Kaja Stamer Ekerholt

CO_2 Emissions by Land Cover Change of Peatlands in Trondheim Municipality

A GIS study of the extent of lost peatlands in Trondheim municipality from 1964 to 2021

Master's thesis in Industrial Ecology
Supervisor: Kristian Hassel
Co-supervisor: Anders Lyngstad
June 2023

Master's thesis

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Norwegian University of Science and Technology
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Abstract

Peatlands are vital components in the global carbon (C) balance because of their high C stocks and ability to function as C sinks under natural conditions. However, peatlands have been under anthropogenic pressure worldwide, which has caused extensive degradation of such areas. Norway is no exception, and land cover changes of peatlands have contributed to increased atmospheric C levels. However, information on peatland extent and status is lacking, resulting in C loss estimates with high uncertainties. To fill this knowledge gap and better understand the effects of peatland degradation, new mapping is necessary.

By mapping land cover changes in peatland areas from 1964 to 2021, this study identifies the areal extent of lost peatlands in Trondheim municipality and evaluates drivers and trends of this change. Further, the emissions stemming from the lost peatlands have been quantified by combining research and mapping. Three scenarios were constructed to detect differences in CO_2 emissions from degraded peatlands, and thus acknowledge the importance of precise peat depth estimates. Scenario 1 constitutes the mean of the collected peat depths, while scenarios 2 and 3 constitute a minimum and a maximum estimate, respectively.

The results reveal that 16% of the peatland areas present in Trondheim municipality in 1964 were lost by the year 2021. The lost peatlands are restricted to elevations below 300 metres above sea level, where the majority have undergone a transformation to infrastructure. 37% of the peatland loss is attributed to the degradation of Heimdalsmyra. For scenarios 1, 2, and 3, the loss of peatlands equals 2.3, 1.2, and 3.5 million tonnes of CO_2 emissions, respectively. Although emissions from degraded peatlands in Trondheim municipality are projected to decrease due to national regulations and initiatives on restoration and conservation, supplementary measures are required to abate the C loss to a minimum.

Sammendrag

Myrer er essensielle komponenter i den globale karbonbalansen på grunn av deres store karbonlagre og deres evne til å fungere som karbonsluk under naturlige forhold. Myrområder har imidlertid blitt utsatt for menneskelig påvirkning over hele verden, noe som har forårsaket omfattende forringelse av slik natur. Norge er intet unntak, og arealendring av myrområder har bidratt til økte nivåer av atmosfærisk karbon. Imidlertid mangler informasjon om omfanget og tilstanden til myrområdene, noe som gjenspeiles i store usikkerheter i estimater av karbontap. Ny kartlegging er nødvendig for å fylle dette kunnskapshullet og få en større forståelse for effektene av å ødelegge myr.

Ved å kartlegge endringer i arealbruk av myrer fra 1964 til 2021, identifiserer denne studien omfanget av tapte myrområder i Trondheim kommune og evaluerer drivkreftene og trendene for denne endringen. Videre, ved å kombinere litteratursøk og kartlegging har utslippene som stammer fra tapte myrområder blitt kvantifisert. Tre scenarier ble konstruert for å belyse ulikheter i CO_2-utslipp fra nedbrutt myr, og dermed erkjenne betydningen av nøyaktige estimater for myrdybde. Scenario 1 utgjør gjenomsnittet av de innsamlede myrdybdene, mens scenarie 2 og 3 utgjør henholdsvis et minimums- og et maksimumsestimat.

Resultatene viser at 16 % av myrområdene som var til stede i Trondheim kommune i 1964, var gått tapt innen 2021. De tapte myrene er lokalisert under 300 meter over havet, hvor flertallet har blitt transformert til infrastruktur. 37 % av tapet kan tilskrives nedbyggingen av Heimdalsmyra. For scenarier 1, 2 og 3 tilsvarer tapet av myrområder henholdsvis 2,3, 1,2 og 3,5 millioner tonn CO_2-utslipp. Selv om utslippene fra myrområder i dårlig økologisk tilstand i Trondheim kommune forventes å avta på grunn av nasjonale reguleringer og initiativer for restaurering og bevaring, kreves det supplerende tiltak for å begrense karbontapet til et minimum.

Preface

This master's thesis is the continuation of my project thesis that was carried out in the fall semester of 2022 and marks the end of my MSc in Industrial Ecology at the Norwegian University of Science and Technology (NTNU) in Trondheim.

First and foremost, I would like to express my gratitude to Kristian Hassel and Anders Lyngstad from the Department of Natural History at the NTNU University Museum for their willingness to act as my supervisors as I wanted to explore peatland loss in Norway. Their accessibility, constructive feedback, and generous sharing of their vast knowledge have been very valued and have further sparked my interest in the subject of peatlands. I would also like to extend my gratitude to Marc Daverdin at the NTNU University Museum for willingly imparting his GIS expertise to me. Last but not least, I want to thank my classmates for their support, interesting discussions, and smiles throughout this work, and a thanks to my family for moral support.

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List of Abbreviations

AR5	National Land Resource Map at scale 1:5000
C	Carbon
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CH_4	Methane
CO_2	Carbon dioxide
DMK	Digitalt markslagskart
FAO	Food and Agriculture Organization of the United Nations
FKB	Felles kartdatabase
GHG	Greenhouse gas
GIS	Geographic Information System
GWP	Global warming potential
IPCC	International Panel on Climate Change
IUCN	International Union for Conservation of Nature
LULUCF	Land Use, Land Use Change and Forestry
M A.S.L.	Metres above sea level
N_2O	Nitrous oxide
NIBIO	Norwegian Institute of Bioeconomy Research
NiN	The EcoSyst framework (Natur i Norge)
NMA	Norwegian Mapping Authority
RF	Radiative forcing
SOM	Soil organic matter
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

Human activities are estimated to have caused an increase in global surface temperature of between 0.8°C to 1.3°C, compared to pre-industrial levels (IPCC, 2021). Over the twenty-first century, a global warming of 2.8°C is expected with current policies (UNEP, 2022). With current pledges, the rise in temperature will only be limited to 2.6°C and 2.4°C for unconditional and conditional contributions, respectively (UNEP, 2022). As global warming represents a risk to human and natural systems, additional pledges must be enforced to limit the global rise in temperature to well below 2°C, as per the goal of the Paris Agreement (UNFCCC, 2015). To achieve this goal, reduction in greenhouse gas (GHG) emissions must be coupled with carbon dioxide removal (CDR) (IPCC, 2018). In this regard, implementation of technology-based CDR such as carbon capture and storage (CCS) should be part of the solution. However, to make this technology both efficient and profitable, further investigation is required (Villa & Bernal, 2018). Nature-based CDR is denoted as an efficient and cost-efficient approach to combat climate change (IPCC, 2019). EU's 2030 climate and energy framework emphasises that the Land Use, Land Use Change and Forestry (LULUCF) sector, including peatlands, will play a central role in achieving the Paris Agreement (European Parliament, 2018).

Peatlands are a type of wetland ecosystem characterized by the accumulation of soil organic matter (SOM) over time, known as peat (Halvorsen, 2016; Rydin & Jeglum, 2013). This process occurs due to water-saturated conditions that hinder the full decomposition of the organic matter (Rydin & Jeglum, 2013). Peat depth is used as a defining feature of peatlands, although the definition varies internationally as different depths are used (Joosten & Clarke, 2002). The International Mire Conservation Group uses a minimum peat depth of 30 cm in their peatland statistics, which is also used in Norway's National Land Resource Map at scale 1:5000 (AR5) (Bjørdal & Bjørkelo, 2006; Joosten & Clarke, 2002). Hence, this study will use the definition of peatland as an ecosystem with a minimum peat depth of 30 cm. It is important to note that a mire and a peatland are distinct terms, as a mire refers to an area with water-demanding vegetation that accumulates peat (Moen et al., 2011). A minimum peat depth of 30 cm is thus not included in the definition of a mire.

During photosynthesis, peatland vegetation captures atmospheric carbon dioxide (CO_2). This carbon (C) sequestration leads to a gradual accumulation of SOM, and the peatland ecosystem acts as a C sink (Villa & Bernal, 2018). However, whether a peatland function as a C sink or source depends on the net balance of its C fluxes, ultimately determining whether it has a net negative or net positive radiative forcing (RF) (Villa & Bernal, 2018). Methane (CH_4) emissions, in particular, may hinder peatlands from having a net negative RF (Joosten & Clarke, 2002). It is produced through the anaerobic decomposition of SOM and has a global warming potential (GWP) of 84 and 28 over a 20- and 100-year time horizon, respectively (Myhre et al., 2013). Hence, the degree to which peatlands have a net positive or net negative RF may vary, but there is strong scientific consensus that they contain a substantial C stock below the ground (Yu, 2012).

1.1 The Importance of Peatlands in the Global Carbon Balance

Peatlands only cover about 3% of the global land area yet are storing C equivalent to more than the global forest biomass and about 60% of the atmospheric C (Joosten, 2015; UNEP, 2016). On average, peatlands have a C stock in the peat of 1125 tonnes of C ha^{-1}, making them the most C-dense terrestrial ecosystem (Joosten et al., 2016). Under natural conditions, peatlands operate as a C sink (Minasny et al., 2019). However, human intervention has resulted in a worldwide degradation of peatlands, especially in areas with substantial population pressure (Joosten, 2016). 0.3% of the world's peatlands have been degraded which has resulted in emissions corresponding to a disproportionate 5% of total anthropogenic CO_2 emissions (Joosten, 2016). Hence, despite covering a small area they contribute substantially to global anthropogenic CO_2 emissions, which emphasises their importance in the global C balance.

1.2 Peatlands in Norway

Peatlands have formed in Norway since the last glacial period around 12 000 years ago, with a subsequent net increase in their areal extent and peat depth (Lyngstad et al., 2022b). However, since the industrialization era, starting in 1750, human activity has caused extensive damage to peatlands, particularly in lowland areas close to cities and agricultural land (Magnussen et al., 2018). Land conversion to agriculture, forestry, pasture, and infrastructure development, including roads, industry, and residential areas, have been the primary interventions in the lowlands (Norwegian Biodiversity Information Centre, 2018). Until the post-war era, peat extraction was also a main intervention (Magnussen et al., 2018). To achieve the desired land cover change, extensive ditching and drainage have been performed. The process lowers the water table and allows oxygen to enter, meaning the process is ceasing CH_4 emissions, but simultaneously increasing CO_2 and nitrous oxide (N_2O) emissions (Bartlett et al., 2020). Consequently, the sites become C sources, contributing to a net positive radiative forcing (Bartlett et al., 2020). While the peat accumulation rate is approximately 1 mm per year, the physical interventions that disrupt the water level occur instantaneously (Moen et al., 2011).

