decision-making in practical forestry.

The specific objectives of the study are:

i) Produce a spatial database that enables precision management for drained peatland forests including productivity classification derived from MSNFI growing stock volume time series 2000–2021, combined with information on drainage intensity and site fertility class.
ii) Examine the productivity distribution regionally and compare productivity classification with earlier classification of economic feasibility for timber production considering observed trends in average temperature sums.
iii) Explore the factors affecting productivity with a multinomial logistic regression model.

Materials and methods

The use of materials for productivity classification is presented in a flowchart (Fig. 1).

Materials

Multi-source national forest inventory thematic maps

Multi-Source National Forest Inventory (MSNFI) of Finland produces thematic map layers of forest variables including growing stock and site characteristics (Mäkisara et al. 2016). MSNFI combines information from field measurements of the field-based national forest inventory (NFI) plots, remote sensing imagery, and digital maps, producing spatially continuous wall-to-wall map information of forest variables such as site characteristics, growing stock volumes per tree species, stand mean diameter and height. Satellite imagery is used for predicting forest variables for each pixel using NFI field plot measurements as reference data. Digital maps are used for separating forestry land from other land cover types. The MSNFI maps are updated with approx. 2-year intervals. The current data format of MSNFI thematic maps is raster data with a spatial resolution of 16 m.

Canopy height model

A canopy height model (CHM) is based on airborne laser scanning (ALS) acquired by the National Land Survey of Finland (NLS) 2008–2019. The ALS-based CHM data utilized in this study was provided by Finnish Forest Centre (2023). The CHM has been derived as the difference between the digital surface model (DSM, 1 m pixel size) created of the first returns of the ALS data and the digital terrain model (DTM, 1 m pixel size) based on the ground returns of the ALS data. Thus, the CHM represents the height of the trees and other vegetation.

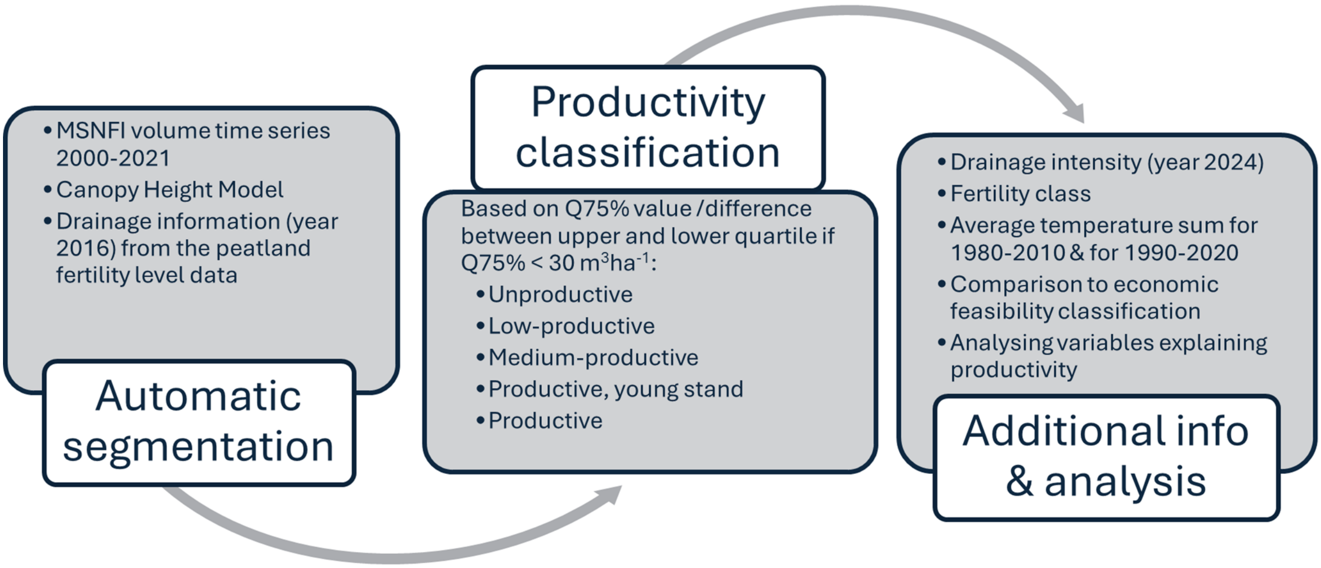

Fig. 1 Flowchart summarizing the materials and methods used in the productivity classification

Peatland fertility level data

The peatland fertility level data (GTK 2023) contains general distribution and occurrence of fertility classes and drainage states in Finland (Middleton et al. 2023). The data is in 10 m × 10 m pixel format raster data. The dataset was generated with machine learning model using remote sensing and other spatial data and trained with field observed reference data of fertility classes and peatland land use classes (Middleton et al. 2023). The peatland fertility level dataset separated drained and undrained peatlands from each other based on drainage information dated to year 2016 (Middleton et al. 2023). Classifying streams to ditches or natural streams is a complex task. The drainage status procedure described in Middleton et al. (2023) extracts streams with less than 2 m in width and recognizes the artificial ditches based on the straightness of the waterlines. The peatland pixels were defined as drained when the pixel centre was located no further than 40 m distance from nearest drainage ditch. In northern Lapland, highly varying topography results in naturally straight streams. Since ditching has been minimal in this region, peatlands in this area were not classified as drained.

Topographic database

For extracting drainage intensity (ditch density and ditch spacing), we used the latest data on streams (including ditches) in the Topographic Database of Finland (NLS 2024). Data of streams is updated to the Topographic Database each year. While the streams with width less than 2 m are still largely missing in the agricultural areas, the ditches in the forest areas are relatively accurately mapped.

Finnish Meteorological Institute data for temperature sums 1981–2020

Accumulated yearly effective temperature sum (TS) was calculated as the sum of the positive differences between diurnal mean temperatures and 5°C reference temperature value from the 10 km × 10 km gridded data by Finnish Meteorological Institute (2016). In this study, we used the value of the accumulated TS at year's end. For considering observed climate trends, two periods were used to extract the 30-year averages of TS (1981–2010 and 1991–2020, Fig. 2).

Methods

Peatland stand delineation by automatic segmentation

In the delineation of peatland stands, the following input data layers were applied: ALS based canopy height model and MSNFI stand height, MSNFI volumes of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) and deciduous trees, and the map of drained and undrained peatlands from the peatland fertility level dataset (GTK 2023; Middleton et al. 2023). For the automatic stand segmentation, all input layers were resampled to similar resolution as the peatland fertility level dataset (i.e. 10 m), if their original resolution was different. The area of interest for this study was defined as the intersection between the area of the peatland fertility level dataset and the area of forestry land in MSNFI maps. The purpose of the automatic image segmentation was the delineation of peatland patches in forestry land to be used as stands in this study.