1.3 The Status of Peatlands in Norway

Grønlund et al. (2010) reported that Norwegian peatlands contain 943 to 1035 million tonnes of C, based on an estimated area of 18 800 km^2 to 21 700 km^2. Although there are high uncertainties in the estimate, it is known that peatlands store large amounts of C below the ground (Villa & Bernal, 2018). Land cover change driven by humans has, however, resulted in degradation of peatlands. Annual emissions from drained peatland areas in Norway are estimated to 5.55 million tonne CO_2-equivalents, corresponding to around 10% of national emissions in 2013 (Joosten et al., 2015). This estimate is based on an area of degraded peatlands of 3618 km^2, while a peatland area of 7000 km^2 is believed to be affected by land cover change, meaning the estimate is showing a minimum of C loss (Joosten et al., 2015). Under EUs framework, the LULUCF sector is committed to achieve net zero emissions by 2030 (European Parliament, 2018). Thus, member states, including Norway, are committed to report GHG emissions and removals from peatlands. Consequently, increased knowledge about Norwegian peatlands is needed.

1.4 Global Initiatives and National Regulations of Peatlands

Concerns of peatland degradation, including elevated GHG emissions, have sparked international interest (Minasny et al., 2019). Consequently, actions on the conservation of peatlands have been established through international initiatives and national regulations. International initiatives include the Ramsar Convention and the Global Peatlands Initiative led by the United Nations Environment Program (UNEP). Their common goal is to secure sustainable management of peatlands (Global Peatlands Initiative, 2023; Ramsar Convention, 2015). Whereas Ramsar sites are protected wetlands of international importance, including 63 areas in Norway with a coverage of 1200 km^2, the Global Peatland Initiative provides an updated assessment of the world's peatlands (Bartlett et al., 2020; Global Peatlands Initiative, 2023; Ramsar Convention, n.d.). Further, national regulations on the conservation of peatlands have been implemented. Ditching for forestry was forbidden in 2006, however, maintaining existing ditches is allowed (Forskrift om berekraftig skogbruk, 2006, § 5) The cultivation of peatlands for agriculture was forbidden from 2020, but dispensation may be given (Forskrift om nydyrking, 2020, § 5a). Iversen et al. (2021) state that it is a paradox that the legislation only applies to the cultivation of food and no other area purposes such as infrastructure. Hence, repealing the ban has been proposed and the enforcement is awaiting (Endringslov til jordlova (oppheve forbudet mot nydyrking av myr), 2021, § 11). Despite protected Ramsar sites and national regulations, Norwegian peatlands are threatened by human pressure. Thus, additional information is needed to understand their importance in the global C balance and how to safeguard them.

1.5 Peatland Mapping

Mapping and monitoring of peatlands is essential to understand their extent and status (Minasny et al., 2019). Combining mapping of historical peatlands with mapping of peatlands present today, allows us to identify the extent of lost peatlands out of total peatland coverage. Consequently, mapping provide valuable information that can support actions on the restoration and conservation of peatlands and engage multi-stakeholders in their pursuit to mitigate climate change (Minasny et al., 2019). There are several mapping data types which are suitable for different purposes depending on the individual project specifications. Manual in-situ and remote sensing using aerial photos, LiDAR, or satellite imagery are examples of data types for mapping (Venter et al., 2021). By manual in-situ mapping it is meant on site mapping, also referred to as field work. Compared to remote sensing, it is costly and time consuming (Venter et al., 2021). LiDAR uses laser scanning to measure distances to Earth, consequently creating point clouds of data (National Oceanic and Atmospheric Administration, 2023; Venter et al., 2021). Satellite images are taken with a series of electronic scanners by satellites orbiting the Earth (Nearmap, 2022). An aerial photo, also called an orthophoto, refers to a photo taken from an aircraft, while an aerial photo project refers to a series of photos taken at regular intervals (Nearmap, 2022).

Distinguishing peatland categories when mapping relies on a classification system. The EcoSyst framework (NiN) classifies the variation in Norwegian nature based on a set of criteria and principles (Halvorsen et al., 2015; Halvorsen et al., 2020). The system is developed by experts on behalf of the Norwegian Biodiversity Information Centre (Halvorsen et al., 2015). NiN is based on a typification system and an attribute system which needs to be combined to obtain a complete description of the variation in Norwegian nature (Halvorsen et al., 2015). A detailed description of the classification of peatlands based on NiN is given in Appendix 1.

1.6 Objectives

The project thesis *Assessing Peatland Categories and Peat Depth in Trondheim Municipality to Estimate the Carbon Stock* by Ekerholt (2022) laid the groundwork for the master's thesis. Building on the findings and the identified information gaps in the project thesis, this study aims at expanding the knowledge in the field and address further research questions that emerged from the initial study.

To better understand the effect drained peatlands have on the global C balance, new and extensive mapping is needed (Joosten et al., 2015; Norwegian Environment Agency, 2022). The Norwegian Environment Agency (2022) states that there is a lack of information on peatland categories, their coverage, and the extent of lost peatlands in Norway. Mapping land cover changes allows us to identify the areal extent of lost peatlands and to better understand drivers and trends of the environmental change (Zhou et al., 2021). The findings can thus provide valuable information for future community planning. Further, combining research and mapping allows us to quantify the emissions stemming from land cover change. Trondheim is the most densely populated municipality in Trøndelag county, which is the region with the largest coverage of peatlands in Norway (Hofsten et al., 2017; Statistics Norway, 2022a). This makes Trondheim an interesting study area. Further, Trondheim is representative for the development of urban areas in Norway during the last decades, with urban expansion around the old city centres (Statistics Norway, n.d.). The aim of this study is to identify lost peatlands in Trondheim municipality from year 1964 to year 2021 and estimate how much C emissions this has caused to be released into the atmosphere. Further, the goal is to assess what the former peatlands have been transformed into, which may enable the prediction of where future degradation of peatlands is most likely to take place. Lastly, the goal is to estimate what future degradation will entail in terms of C emissions. Based on this, the following research questions are asked:

1. *What is the extent of lost peatlands in Trondheim municipality from 1964 to 2021?*
2. *What land use categories have the former peatlands in Trondheim municipality been transformed into, and where are they located?*
3. *How much carbon has the loss of peatlands in Trondheim municipality from 1964 to 2021 caused to be released into the atmosphere?*

2 Method

This section details the thesis methodology. The main method was mapping of peatlands using the QGIS database system. Further, a quantitative study was undertaken to evaluate the C loss resulting from land cover change, and thereby degradation of peatlands. The quantitative study comprises three scenarios illustrating CO_2 emissions from peatlands in Trondheim municipality with different peat depths. A literature study lays the foundation for the background study of the thesis, in addition to the choice of peat depths in the three scenarios. Further, the scope of the study is given, followed by a description of the literature review, a description of the QGIS methodology, and the methodology for the quantitative study on C loss.

2.1 Scope

The study area is Trondheim municipality before it was merged with Klæbu municipality in 2020, shown in Figure 1. It is located in Trøndelag county in Central Norway. With an annual average population growth of 1.66%, in the last 10 years, the human pressure on the ecosystems is expected to have been substantial during the preceding decades (Eiksund, 2014). Consequently, transformation of peatland areas to other purposes was an expected outcome of the analysis. Although the results apply for Trondheim municipality it is reasonable to assume that the methods used may be transferrable to other sites in- or outside of Norway.

Peatland is the wetland ecosystem with the largest storing capabilities of C, and it is thus an interesting objective when assessing its importance from a climate mitigation perspective (Villa & Bernal, 2018). It also has a distinctive and well-known ecology that differs from other types of wetlands (Norwegian Biodiversity Information Centre, n.d.-c). Further, the study was limited to examine peatlands as 90%, out of Norway's total wetland coverage of 10%, are peatlands (Magnussen et al., 2018). Thus, the study is more likely to be representative for sites outside of Trondheim municipality. Lastly, the C stock in peat soil is the one assessed as it contains largest amounts of C followed by the plant biomass above ground (Agus et al., 2011).