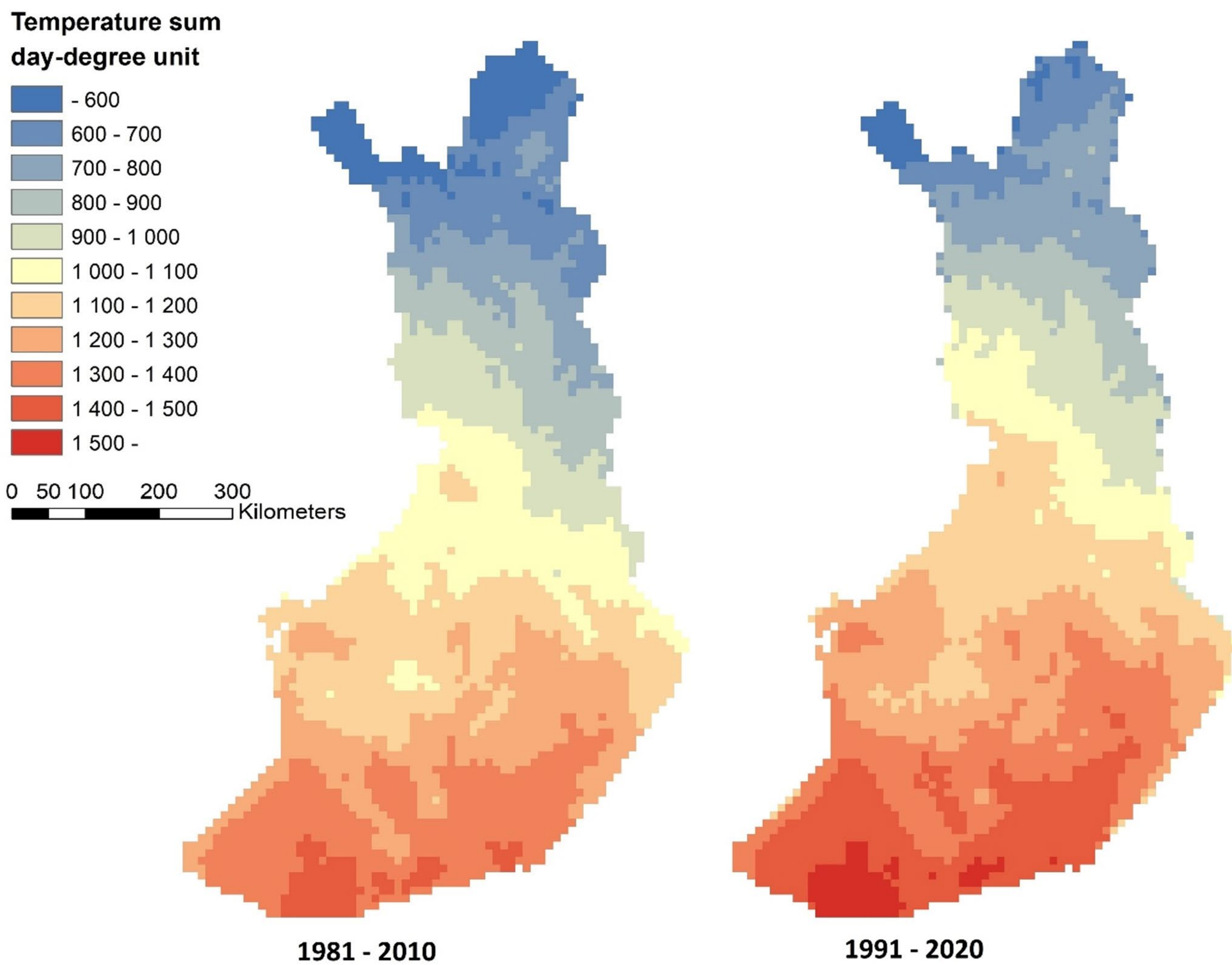

Fig. 2 Average yearly effective temperature sums for periods 1981–2010 and 1991–2020 (Finnish Meteorological Institute 2016)

The resolution of 10 m was considered appropriate for peatland mapping, as it captures areas larger than individual trees yet smaller than typical forest stands or larger mapping units that would cover "mixed pixels" losing part of the variation between the stands. This intermediate resolution enables the effective estimation of stand-level variables such as volume, while minimizing the limitation associated with very small or large mapping units.

Image segmentation is a technique that aims at producing spatially continuous and detached units (i.e. segment areas are mutually exclusive) that are homogeneous in relation to their ecological characteristics (Haralick and Shapiro 1985). For this purpose, we applied segmentation algorithm that combines features of edge-detection and region-merging based approaches: "Image segmentation with directed trees" (Narendra and Goldberg 1980). We utilized software that is based on modified implementation of the algorithm, as described by Pekkarinen (2002, 2004). The initial phase of the segmentation is based on edge detection methods (i.e. recognizing locations of significant changes in input data, such as stand borders). The edge detection process is local in character and thus, it does not assume spectral uniformity over the entire area of analysis. The consecutive phase of segmentation is based on region merging, where initial segments were merged into larger units (here stands) based on user-defined minimum area allowed for the segments. The segment minimum area was set as 0.25 ha in Southern Finland, and 0.5 ha in northern Finland.

Extraction of volume data for peatland stands

For assessing the productivity of each forestry-drained peatland stand, the average stand volume from MSNFI maps covering the period 2000–2021 was calculated (for each inventory date: 2000, 2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019 and 2021). In practice, the actual date of satellite data often varied ± 1 year from the nominal inventory year in parts of the country, mainly due to poor availability

Table 1 Productivity classes for drained peatland forests. Classes 1 and 3 will be collectively called "poorly productive"

Productivity class	Description
1	Unproductive, upper quartile (Q75%) volume < 30 m^3ha^{-1}
2	Productive, young stand, Q75% volume < 30 m^3ha^{-1}, growth > 1 m^3ha^{-1} yr^{-1} *
3	Low-productive, Q75% volume 30–45 m^3ha^{-1}
4	Medium-productive, Q75% volume 45–60 m^3ha^{-1}
5	Productive, Q75% volume > 60 m^3ha^{-1}

*Due to growth rate, (Q75% m^3ha^{-1}-Q25% m^3ha^{-1})/21 yr > 1m^3ha^{-1} yr^{-1}, this class is treated as productive

of cloudless satellite images. The satellite image-based volume predictions at the level of individual image pixels often are prone to random fluctuation not related to actual forest development, causing sometimes extreme values that increase/decrease the maximum/minimum volume estimates. To avoid unrealistic assessments, we used the upper (75%) and lower (25%) quartiles of the MSNFI volume time series as the estimated maximums and minimums. Due to the absence of extensive stand growth data, the MSNFI volume time series was considered as the most appropriate proxy for evaluating stand-level productivity.

Criteria for classifying productivity of drained peatland forests

Drained peatland forest stands were classified into five productivity classes (Table 1) based on the upper and lower quartiles in the MSNFI volume time series (Figure S1 in Online Supplement). The class-specific volume thresholds were based on the approach by Laiho et al. (2016), including, for example, a volume threshold of < 30 m^3ha^{-1} to define unproductive stands. However, the classification was adjusted to account for young stands, where the upper quartile value of volume time series was low (i.e. < 30 m^3ha^{-1}), but the current productivity – estimated from the difference between the upper and lower quartiles – was high enough to be judged as productive. These stands were assigned to class 2. Stands with 30–45 m^3ha^{-1} upper quartile value for volume formed class 3, following the studies by Laiho et al. (2016) and Kojola et al. (2015), which consists of those stands where growth is over 1 m^3ha^{-1} yr^{-1} but management is unprofitable at least with present levels of prices and costs. The regional prevalence of the productivity classes was calculated as an aggregation of the stand level classes in each region of Finland.

We compared the MSNFI time series-based productivity classification to the earlier classification of economic feasibility for timber production applied in Finland. The earlier classification was based on estimated future stand growth (generated by Motti stand simulator, see, e.g., Kojola et al. 2008) and timber revenues and regeneration costs (900 € ha^{-1}) assuming 3% interest rate (see details in Äijälä et al. 2019, pp. 239). Technically, the economic feasibility corresponds to a situation where the bare land value of future generations is positive (for detailed notation on assessing the bare land value, see Ahtikoski and Hökkä 2019, Eq. 1). The input variables for the classification of economic feasibility were local temperature sum and the site fertility class (Table 2; Äijälä et al. 2019; Kojola et al. 2013).

Table 2 Estimated economic feasibility of timber production in forestry-drained peatlands (assuming 3% interest rate and 900 € ha^{-1} regeneration costs) in various climatic areas (temperature sums, day-degree units [d.d.]) across fertility classes. Symbol "+" indicates economic feasibility (i.e., positive bare land value for future generations) while "-" shows economically infeasible cases, i.e., a negative bare land value. Table is based on Äijälä et al. (2019)

Fertility class	Temp. sum < 900 d.d	Temp. sum 900–1125 d.d	Temp. sum 1126–1150 d.d	Temp. sum > 1150 d.d
Herb rich type	+	+	+	+
Vaccinium myrtillus type	+	+	+	+
Vaccinium vitis-idaea type	–	+	+	+
Dwarf shrub type	–	–	–	+
Cladina type	–	–	–	–

We calculated the area of forestry-drained peatlands judged as economically infeasible for timber production according to two different 30-yr climate periods, to consider how the observed climate trends are reflected in average temperature sums, and how they affect the feasibility assessment.

Calculating ditch density and ditch spacing

Ditch density was calculated as total ditch length in the stand divided by the surface area of the stand. Generally, assuming evenly spaced ditches, a ditch density of 250 m ha^{-1} corresponds to 40 m ditch spacing. Ditch density does not directly translate into ditch spacing, since the stands vary in their shape and in their ditch constellation, and thus, ditch spacing was calculated for stands using the majority value within the stand from the maximum distance to stream raster (Fig. 3). This maximum distance to stream raster was calculated by first determining the Euclidean distance to stream network in 2 m resolution with WhiteboxTools (Lindsay 2018) and then resampled to 40 m x 40 m grid size using the maximum distance value (Fig. 3). For each stand, the extracted majority value was multiplied by 2 to get ditch spacing.

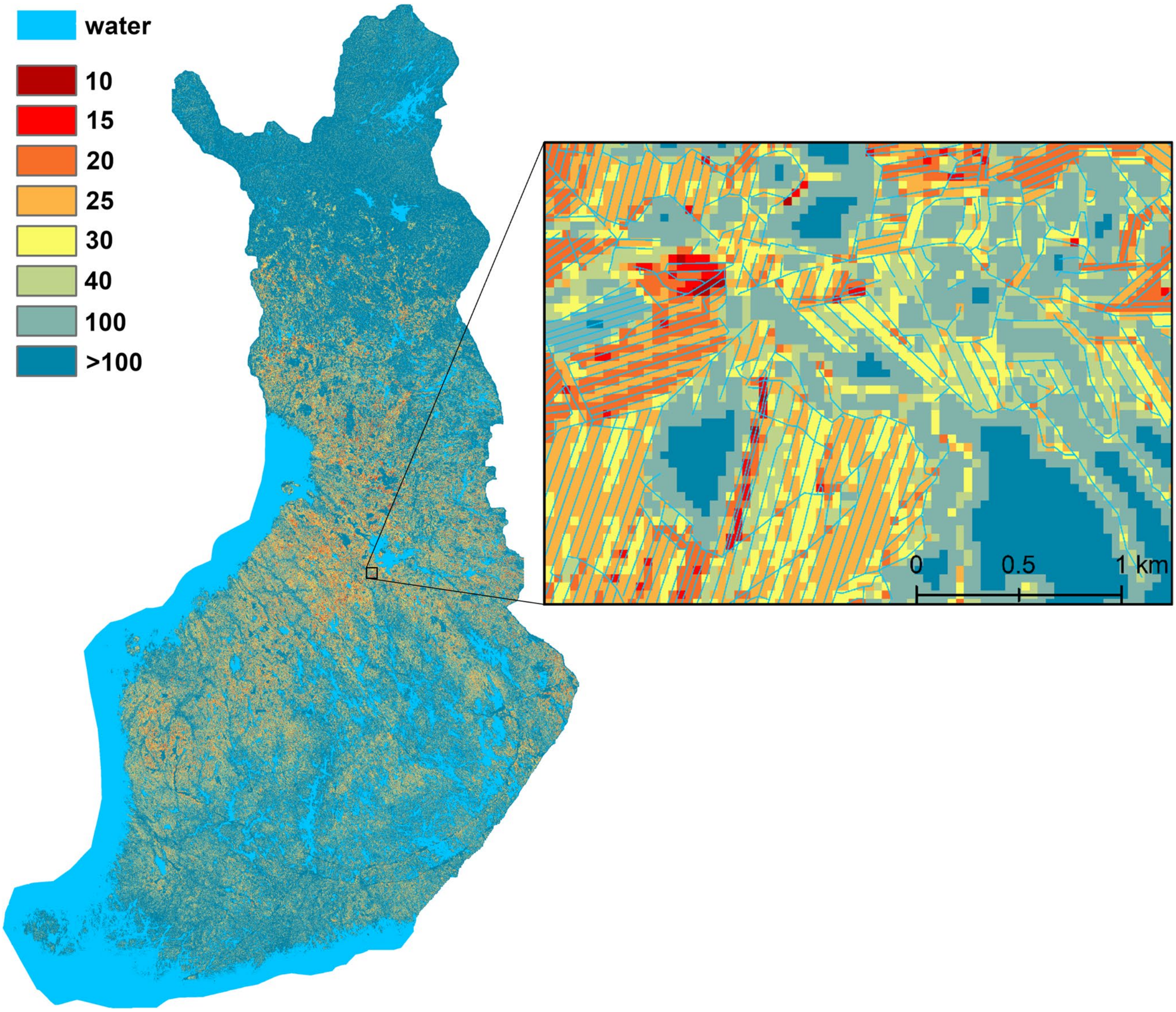

Fig. 3 Maximum distance [m] to nearest stream based on the streams in the Topographic Database 2024 (NLS 2024)

Exploring factors affecting the productivity

We used the *LogisticRegression* function from the *sklearn.linear_model* module in Python (Jolly 2018) for exploring productivity class distribution. Five predictors were used, all numerically represented and treated as ordinal variables: ditch density ('DitchDen'), temperature sum ('TS19912020'), fertility class ('Fer_Maati', classes 14, 33, 56, 72 and 92, the higher the number, the lower the fertility), MSNFI-based forest land class ('Land_cl', classes 1–3, from good to poor productivity), and geographic region ('Region', the lowest numbers represent southern regions increasing towards the north). The target variable was the categorical productivity class ('Prod_cl').