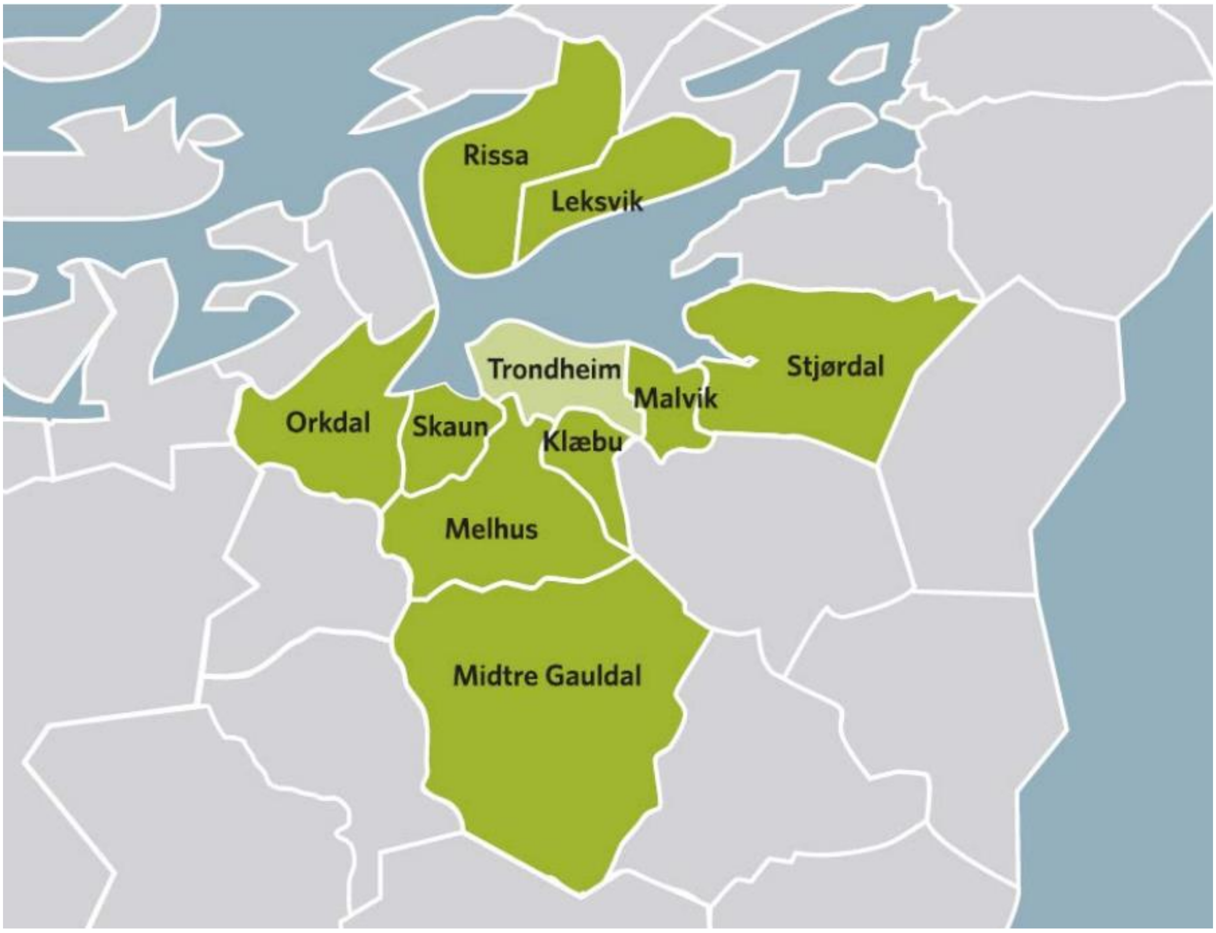

Figure 1: Map of Trondheim municipality, with neighboring municipalities, prior to the merge with Klæbu municipality 01.01.2020 (Trondheimsregionen, 2016).

2.2 Literature Review

A literature review lies as a basis in this study. To obtain literature, a literary search in the scientific databases Scopus, ORIA, and Google Scholar has been conducted. To narrow the search to identify key aspects of the topic, there has been used keywords like peatlands, lost peatlands, peat depth, and carbon stock. The "snowball" method, which means identifying references in key papers to obtain relevant research, was used.

Norge i Bilder holds the main source of the mapping in QGIS. It is a website made in a collaboration between Norwegian Public Roads Administration, Norwegian Institute of Bioeconomy Research (NIBIO), and the Norwegian Mapping Authority (NMA) (Geodata AS, 2016). The website provides a collection of aerial photo projects of Norway that can be exported and used in further analysis in digital database systems such as Geographic Information System (GIS).

AR5 is a main source in this study as it provides map datasets and information on defining features of peatlands. It is a comprehensive dataset and national land capability classification system in Norway (NIBIO, 2019). Peatlands are classified as a surface type in AR5, which is the primary level of classification in AR5 determined based on vegetation and cultivation criteria (NIBIO, 2019). AR5 was derived from "Digitalt markslagskart" (DMK) in the Economic Map series of Norway in 2008, which contains information on peatland properties, such as vegetation, peat depth, and peat decomposition level (NIBIO, 2019). AR5 is included in "Felles kartdatabase" (FKB) as a Geovekst dataset, hence the name FKB-AR5 for the map datasets (NIBIO, n.d.). NIBIO is professionally responsible for AR5 and updates the dataset periodically by incorporating new aerial images into the map (NIBIO, n.d.). This process occurs approximately every 5-8 years, as agreed through Geovekst. Municipalities are responsible for regularly updating the map by capturing land cover changes the municipality becomes aware of through its management tasks (NIBIO, n.d.).

2.3 GIS

GIS is a set of tools that transforms geographic data to geographic information (Rød, 2015). It helps us to understand spatial patterns and relationships (National Geographic, n.d.). QGIS is an Open Source GIS that allows users to create, analyse, edit, visualize, and export geospatial information (QGIS, n.d.).

2.3.1 Data Collection

To quantify the extent of lost peatlands in Trondheim municipality, historical and current aerial photo projects have been analysed and compared. The aerial photo projects were chosen based on good coverage of the study area, and a time period covering approximately the last 50 years. This time period was chosen to align with the time spans relevant in the International Union for Conservation of Nature (IUCN) red list methodology (Bland et al., 2017). The selected aerial photo projects are "Trondheim-Meldal 1964", shown in Figure 2, and "Trondheim kommune 2021", shown in Figure 3, obtained from Norge i Bilder (Norwegian Mapping Authority et al., n.d.). "Trondheim-Meldal 1964" is in black and white and has a resolution of 0.2 metres, while "Trondheim kommune 2021" is in colours and has a resolution of 0.1 metres. Further, the FKB-AR5 map layer "fkb_ar5_trondheim_myr", showing the peatlands present in Trondheim, has been imported to QGIS, shown as pink polygons in Figure 2 and Figure 3. To be able to make better assessments, the features bedrock and roads in FKB-AR5 was used. To supplement the assessment, a map layer showing the elevation was used. A map layer of the border of Trondheim municipality, shown as a red line in Figure 2 and Figure 3, was added to display the study area.

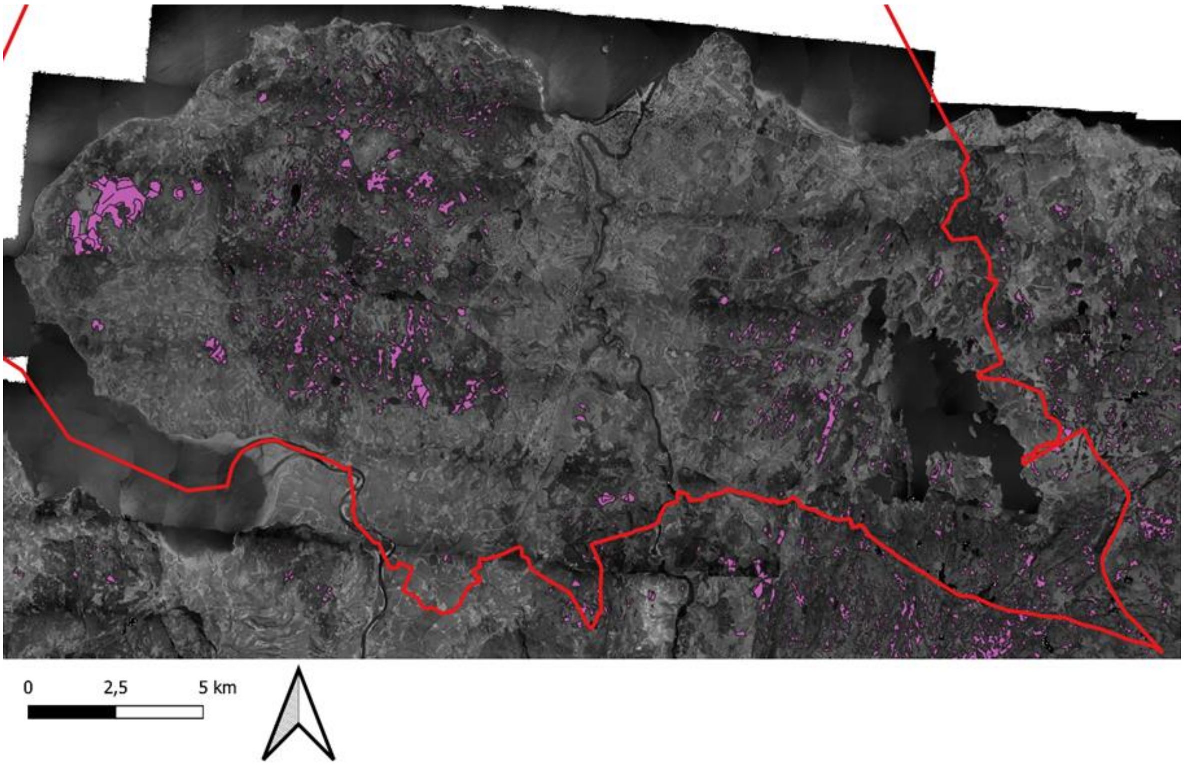

Figure 2: The aerial photo project "Trondheim-Meldal 1964" with FKB-AR5 map layer showing peatlands present in Trondheim municipality in pink polygons. The red line shows the border of Trondheim municipality before it was merged with Klæbu municipality.

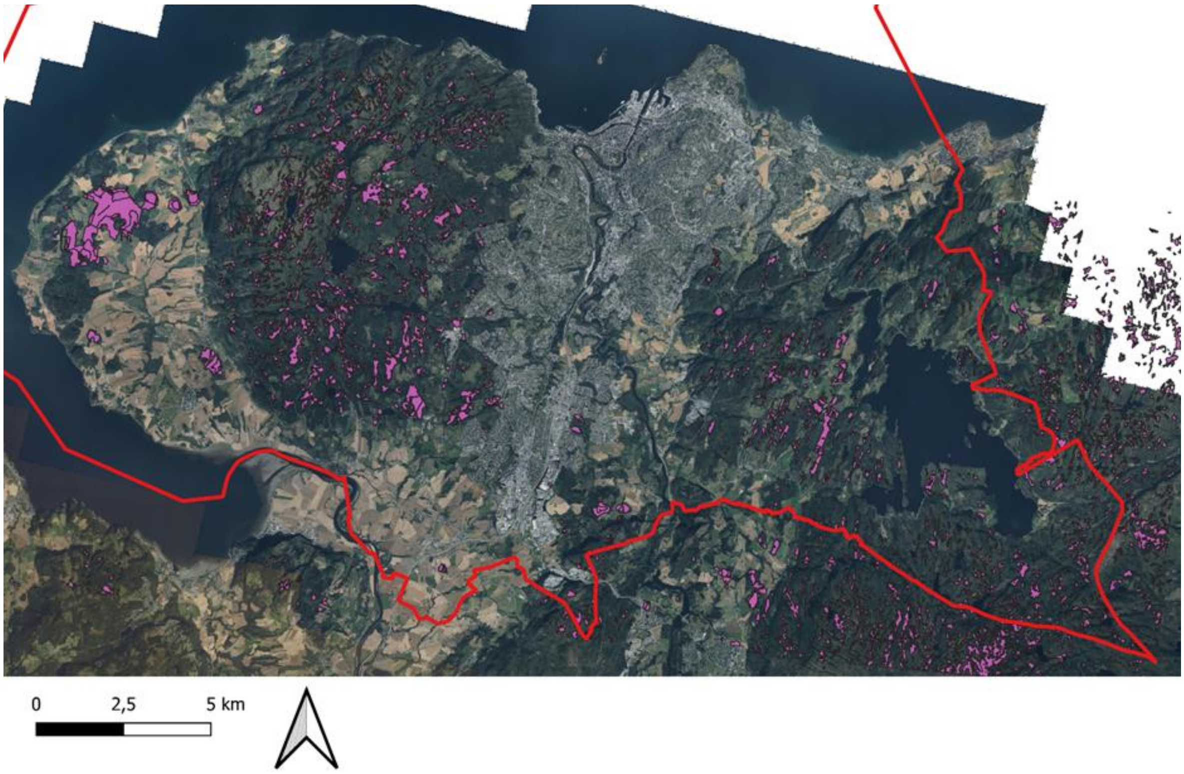

Figure 3: The aerial photo project "Trondheim kommune 2021" with FKB-AR5 map layer showing peatlands present in Trondheim municipality in pink polygons. The red line shows the border of Trondheim municipality before it was merged with Klæbu municipality.