Dataset of the chosen predictors and target variable was split into training (80%) and testing (20%) subsets using stratified random sampling to preserve class distribution. To ensure comparability between variables with different scales, all predictors were standardized using z-score normalization:

$$X' = \frac{X - \mu}{\sigma}, \tag{1}$$

where X' is the standardized value, X is the original feature, μ is the mean, and σ is the standard deviation.

The model was trained as a multinomial logistic regression with class balancing applied and fitted using the '*LBFGS'* solver (Limited-memory Broyden-Fletcher-Goldfarb-Shanno solver is suitable for multiclass classification problems, Byrd et al. 1995). The maximum number of iterations was set to 500 to allow for convergence. The trained model was applied to the test set to generate predictions. Performance was assessed using accuracy which informs about the overall proportion of correctly classified observations, and precision, recall, and F1-score, which are evaluated for each class to determine the model's ability to correctly identify productivity classes. The model coefficient values are explored to interpret the effect of each variable. The uncertainty of coefficients was quantified using nonparametric bootstrap (200 replicates seeded with random state [42+0…199] from the training subset).

Results

Productivity classification of drained peatland forests based on MSNFI time series

The productivity assessment based on MSNFI volume time series indicates that approx. 83% of forestry-drained peatlands had either good or at least medium productivity (Table 3). Of the remaining area, approx. 8% was unproductive, and 9% had low productivity. In southern Finland, over 90% of forestry-drained peatlands had good or at least medium productivity. In Kainuu and North Ostrobothnia regions of northern Finland, the proportion of stand area with good and medium productivity was still over 80%. In Lapland (excluding the three northernmost municipalities, where practically all peatlands were undrained), the proportion of poorly productive stand area was approx. 40% of the total forestry-drained peatland area.

Table 3 Regional and national areal proportions of productivity classes. The values represent percents of total forestry-drained peatland area. See Table 1 for class specifics

Region	Unproductive (Class 1)	Low-productive (Class 3)	Medium-productive (Class 4)	Productive (Classes 5, 2)
01 Uusimaa	0.7	0.9	1.0	97.4
02 Southwest Finland	1.7	1.4	1.7	95.3
04 Satakunta	3.1	2.4	2.8	91.7
05 Kanta-Häme	0.5	0.5	0.9	98.1
06 Pirkanmaa	1.7	1.5	2.4	94.3
07 Päijät-Häme	0.4	0.5	0.9	98.1
08 Kymenlaakso	0.9	0.6	0.9	97.7
09 South Karelia	1.1	0.6	1.1	97.2
10 South Savo	1.0	0.6	1.1	97.3
11 North Savo	2.2	1.9	3.3	92.5
12 North Karelia	2.6	2.6	3.9	90.9
13 Central Finland	1.6	1.8	3.2	93.3
14 South Ostrobothnia	4.6	4.4	5.5	85.5
15 Ostrobothnia	2.6	3.0	4.0	90.4
16 Central Ostrobothnia	7.1	6.5	8.3	78.1
17 North Ostrobothnia	9.7	8.7	10.3	71.2
18 Kainuu	7.3	8.5	11.1	73.1
19 Lapland*	21.6	18.4	19.6	40.4
21 Åland	0.5	1.7	3.3	94.6
Finland	8.7	7.9	9.3	74.1

*Excluding the northern aapa and palsa mire zone, where practically all peatlands were undrained (Middleton et al. 2023)

The poorly productive area covered altogether ca. 780 000 ha, consisting of 410 000 ha of class 1 (stand volume Q75%<30 m^3ha^{-1}) and 370 000 ha of class 3 (stand volume Q75%<45 m^3ha^{-1}) stands (Table 4). The proportion of poorly productive drained peatland of total forestry-drained peatland area was highest in Lapland (southern part of the region, excluding three northernmost municipalities), North Ostrobothnia and Kainuu (Fig. 4). These regions were also the ones with the largest total forestry-drained peatland area (Table 4).

Comparison to earlier economic feasibility classification

The area judged to be economically infeasible for timber production according to the earlier classification method of economic feasibility reached up to 1 136 790 ha (24% of the total drained peatland) when the temperature sum period 1981–2010 was used (Table 4). The area was significantly lower (688 500 ha) when the period of 1991–2020 was used. The results of the MSNFI volume times series, based productivity classification, differed from the economic feasibility classification in many regions, often yielding clearly lower areal estimates for poorly productive area (Table 4, Fig. 5).

The climatic difference between the two reference periods (1981–2010 and 1991–2020) is evident (Fig. 5, Fig. 6). The temperature sums increased remarkably already by shifting the period by ten years, which is mainly due to the prevailing cold summers during the 1980s and the exceptionally warm summers in the 2010s. It suggests that the temperature sums and growing seasons will change even more drastically in the coming years. This influences also the economic feasibility classifications.

The change in the proportion of areas infeasible for timber production is most significant in the northern parts of Finland, and in high-elevation areas of Ostrobothnia, where temperature sum has been a stronger limiting factor for forest growth. There is less change elsewhere, where the temperature sums have typically already exceeded the reference limits used for assessing the suitability for timber production.

Table 4 Area (ha) of poorly productive forestry-drained peatlands (classes 1 and 3) compared to earlier classification of economic feasibility for timber production using two different temperature sum (TS) periods (periods 1981–2010 & 1991–2020)

Region	Unproductive (Class 1)	Low-productive (Class 3)	Poorly productive (Classes 1, 3)	Economically infeasible, TS 1981–2010	Economically infeasible, TS 1991–2020	Drained peatland total
01 Uusimaa	220	290	510	810	810	32,960
02 Southwest Finland	770	630	1400	4140	4140	46,500
04 Satakunta	3100	2390	5490	15,100	13,600	99,610
05 Kanta-Häme	230	260	490	2060	2060	49,190
06 Pirkanmaa	2320	2040	4360	19,020	12,150	135,610
07 Päijät-Häme	120	150	280	600	600	28,050
08 Kymenlaakso	350	220	570	1440	1440	39,300
09 South Karelia	620	320	930	1730	1730	54,180
10 South Savo	1330	860	2190	3620	3620	137,650
11 North Savo	6470	5610	12,080	10,000	5970	287,770
12 North Karelia	10,920	10,800	21,720	56,530	25,370	412,630
13 Central Finland	3770	4180	7950	29,560	9300	230,590
14 South Ostrob	13,770	12,910	26,680	93,670	58,750	296,450
15 Ostrobothnia	2640	2990	5630	13,680	11,910	99,880
16 Central Ostrob	9540	8790	18,330	45,110	30,050	135,050
17 North Ostrob	102,510	91,930	194,440	242,620	179,940	1,052,180
18 Kainuu	44,250	50,970	95,220	103,100	77,470	603,080
19 Lapland*	207,160	176,430	383,590	493,990	249,580	959,050
21 Åland	10	20	30	10	10	1340
Finland total	**410,100**	**371,790**	**781,890**	**1,136,790**	**688,500**	**4,701,070**
% of total drained area	9	8	17	24	15	