2.3.2 Studied Categories

Based on the goal of the study, the categories peatlands in 1964, peatlands in 2021, land cover change to agriculture, forestry and agriculture, fen, bog, area, and metres above sea level were assessed. In the attribute table they were named peat_1964, peat_2021, at_agri, at_forest and at_infra, fen, bog, area and ASL, respectively. The categories peatlands in 1964 and 2021 was chosen to identify if peatlands were lost during the period. Land cover change to agriculture, forest, and infrastructure was chosen as they are found to be the primary interventions of peatlands in the lowlands (Norwegian Biodiversity Information Centre, 2018). Furthermore, to be able to quantify the loss of peatlands from 1964 to 2021, area was interesting to obtain. ASL was chosen as a category to be able to analyse if metres above sea level affected the level of human intervention.

The categories fen and bog were chosen as they are included in AR5 and DMK which is found to be the most comprehensive dataset with classification of peatlands in Trondheim. Literature was found to be uncomplete as mainly single peatland sites were assessed resulting in non-uniform use of a classification system (Flatberg, 1970; Lyngstad et al., 2017a; Moen, 1983; Øien, 2011). Peatland areas are classified by vegetation in DMK, as per the NIN typification system. Two categories are used in DMK; poor vegetation and rich vegetation. NIBIO defines poor vegetation as plant species that grow on peatlands with poor nutrition, relying solely on precipitation for water supply (NIBIO, n.d.). Rich vegetation includes plant species that grow on peatlands receiving water from contact with mineral soil in addition to precipitation (NIBIO, n.d.). In the NiN classification system described in Appendix 1, peatlands with poor vegetation corresponds to V3 Bog, while peatlands with rich vegetation corresponds to V1 Open fen, V2 Mire and swamp forest, and V8 Tidal and alluvial swamp forest. Moreover, a bog- and fen classification is sensible because it can illustrate the variability in properties among peatland categories. This is because peatlands vary due to differences in internal chemistry and hydrological regimes, caused by variations in vegetation that lead to distinct net primary production rates and decomposition rates (Blodau, 2002).

2.3.3 Assumptions

It is assumed that the information in the AR5 map layer “fkb_ar5_trondheim_myr” was collected using the same methodology, and that it therefore can be assumed to be consistent over time. Further, it is assumed that the peatlands that exist in 2021 also existed in 1964 as the formation of a peatland is a slow process (Moen et al., 2011).

2.3.4 Approach of the Analysis

The first step in the analysis was to categorize objects of interest in the attribute table. Each object of interest including peat_1964, peat_2021, at_agri, at_forest, at_infra, fen, and bog was given a field. Further, to categorize the data, the values indicating yes and no was one and zero, respectively. For example, if an area was considered to be a bog, a value of one was given in the field of bog in the attribute table.

To systematically analyse the study area, a grid layer of 1 x 1 km was used. Thus, one square in the grid was analysed at a time. To assess whether a peatland present in 1964 had been transformed into another land-use purpose within 2021, the aerial photo project "Trondheim-Meldal 1964" was examined closely to identify peatland areas. Further, the aerial photo project "Trondheim kommune 2021" was analysed to identify if the peatland areas was present in 2021 or if the areas was undertaken a transformation. Polygons representing lost peatland areas from 1964 to 2021 was coloured in blue.

An area is classified as a peatland in AR5 based on an overall assessment of the vegetation, the thickness of the peat layer, and the natural drainage conditions at the site (NIBIO, 2021). Hence, polygons in blue, representing lost peatlands between 1964 and 2021 was made based on criteria to be defined as a peatland in AR5. As the aerial photo project "Trondheim-Meldal 1964" is in black and white, the vegetation criteria was based on the dark/light gradient. This is because vegetation typical for fens tends to appear in darker colour tones than the vegetation typical for bogs. To assess whether a lost peatland met the criteria in AR5 of a peat depth of minimum 30 cm, the elevation above sea level was used as a defining feature. This is because areas in the highland tend to have more shallow peat layers (Lyngstad et al., 2012). Consequently, assessing the elevation above sea level can help determine whether an area meet the criteria of a peat depth of a minimum of 30 cm or not. To strengthen the assessment, the analyse was supplemented by a map layer showing the topography in QGIS. As most peatlands are located in relatively flat terrain, the map was used in the assessment as an indicator of whether a peatland most likely was located at a given location or not.

Throughout the assessment, the map layer AR5 showed polygons, marked in pink, of peatlands present in Trondheim. Thus, the task of identifying lost peatlands was limited to outside of these marked areas. Further, the AR5 area type map from NIBIOs mapping service "Kilden" has been assessed simultaneously with the process to help determining if a peatland area was lost between 1964 and 2021. The AR5 area type map also helped to clarify what land-use purpose a given peatland area had been transformed into.

The area was quantified using the area function in the field calculator in the attribute table. ASL was found by making a new map layer with centroids to get the elevation of the centre of each polygon.

2.4 Quantitative Study of Carbon Loss

2.4.1 Scenarios

To estimate CO_2 emissions from lost peatlands one needs to calculate the C stock in the peat. Required data to calculate the C stock are peat depth (e.g., m), bulk density (e.g., g cm^{-3}), organic carbon content (e.g., g kg^{-1}) and peatland area (e.g., m^2) (Agus et al., 2011). According to Grønlund et al. (2010), the C stock in a peat layer can be calculated as follows:

$$C_{stock} = peat\ depth \times bulk\ density \times organic\ carbon\ content$$

A model sensitivity of C stock estimates displayed that the model was most positively sensitive to peat depth compared to bulk density and organic carbon content (Akumu & McLaughlin, 2013). Thus, a change in peat depth is assumed to affect the C stock, and thereby the CO_2 emissions, significantly. Further, it is found that peat depths may vary greatly within and between peatland sites (Norwegian Environment Agency, 2022). Hence, to capture the variety in CO_2 emissions stemming from peatlands with shallow and thick peat layers, three scenarios was constructed. Information on peat depths was obtained from literature. Table 1 shows the peat depths found for bogs and Table 2 shows the peat depths for fens. Mean (± standard deviation) is given in both tables.

Table 1: Peat depths in bogs.

Site	*Mean peat depth (m)*	*Reference*
Høstadmyra (Trondheim)	3.5	(Lyngstad et al., 2017a)
Heimdalsmyra (Trondheim)	3.1	(Long et al., 2022)
Nordmyra (Trondheim)	4.5	(Flatberg, 1970)
Tiller-Flotten (Trondheim)	2.2	(Long et al., 2022)
Dragvollmyra (Trondheim)	5.0	(Long et al., 2022)
Haukvatnet (Trondheim)	4.0	(Long et al., 2022)
Kattem-Oustmyra (Trondheim)	4.0	(Rambøll, 2016)
Fuglmyra (Klæbu)	3.0	(Lyngstad et al., 2017b)
Gaddmyra (Klæbu)	1.7	(Lyngstad et al., 2017b)
Svenmyra (Klæbu)	1.9	(Lyngstad et al., 2017b)
Stormyra at Marøya (Kinn municipality)	0.9	(Øien et al., 2021)
Transect 1, Austneset (Kinn municipality)	2.0	(Lyngstad et al., 2022a)
Transect 2, Austneset (Kinn municipality)	1.9	(Lyngstad et al., 2022a)
Transect 3, Austneset (Kinn municipality)	1.9	(Lyngstad et al., 2022a)
Sjetnemyr nord (Trondheim	3.5	(Holmsen, 1922)
Sjetnemyr (Trondheim)	5.0	(Stangeland, 1897)
Peatland at Stjørdalsøren (Stjørdal)	2.0	(Stangeland, 1897)
Finsmyr (Stjørdal)	2.5	(Stangeland, 1897)
Roknesmyr, area A (Levanger)	1.8	(Stangeland, 1897)
Præstegaardsmyr (Verdal)	4.0	(Stangeland, 1897)
Mean (±SD)	2.9 ± 1.2	

Table 2: Peat depths in fens.

Site	*Mean peat depth (m)*	*Reference*
Postmyra (Klæbu)	1.5	(Lyngstad et al., 2017b)
Sætremyrane (Hornindal municipality)	0.4	(Lyngstad et al., 2015)
Kvalstadvatnet (Kinn municipality)	2.1	(Øien et al., 2021)
Lista 1 (Kinn municipality)	0.7	(Øien et al., 2021)
Lista 2 (Kinn municipality)	0.6	(Øien et al., 2021)
Reppemyr in Strinden (Trondheim)	1.0	(Stangeland, 1897)
Veskemyr, area B, (Levanger)	1.5	(Stangeland, 1897)
Krokstadmyr, area C, (Levanger)	1.5	(Stangeland, 1897)
Skogstadmyr, are B, (Levanger)	0.8	(Stangeland, 1897)
Roknesmyr, area B, (Levanger)	1.3	(Stangeland, 1897)
Ranbergmyr (Steinkjer)	1.3	(Stangeland, 1897)
Mæremyr (Steinkjer)	0.8	(Stangeland, 1897)
Mean (± SD)	1.1 ± 0.5	

Based on peat depths found in the literature, and due to the uncertainty of the peat depth estimates, three scenarios were explored:

1. The mean of the peat depths collected.
2. 50% less than the mean of the peat depths collected.
3. 50% more than the mean of the peat depths collected.