*Southern part, excluding the northern aapa and palsa mire zone, where practically all peatlands were undrained (Middleton et al. 2023)

Exploring productivity through ditch density, fertility and temperature sum

When productivity classes were explored with multinomial logistic regression model, an overall accuracy of 69% was achieved (Table 5). The weighted average precision, recall, and F1-score were 0.83, 0.69, and 0.75, respectively, indicating a moderate level of predictive performance.

The distribution of stands across productivity classes was imbalanced, with productive class 5 being largest, and thus, having the highest performance in the model. The unproductive and low-productive classes (1, 3) had moderate precision (65% and 43%) but lower recall (66% and 31%), suggesting that predictability of these classes is weaker. The medium-productive (4) and productive young stands (2) classes were not easily predicted with the model. Interpretation of variable coefficients is focused on productivity classes 1 and 5.

The results indicate that ditch density and temperature sum were the strongest variables explaining productivity class, with higher drainage and warmer conditions favouring more productive peatlands. Ditch density was associated positively with the productive class (5) and negatively with the unproductive class (1) (Table 6), suggesting that more intensively drained peatlands tend to be more productive. Similarly, temperature sum was positively associated with the productive stands, including productive young stands, and negatively with unproductive and low-productive stands. The coefficient for temperature sum was stronger than for ditch density (Table 6: -0.46 vs. -0.36 for class 1, and 0.68 vs 0.60 for class 5).

The results show that site fertility has a positive effect on productivity (i.e. negative coefficient as the lower the ordinal value, the higher the fertility), and the MSNFI forest land class agrees with the time-series based productivity classification of this study (the lower the value, the better the productivity class in MSNFI forest land class), while geographical region had only a miniscule effect on predicting productivity.

While drainage has aimed at increasing productivity, it has not always succeeded, and the dataset revealed those stands that have been intensively drained but are still poorly productive (Fig. 7). Based on the dataset, the overall mean ditch density was 252 m ha^{-1}, but nearly 18% (~835 000 ha) were estimated to have a higher ditch density (with ditch spacing of 30 m or less), and about 30% had a lower ditch density with ditch spacing greater than 50 m.

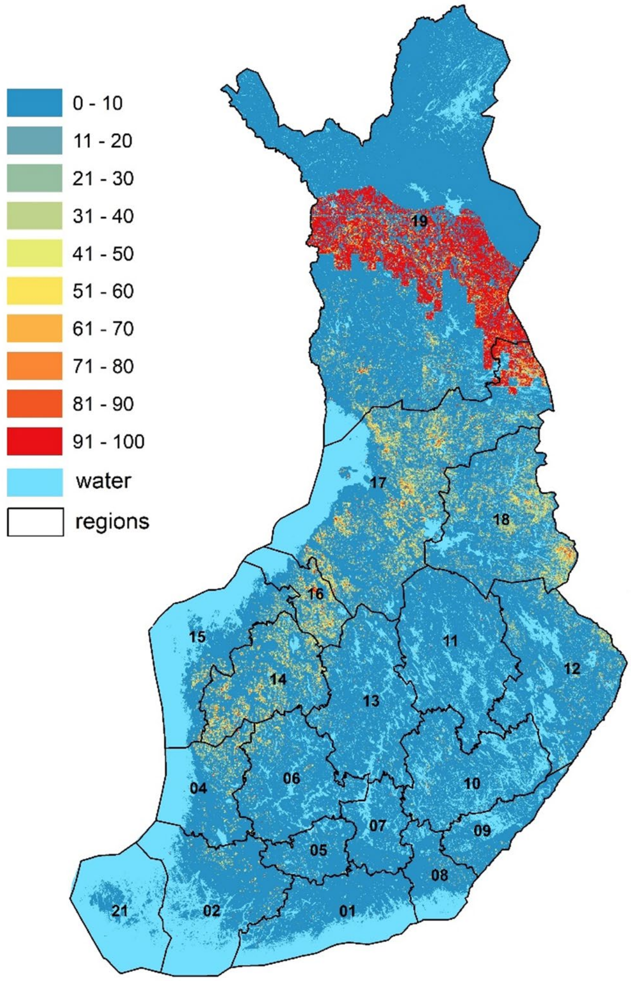

Fig. 4 Proportion [%] of unproductive (class 1) from total drained peatland forests based on stand level MSNFI volume time series mapped in 1 km × 1 km grid. In the most northern aapa and palsa mire zone practically all mires are undrained, resulting in distinct borderline between southern and northern parts of Lapland. The numbered regions are listed in Table 4

Discussion

We developed a methodology to classify stand productivity for an extensive spatial dataset that can support precision management in drained peatland forests. With this spatial dataset, both the poorly productive and productive forestry-drained peatlands can be located and the additional information on their drainage intensity and fertility class provides valuable support for targeting a wide range of peatland management activities from timber production with different management regimes to restoration. Precision forestry considering e.g. tree species composition, fertilization or managing hydrological conditions, can be targeted spatially more explicitly to areas with suitable fertility classes and drainage conditions. This dataset can support more sustainable peatland management planning, which can be supported by public subsidies (METKA in Finland, MAF 2021), aiming to enhance profitable timber production simultaneously with mitigation of the negative impacts induced by managing peatlands. Furthermore, the dataset can support the implementation of the EU Nature Restoration Law (EU Regulation 2024/1991), as well as national greenhouse gas inventories and carbon removal certification in the context of carbon farming.

Accurate spatial data on drained peatlands are also important considering the EU Freshwater Directive (EU Directive 2000/60/EC; Minasny et al. 2023) and the provided spatial dataset can support identifying nutrient-export hotspots. Nutrient-poor sites may be prioritized for restoration due to their low risk of nutrient runoff and methane emissions, whereas nutrient-rich sites may require additional considerations to prevent water quality deterioration in adjacent ecosystems (Koskinen et al. 2017; Juutinen et al. 2020). On the other hand, nutrient-rich sites, especially those that were densely forested already at their natural state, have become relatively rare because they were primarily drained due to higher productivity expectations (Keltikangas et al. 1986; Hörnberg et al. 1998).

The majority (83%) of forestry-drained peatlands in Finland were classified as productive or medium-productive, which is consistent with previous analyses (Laiho et al. 2016) and with the results of the NFI (Korhonen et al. 2024), although the area estimates differ to some extent. The classification presented here resulted that altogether 17% (780 000 ha) was poorly productive (classes 1, 3), mostly located in northern Finland. The area of the lowest productivity class 1 (unproductive; 410 100 ha) was only slightly higher compared to the area estimate of 367 000 ha by Laiho et al. (2016).

It is not surprising that the classification results are highly dependent on the applied criteria for the classification. There are no natural, "true" boundaries for the productivity classes, but they depend on subjective choices guided by economic analyses and understanding of ecosystem functions. The highest area estimate (1.14 million ha, Table 4) for economically infeasible peatland forests was given by the earlier classification (Äijälä et al. 2019), which was based on the temperature sum from the period 1981–2010. Using the more recent temperature sum from the period 1991–2020, the economically infeasible area dropped to 690 000 ha, which aligns closer to the level of the estimate on poorly productive area (classes 1, 3). The shift in the reference period by ten years significantly affected the estimate of the economically infeasible area, particularly in the northernmost regions, Northern Ostrobothnia, Kainuu, and southern Lapland. This shift aligns well with earlier findings that postdrainage productivity of peatland forests depends on climatic conditions (e.g., Heikurainen and Seppälä 1965;

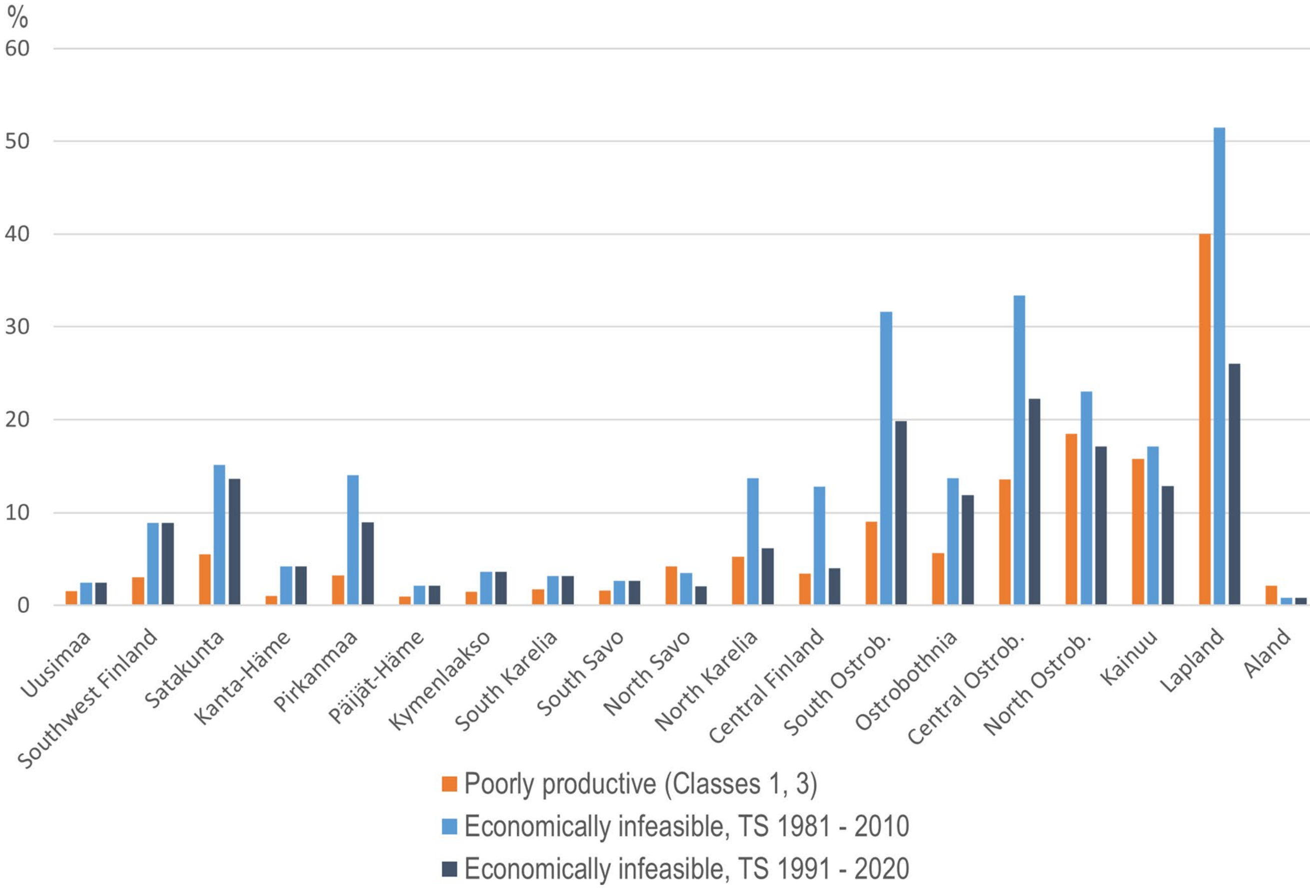

Fig. 5 Proportion [%] of poorly productive from all forestry-drained peatlands by regions and proportions [%] of economically infeasible forestry-drained peatlands from all forestry-drained peatlands by regions calculated using two different periods for temperature sum (TS), 1981−2010 and 1991−2020

Hånell 1988), and indicates that the productivity estimates should probably be updated at around 10-year intervals, depending on the intensity of climatic changes.

Productivity further depends on the availability of N, but also of P and K, for forest growth (e.g., Kaunisto and Paavilainen 1988; Laurén et al. 2021). The fertility classes identified based on ground vegetation generally reflect quite well the variation of the total pools of these nutrients in the surface peat (Westman and Laiho 2003). The pools of N and P in the rooting zone are generally manyfold in comparison with the amounts bound in aboveground tree biomass (Westman and Laiho 2003), and their availability largely depends on temperature-dependent soil processes. Higher contents of N and P in peat are required to support a certain plant community in colder than in warmer climate (Westman and Laiho 2003), because the proportion of plant-available N and P of the total content decreases with decreasing temperature sum (Sundström et al. 2000). On the other hand, the pools of K in the rooting zone are relatively low in deep-peat sites (Westman and Laiho 2003), and K availability is not much enhanced in a warmer climate as most of the K in peat is in a soluble form to begin with (Starr and Westman 1978). With the warming climate, at least some northern forestry-drained peatlands may, thus, gradually transform into a higher fertility class with higher productivity, facilitated by their soil N and P contents. While some areas may transition out of the poorly productive category, many of the least fertile *Cladina*-class sites likely remain poorly productive due to their soil N concentration being so low ($<1\%$) that N availability will remain inadequate even under warmer conditions (Kaunisto 1982). Currently, 29% of the poorly productive area is *Cladina*-class.