The peat depths of the three scenarios are given in Table 3.

Table 3: The three scenarios with peat depths in bogs and fens.

Scenario	*Bog*	*Fen*
Scenario 1	2.9 m	1.1 m
Scenario 2	1.5 m	0.6 m
Scenario 3	4.4 m	1.7 m

The peat depth scenarios were multiplied with bulk density and organic carbon content to obtain the C stock. Bulk density is the dry weight of soil per unit soil volume, whereas organic carbon content is the mass of C per unit weight of soil (Agus et al., 2011). As there is a lack of site-specific information on bulk density and organic carbon content, the values are mainly obtained from research outside Norway. It is found that bulk density values vary significantly between bogs and fens (Akumu & McLaughlin, 2013). Consequently, mean values of the estimates by Akumu & McLaughlin (2013), Tomlinson & Davidson (2000), and Turunen et al. (2002) is used for bogs and by Minkkinen & Laine

(1998), Yu et al. (2014), and Akumu & McLaughlin (2013) for fens. Calculations by Akumu & McLaughlin (2013) shows that there are small variations in organic carbon content between bogs and fens, meaning the same values can be used for both peatland categories. Further, Lyngstad et al. (2017) shows an intermediate value compared to Akumu & McLaughlin (2013) and Malmer & Holm (1984), used as estimates of organic carbon content for bogs and fens. Values of the parameters bulk density and organic carbon content are shown in Table 4.

Table 4: Values of the parameters bulk density and organic carbon content to estimate the carbon stock in peatlands.

Peatland category	*Bulk density (g cm^{-3})*	*Organic carbon content (g kg^{-1})*
Bog	0.081	470
Fen	0.113	470

To obtain the total C stock of lost peatlands in Trondheim municipality, the C stock was multiplied with the area of lost bogs and fens. Further, to convert the C stock to CO_2 emissions, a conversion factor of 3.67, based on the molecular weight of CO_2, was used (Lohberger et al., 2017).

2.4.2 Assumptions

It is assumed that the C stored in the peatlands are instantly released into the atmosphere in the form of CO_2. It is documented that the C stored in peatlands is released over time (Günther et al., 2020), thus assuming instant loss of the C stored in the lost peatlands represents a limitation of the study as it does not reflect the reality. When considering emissions from degraded peatlands, CO_2 are the most important GHG as it contributes to the largest share of the emissions (Grønlund et al., 2006). However, to obtain a precise representation of the C loss from peatlands, emissions should be allocated among CH_4, N_2O, and CO_2, as all three gases contribute to the overall C flux of the ecosystem (Grønlund et al., 2006).

3 Results

In this section the results comprising the extent of lost peatlands are given, followed by what land use category the former peatlands have been transformed into. Lastly, C loss estimates are presented.

3.1 Extent of Lost Peatlands

7.2 km^2 of the peatland area present in Trondheim municipality in 1964 have been lost by the year of 2021 (Table 5). This corresponds to 1014 football fields. Peatland area in 2021, obtained from the map layer "fkb_ar5_trondheim_myr", equals 37.5 km^2. When adding the extent of lost peatlands with peatland area in 2021 it sums up to 44.7 km^2, representing peatland area present in Trondheim municipality in 1964. Representing the numbers in percentage share shows that 16% out of total peatland area have been lost between 1964 and 2021, while 84% of the peatland area present in 1964 is still intact.

Table 5: Lost peatland area (km^2) in Trondheim municipality from 1964 to 2021 and the percentage share of lost peatlands from 1964 to 2021.

Peatland area 1964	Peatland area 2021	Area of lost peatlands from 1964 to 2021
44.7 km^2	37.5 km^2	7.2 km^2
100%	84%	16%

The degradation of Heimdalsmyra constitute a substantial amount of 37% out of the total area of lost peatlands (Figure 4). In areal extent it equals 2.6 km^2 which corresponds to approximately 371 football fields. The remaining area of degraded peatlands account for 63% of total area of lost peatlands in Trondheim municipality from 1964 to 2021.

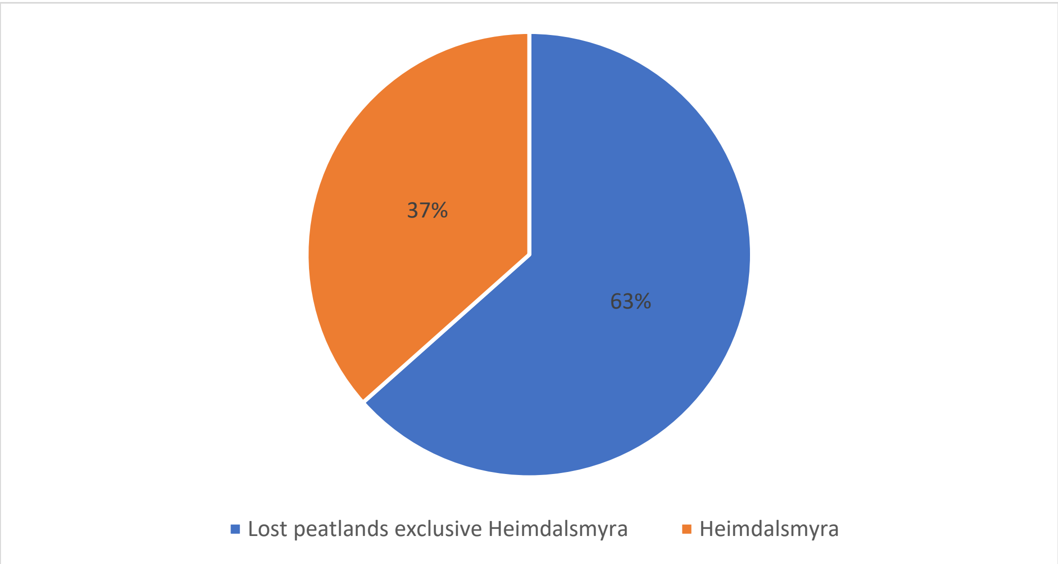

Figure 4: Heimdalsmyras share of the total area of lost peatlands in Trondheim municipality from 1964 to 2021.

Excluding Heimdalsmyra from the estimated loss of peatland area from 1964 to 2021 represent a substantial decline from 16% (Table 5) to 10% (Figure 5). Meaning, the degraded peatland area at Heimdalsmyra is excluded from lost peatland area from 1964 to 2021 and added to the peatland area present in Trondheim municipality in 2021.

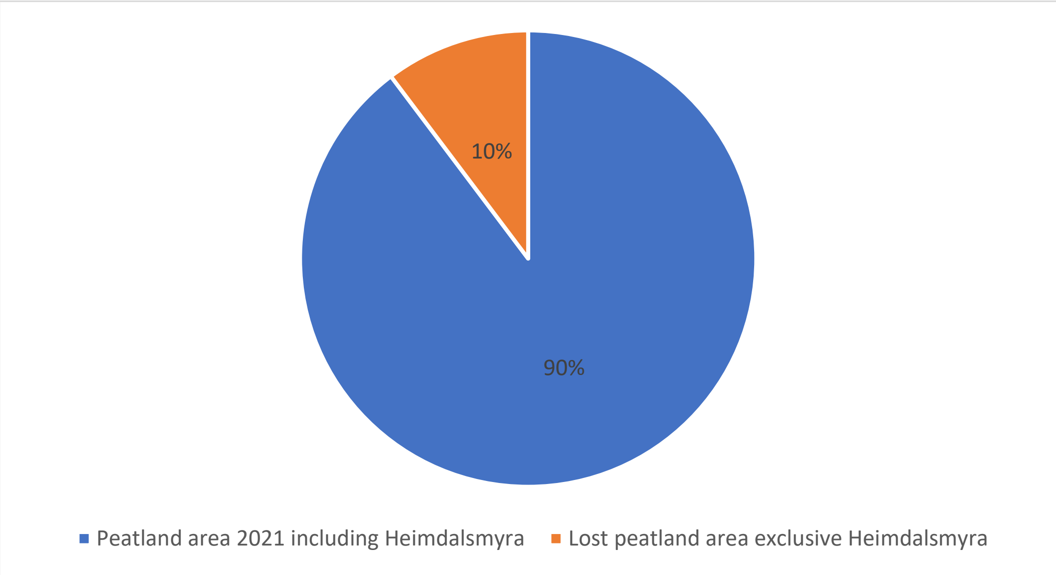

Figure 5: Share of lost peatland area exclusive Heimdalsmyra in Trondheim municipality from 1964 to 2021.

The peatland categories are relatively evenly distributed in the estimate of lost peatland area from 1964 to 2021 in Trondheim municipality with a share of 45% of fens and 55% of bogs (Figure 6). The share corresponds to 3.3 km^2 and 4.0 km^2, for fens and bogs, respectively.

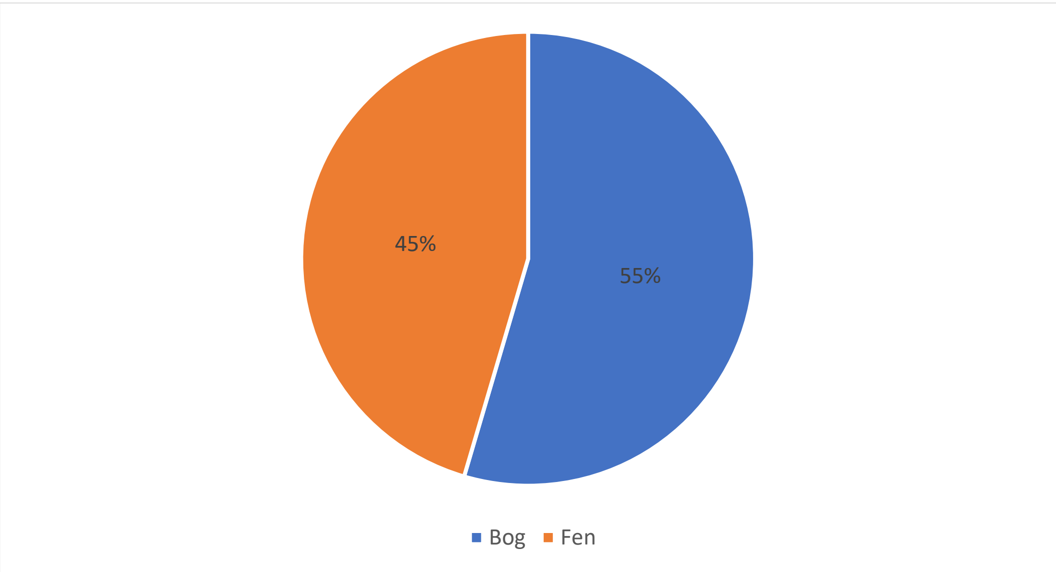

Figure 6: Share of lost bogs and fens based on area (km^2) in Trondheim municipality from 1964 to 2021.