As a factor affecting productivity, the continued sufficiency of nutrients for forest growth has been questioned as relatively high amounts of K and boron, especially, are removed with harvested wood (Nieminen et al. 2016; Sarkkola et al. 2016). Nutrient shortages may be remedied with fertilization, which is typically economically viable on N-rich ("*V. myrtillus*", "*V. vitis-idaea)* sites (Hökkä et al. 2024). However, further studies of the development of the nutrient status in drained peatland forests is needed for forecasting the extent to which fertilization is needed to maintain

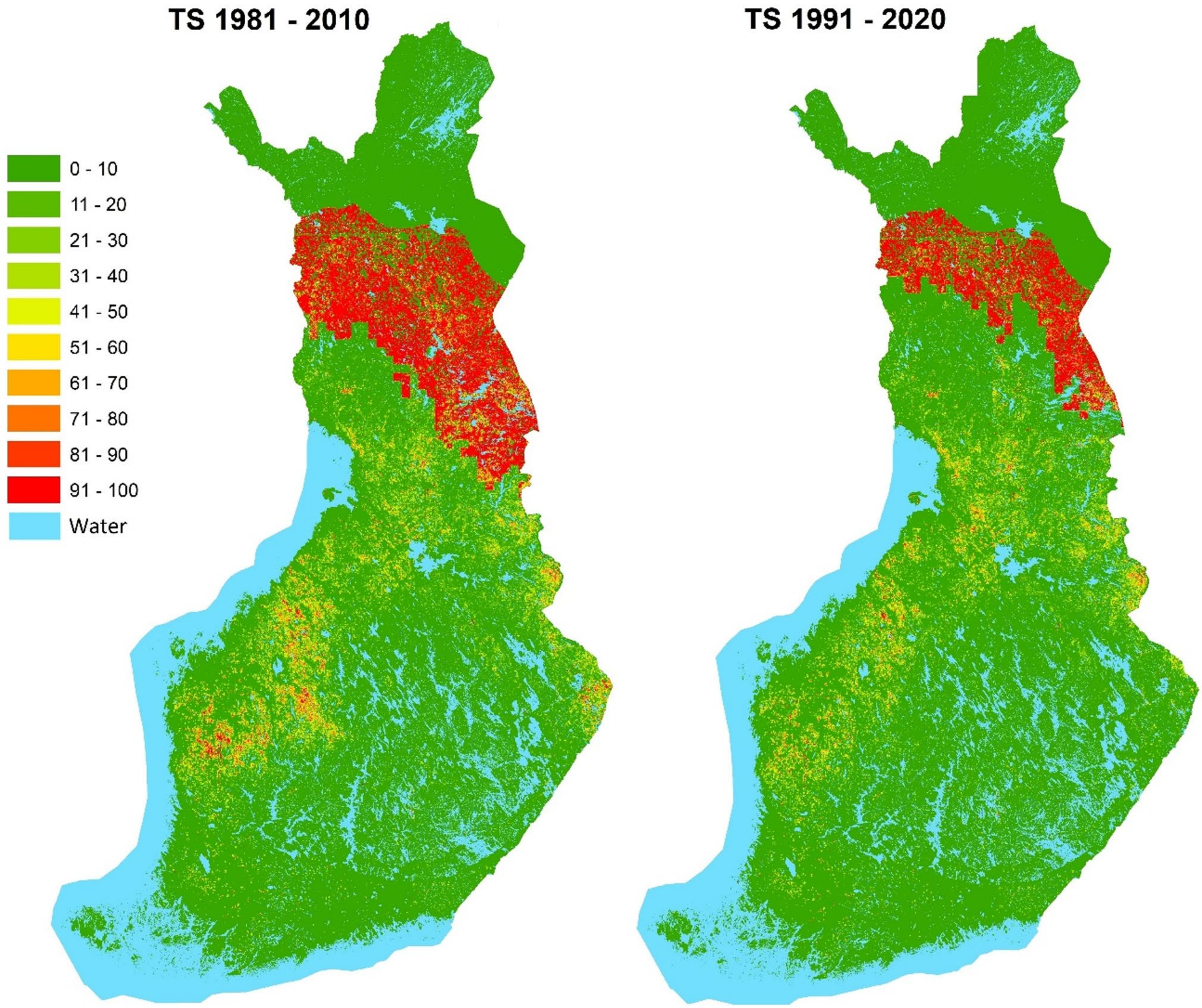

Fig. 6 The proportion [%] of forestry-drained peatlands from all forestry-drained peatlands where timber production is classified as economically infeasible based on temperature sum (TS) and site fertility class

Table 5 Performance table of the multinomial logistic regression model

Productivity class	Precision	Recall	f1-Score	n
1	0.65	0.66	0.65	60,113
2	0.01	0.58	0.02	1277
3	0.43	0.31	0.36	58,175
4	0.20	0.45	0.27	71,416
5	0.95	0.75	0.84	677,697
accuracy			0.69	868,678
macro avg	0.45	0.55	0.43	868,678
weighted avg	0.83	0.69	0.75	868,678

future productivity that is shaped by both management and climate change. Furthermore, optimizing stand management with fertilization by ideally choosing the timing for thinnings, fertilization(s), and final cut improves further the profitability (Ahtikoski and Hökkä 2019). Such an intensive

Table 6 Multinomial logistic regression model coefficients with standard errors for the predictors

Productivity class	Ditch density	TS 1991–2020	Fertility class	Forest land class	Region
1	-0.36 (0.01)	-0.46 (0.01)	0.27 (0.01)	1.00 (0.01)	-0.08 (0.02)
2	-0.69 (0.02)	0.46 (0.02)	0.27 (0.01)	0.20 (0.01)	-0.07 (0.02)
3	0.12 (0.01)	-0.35 (0.01)	0.04 (0.00)	0.38 (0.00)	0.02 (0.01)
4	0.33 (0.01)	-0.32 (0.01)	-0.12 (0.00)	-0.28 (0.00)	0.12 (0.01)
5	0.60 (0.01)	0.68 (0.01)	-0.45 (0.01)	-1.30 (0.01)	0.02 (0.01)