3.2 Land Cover Change of peatlands

Land cover change to infrastructure have been most abundant with a share of 66%, followed by land cover change to agriculture and forestry accounting for 24% and 10%, respectively (Figure 7). In area, land cover change to infrastructure, agriculture and forestry accounts for 4.7 km^2, 1.8 km^2, and 0.7 km^2, respectively. In football fields it corresponds to around 658 for infrastructure, 252 for agriculture and 98 for forestry.

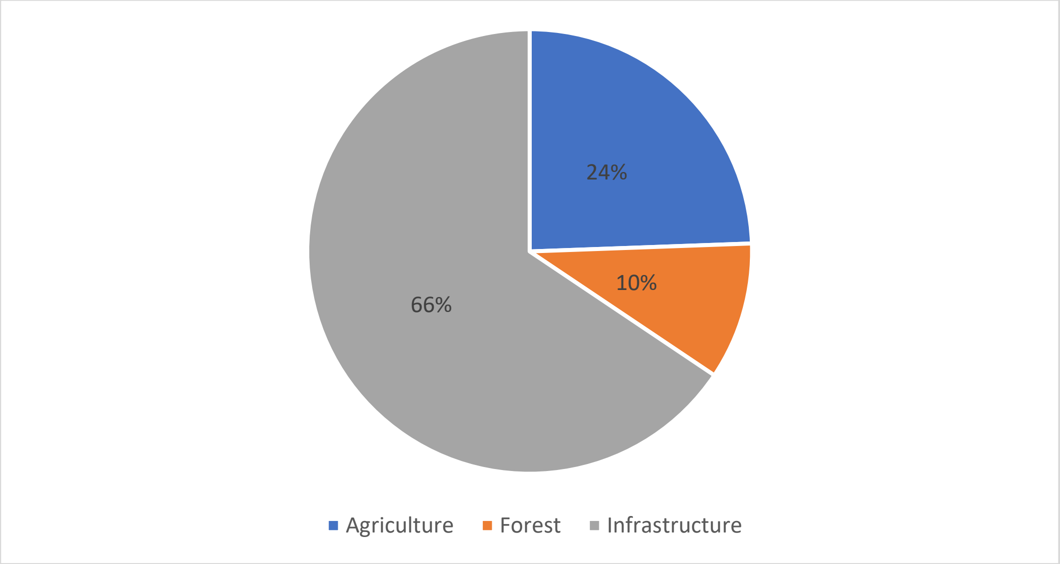

Figure 7: Share of peatland area (km^2) lost to agriculture, forestry, and infrastructure in Trondheim municipality from 1964 to 2021.

The lost peatlands, shown as blue polygons in Figure 8, are located in lowland areas outside the city centre of Trondheim. As displayed in Figure 4, Heimdalsmyra, shown as a cluster of blue polygons located south of Trondheim city centre, accounts for a great proportion of the area of lost peatlands.

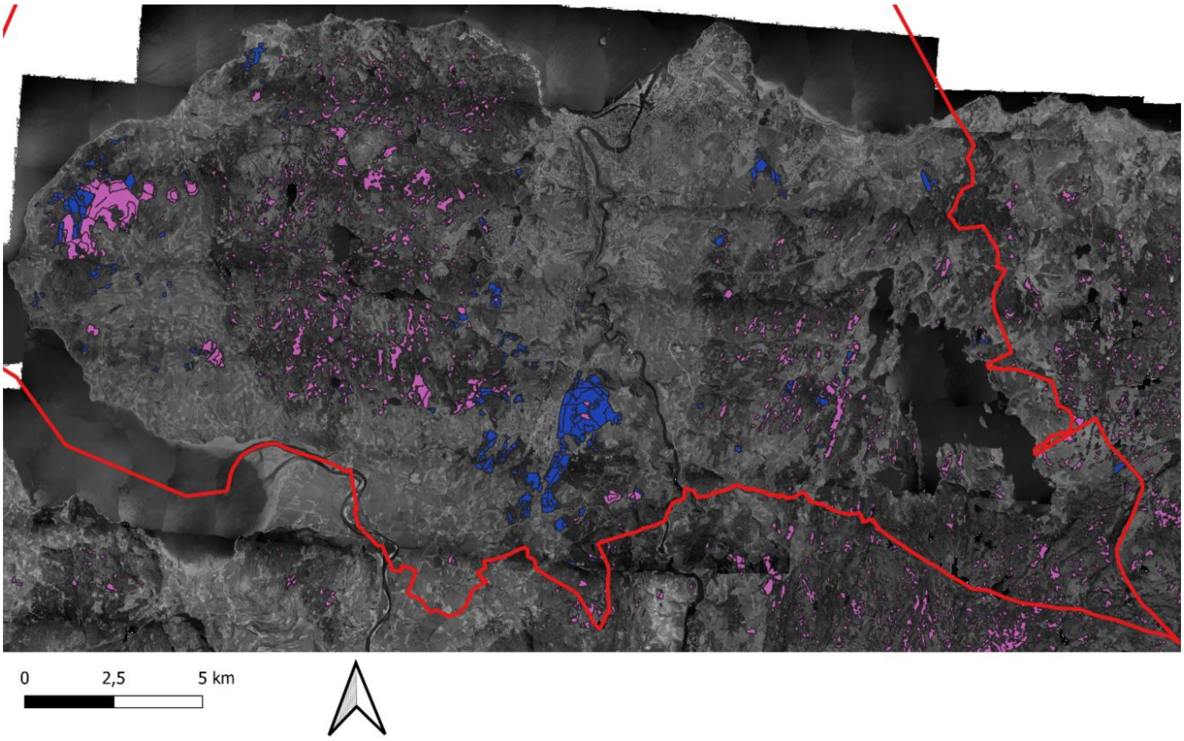

Figure 8: The aerial photo project "Trondheim-Meldal 1964" with blue polygons illustrating lost peatlands from 1964 to 2021. FKB-AR5 map layer shows peatlands present in Trondheim municipality in pink polygons and the red line displays the border of Trondheim municipality before it was merged with Klæbu municipality.

The distribution of peatland area (m^2) present in Trondheim municipality in 2021 along the elevation gradient is illustrated in Figure 9. The peatlands are relatively evenly distributed between 100 and 500 metres above sea level (m a.s.l.), while there are few peatlands located below 100 m a.s.l. and above 500 m a.s.l.

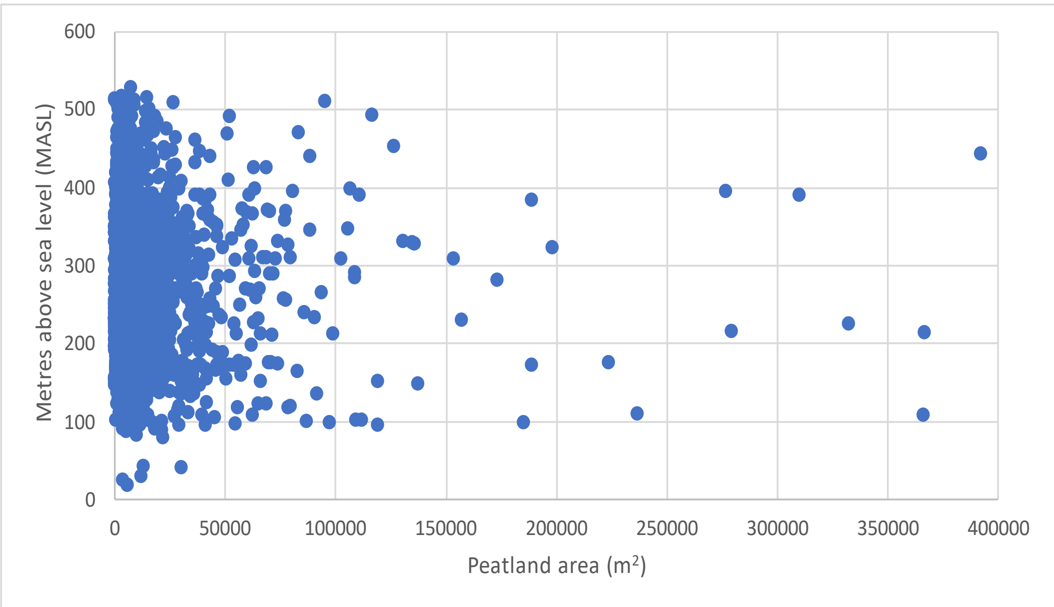

Figure 9: Distribution of peatland area (m^2) in metres above sea level in Trondheim municipality in 2021.

Lost peatland area (m²) in Trondheim municipality from 1964 to 2021 is, however, located in lowland areas in altitudes between 0 and 300 m a.s.l. as shown in Figure 10.

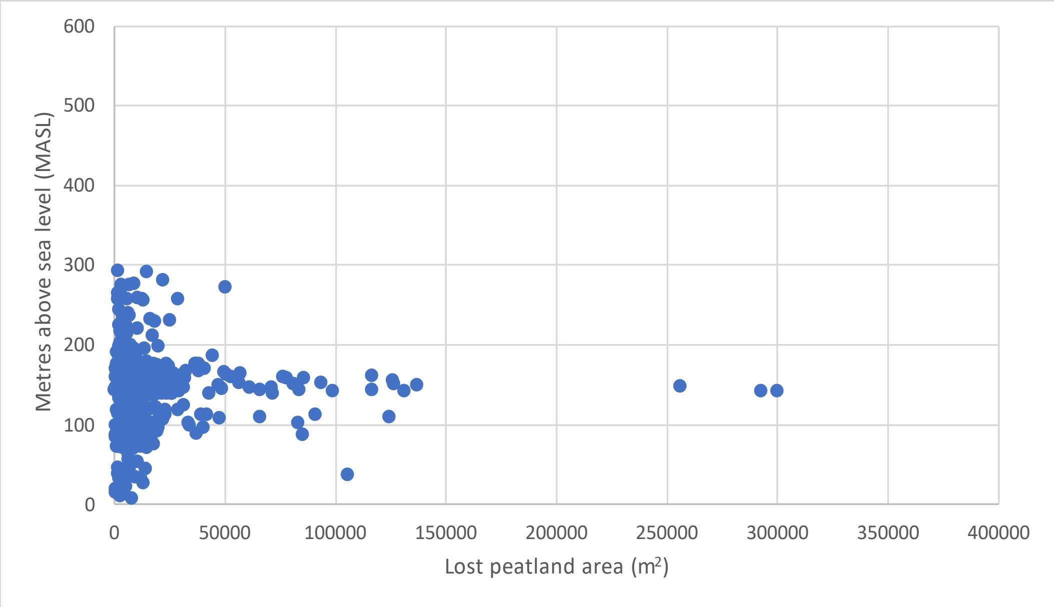

Figure 10: Distribution of lost peatland area (m²) in metres above sea level in Trondheim municipality from 1964 to 2021.

Grouping the lost peatlands into elevation intervals (Figure 11) shows that the elevation interval where most peatlands are lost between 1964 and 2021 is 100-150 m a.s.l., followed by the elevation interval 150-200 m a.s.l.

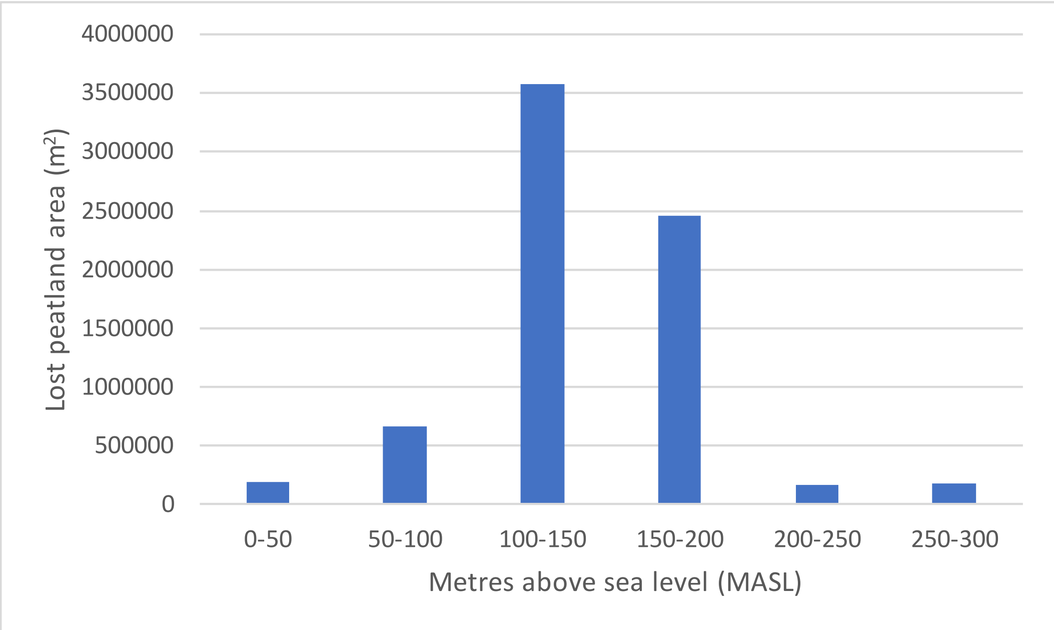

Figure 11: Lost peatland area (m²) in Trondheim municipality from 1964 to 2021 grouped in elevation intervals.

3.3 Carbon Loss by Land Cover Change of Peatlands

The C stock in Trondheim municipality for three peat depth scenarios for bog and fen is shown in Figure 12, while Figure 13 display the C loss from 1964 to 2021. The calculations are described in section 2.4.1. In both Figure 12 and Figure 13, the peat depth correlate with the C stock and C loss. Meaning, scenario 2, with the smallest peat depths also have the lowest C values, followed by scenario 1 and scenario 3, with the largest peat depths and highest C values.

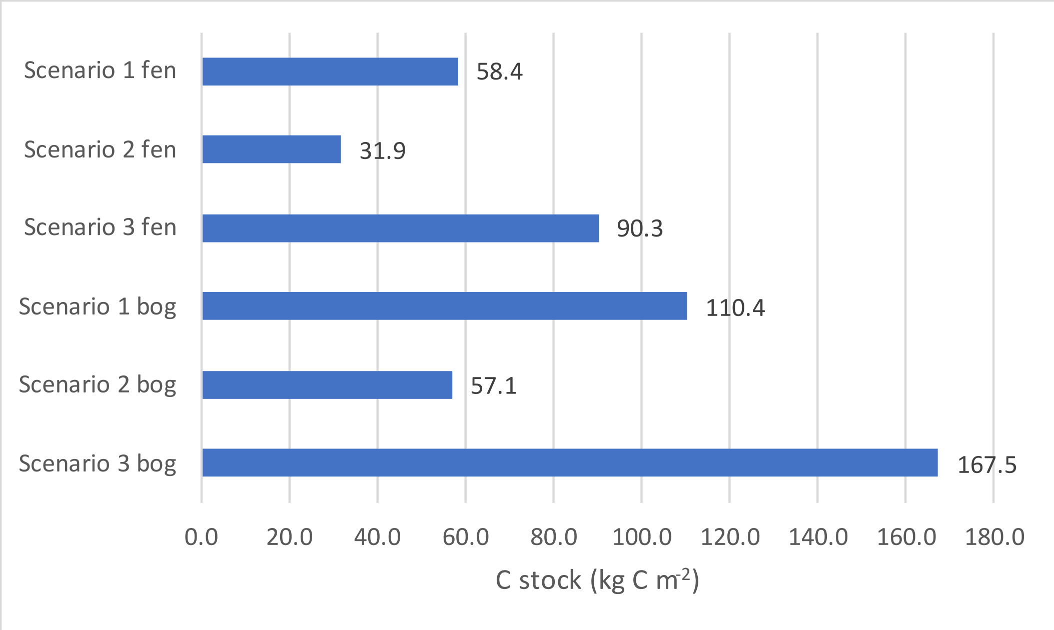

Figure 12: C stock for peat depth scenarios 1, 2, and 3 for bogs and fens.

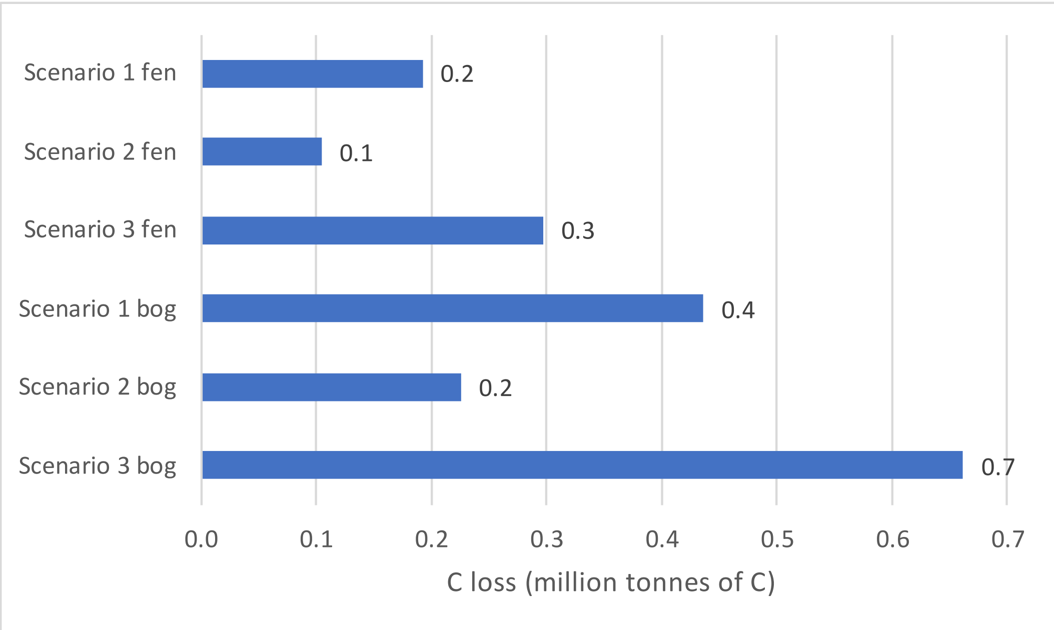

Figure 13: C loss for peat depth scenarios 1, 2, and 3 for bogs and fens.

The CO_2 emissions stemming from the bog scenarios in Trondheim municipality from 1964 to 2021, double the CO_2 emissions from the respective fen scenario (Figure 14). Scenario 3 bog, with the thickest peat layer, represent the largest emissions of 2.4 million tonnes of CO_2, while scenario 2 fen, with the thinnest peat layer, represent the lowest emissions of 0.4 million tonnes of CO_2.

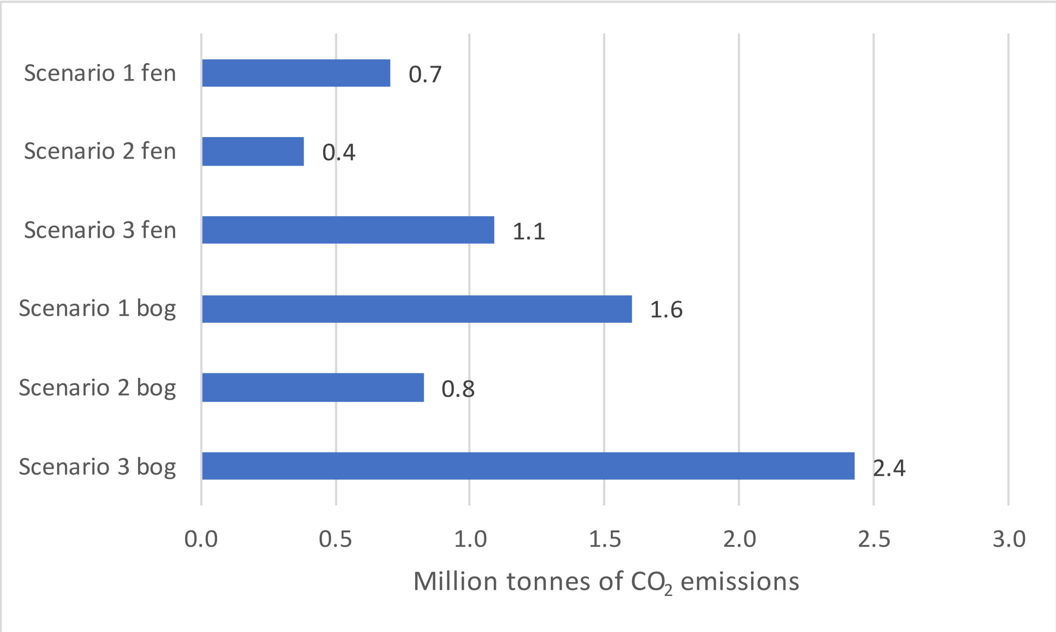

Figure 14: CO_2 emissions from the peat depth scenarios.