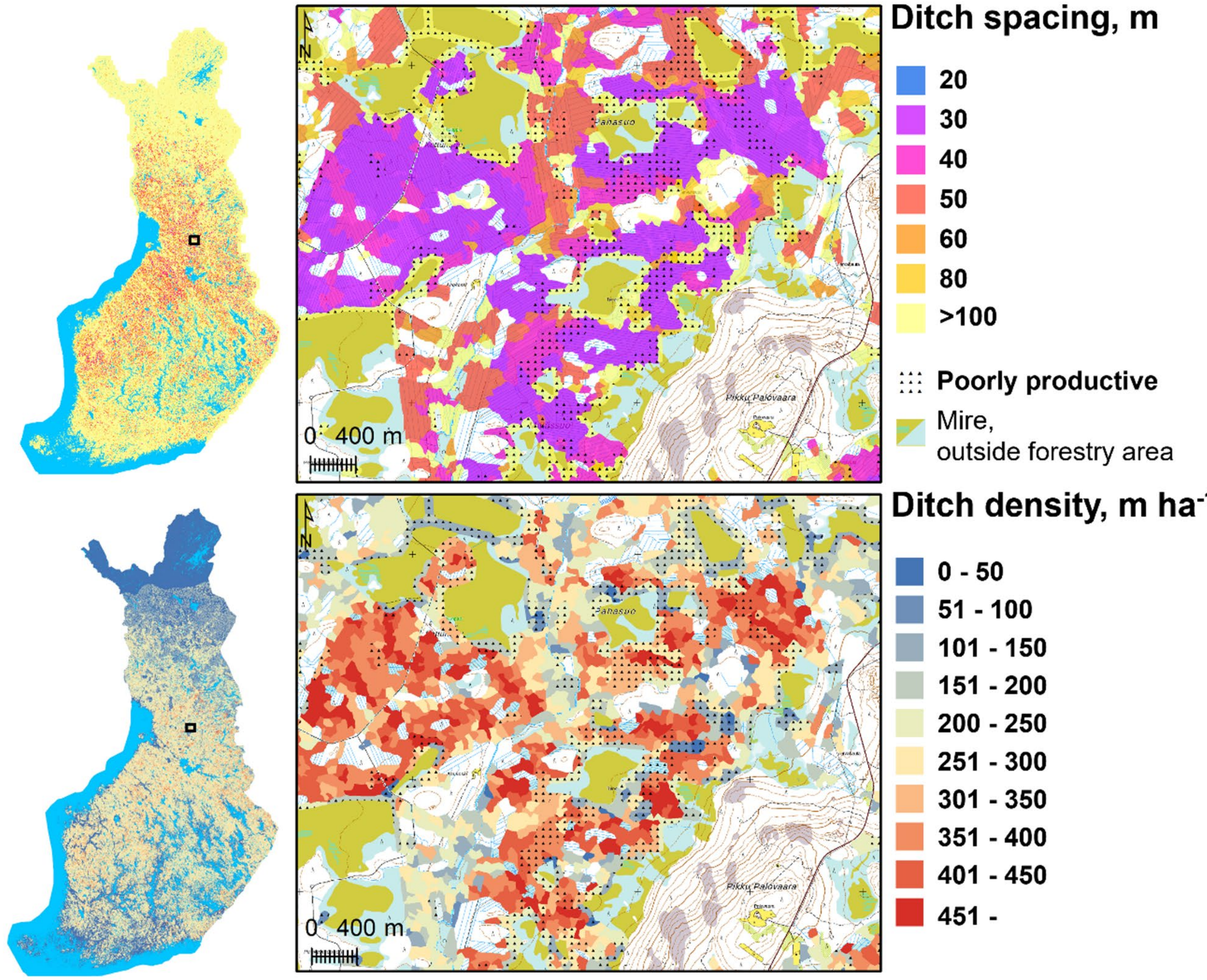

Fig. 7 Example on the ditch spacing, ditch density and productivity class information along with the identification of intensively drained but poorly productive forestry-drained peatland stands provided by the dataset

management requires a reliable classification based on productivity to avoid misallocation of resources, i.e., misplaced investments on silviculture.

It remains, in any case, uncertain how productivity will develop when temperature sums and length of growing periods increase. Even though an increase in temperature sum may enhance growth (e.g., Henttonen et al. 2017), for some time and some tree species (Mäkinen et al. 2022; Henttonen et al. 2024), forest productivity responses may also strongly depend on changes in moisture conditions, and increasing drought stress may lead to lower productivity (e.g., Hember et al. 2016; Sulla-Menashe et al. 2018; Mirabel et al. 2023). Earlier, it has been supposed that drought would not limit productivity in drained peatland forests, but this supposition may prove wrong, depending on both climatic changes and management decisions (Laudon et al. 2024; Shekhar et al. 2024; Hökkä et al. 2025). Further, increased pest activity could challenge forest growth under higher temperatures (Laudon et al. 2024) and introduce costs in the management chain. Economic feasibility depends not only on productivity and revenues but also on costs generated by silvicultural measures, i.e. the whole management regime. The potential effects of future threats on productivity and ecosystem stability in drained peatlands are not yet fully understood and require further investigation.

Changes in management or restoration efforts are more effective when applied to larger, contiguous areas rather than scattered stands. A spatial dataset supports considering structural and functional connectivity of the ecosystem to be restored. This dataset has already been applied to identify poorly productive stands in state-owned forests near the protected and nature conservation areas that could be restored (Kekkonen et al. 2024). The approach used here for calculating drainage intensity with yearly updated ditch data provides a relatively straightforward method to track restored peatlands, allowing then more labor-intensive satellite data monitoring subsequently targeted to identified restoration areas. Based on the dataset, the area of stands with ditch density almost zero was 59 600 ha (50% *V. vitis-idaea*, 20% herb-rich), which corresponds to recent expert estimates of the restored area (Luonnonvarakeskus 2024; Laine et al. 2024). Furthermore, areas that have not improved from poor productivity despite the high ditch density, could be considered for alternative management than timber production. Targeting restoration and financial support to such areas could help meet the goals of EU Nature Restoration Law and the EU Freshwater Directive.

The dataset produced in this study provides precise stand boundaries due to high resolution source materials and attribute information based on the recent peatland fertility level data and analysis of drainage intensity. Unlike the productivity-related classification of forest land type in MSNFI, which is heavily influenced by the status of tree cover (and the effect of cuttings) at the time of satellite imagery, this time series-based approach provides a more stable and reliable productivity classification compared to previous studies (Laiho et al. 2016). This dataset not only facilitates the ongoing assessment and management of peatlands but also enhances the ability to model and predict changes in productivity and GHG emissions in response to varying drainage intensities and management practices, both significantly affecting forest growth and GHG emissions (Palviainen et al. 2024).

Conclusions

This study provides a nation-wide dataset for precision management of drained peatland forests. With a long time series, the dataset enabled accurate assessments of peatland productivity, providing a baseline for facilitating targeted restoration and management strategies. The availability of detailed information on drainage intensity is particularly beneficial, as it influences both water quality and GHG emissions, key components in peatland management and restoration.

Climate change presents a dynamic challenge to the definition and management of poorly productive areas. Some of these areas may change towards more productive sites, but the overall impact on productivity, including potential shifts in forest growth patterns and GHG emissions, remains uncertain. It is, thus, crucial to continually monitor and adapt management strategies.

The dataset provides a foundation for identifying areas where restoration efforts can be effectively targeted. It also highlights cases where drainage may have led to ineffective or even counterproductive investments. The dataset can be used to explore alternative management practices for the poorly productive areas, such as carbon trading, which could offer forest owners new revenue streams while supporting ecological restoration efforts. The dataset can help to focus private investments to feasible targets and to allocate the forest subsidies effectively.

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Data availability Availability of data and material (data transparency): The dataset is available as Zenodo record: https://doi.org/10.5281/zenodo.15260366

Declarations

Conflicts of interest The authors declare no competing interests.

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