All the scenarios with bogs and fens combined are responsible for higher CO_2 emissions than domestic aviation in Norway in 2021 (Figure 15) (Statistics Norway, 2022b). Scenario 3 is also closely corresponding to CO_2 emissions stemming from domestic shipping and fishing in Norway in 2021 (Statistics Norway, 2022b).

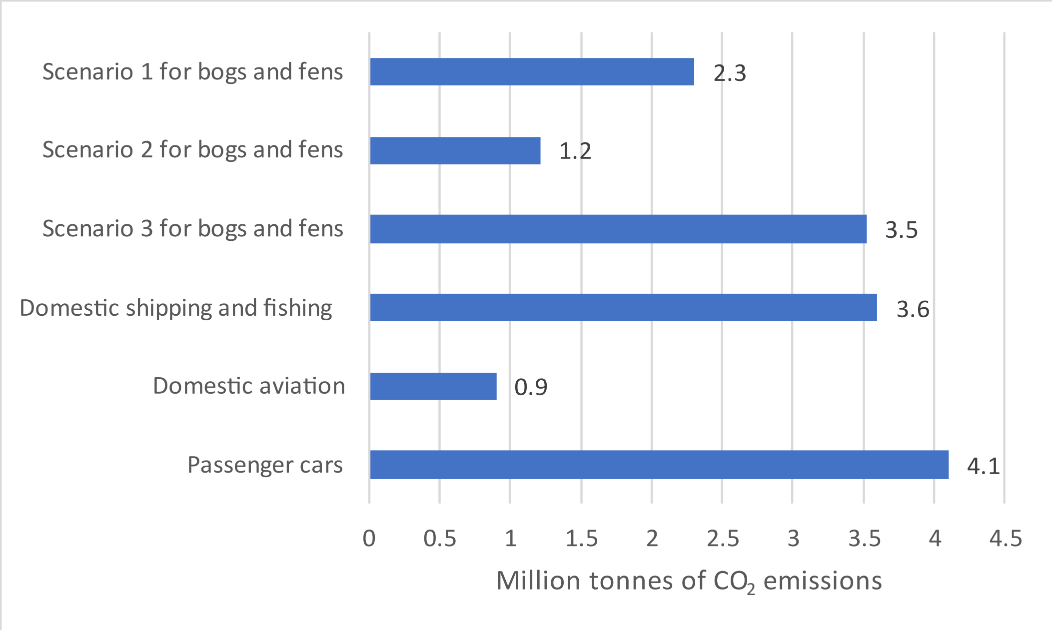

Figure 15: CO_2 emissions by emission source in Norway in 2021, obtained from Statistics Norway (2022b), compared to CO_2 emissions stemming from the peat depth scenarios of bogs and fens combined.

0.04, 0.02, and 0.06 million tonnes of CO_2 are emitted annually from the combined bog and fen scenarios 1, 2, and 3, respectively (Table 6). It is calculated by dividing the values from Figure 15 by the mapping period of 57 years. Per area calculations show that the emissions from the combined scenario 3, with 8.5 kg CO_2 m^{-2} $year^{-1}$, are substantially higher than from the combined scenarios 1 and 2 with 5.6 and 2.9 kg CO_2 m^{-2} $year^{-1}$, respectively.

Table 6: Annual CO_2 emissions from the combined scenarios.

Scenario	*CO_2 emissions (Million tonnes of CO_2 $year^{-1}$)*	*CO_2 emissions (kg CO_2 m^{-2} $year^{-1}$)*
Scenario 1	0.04	5.6
Scenario 2	0.02	2.9
Scenario 3	0.06	8.5

The share of CO_2 emissions stemming from the combined scenarios, out of total CO_2 emissions in Norway in 2021, is given in Figure 16 (Statistics Norway, 2022b). CO_2 emissions from the combined peat depth scenario 1 corresponds to 4.7% of total CO_2 emissions in Norway in 2021. The combined peat depth scenarios 2 and 3 correspond to 2.5% and 7.2% of total CO_2 emissions in Norway in 2021, respectively.

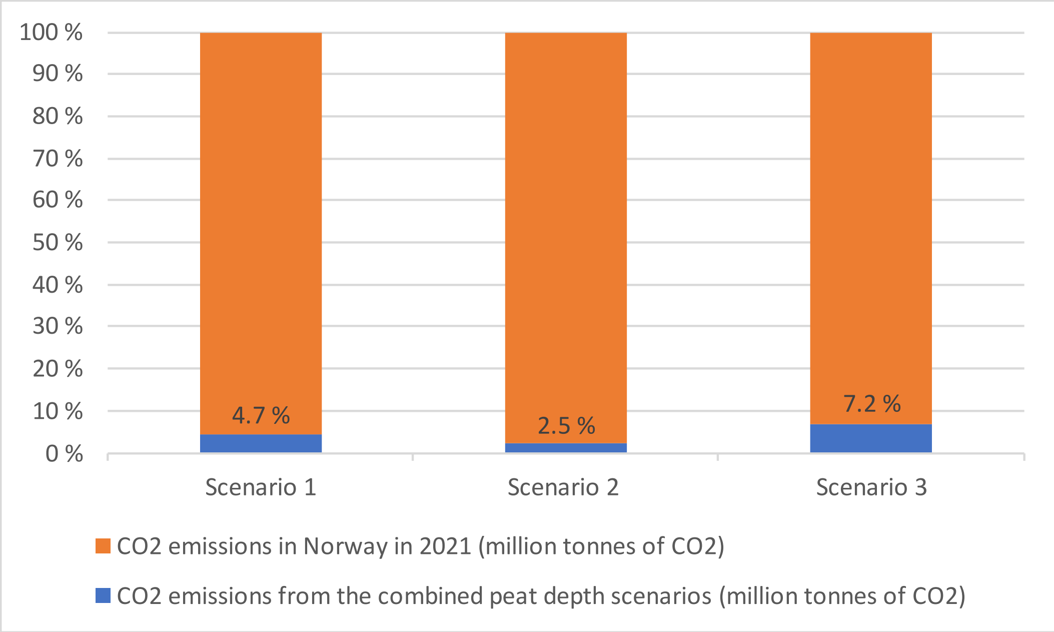

Figure 16: Share of CO_2 emissions stemming from the combined scenarios out of total CO_2 emissions in Norway in 2021 obtained from Statistics Norway (2022b).

4 Discussion

This study shows that 16% of the peatlands present in Trondheim municipality in 1964 has been lost by the year 2021. The lost peatlands are located in lowland areas, where the majority has disappeared due to infrastructure development. Assuming scenario 1, which is based on intermediate peat depths, the lost peatlands represent 2.3 million tonnes of CO_2 emissions. These findings are important as they help us to understand how community development impact environmental change (Zhou et al., 2021). Further, it can provide valuable information for future community planning.

4.1 Extent of Lost Peatlands

Sixteen percent of the peatland area in Trondheim municipality in 1964 were lost by 2021, corresponding to 7.2 km^2 (Table 5). Zhou et al. (2021) found that there has been a decrease in wetland area of 18%, equal to 5 870 km^2, in Norway from 1992 to 2018. They use the legend "Shrub or herbaceous cover, flooded, fresh-saline or brackish water" by the European Space Agency for wetlands (European Space Agency, 2017). There are several reasons why the estimates vary. Wetlands include more nature types that have experienced significant declines than the subgroup peatlands, and Zhou et al. (2021) studied a larger area than this study (Magnussen et al., 2018). The land cover dataset used by Zhou et al. (2021) has a spatial resolution of 300 m while the spatial resolution are 0.2 m and 0.1 m for "Trondheim-Meldal 1964" and "Trondheim kommune 2021", respectively. Consequently, smaller land cover changes may have been detected in this study than in the study by Zhou et al. (2021). Despite variations in the estimates, both studies show a declining trend of peatland areas in Norway.

Joosten et al. (2015) found that ~7000 km^2 of the original peatland area in Norway, which was ~44 700 km^2 based on the extent 150 to 200 years ago, are degraded. In this study, it is found that 7.2 km^2 of the peatlands in Trondheim municipality were lost between 1964 and 2021, with an original peatland area of 44.7 km^2 (Table 5). The estimated percentage decrease (16%) is similar in these studies, but the year of determination of original peatland area varies. While Joosten et al. (2015) based their estimate on the 1800s, it is likely that the original peatland area in this study would have been larger if it was based on the same timeframe. According to the Antiquarian Committee of Trondheim Municipality (1978), the city of Trondheim has expanded greatly since the industrialization in the 1800s, resulting in loss of peatland areas prior to 1964. However, the merger of neighbouring municipalities (Strinda, Tiller, Leinstrand, and Byneset) with Trondheim in 1964 drastically increased the area of the municipality. In the following decades substantial degradation of peatlands took place such as at Heimdalsmyra, accounting for 37% of the lost peatlands in Trondheim from 1964 to 2021 (Figure 4). This large-scale drainage event has left a mark in the history of Trondheim. Considering the expansion of Trondheim municipality in 1964 and large-scale drainage events like at Heimdalsmyra, it is likely that that the most significant land cover changes occurred after 1964.

Lyngstad et al. (2018), in the National Red List of Ecosystems and Habitat Types, support that the peatland area in Trøndelag county is declining. They report a decrease in bog area, categorised as "near threatened" (Lyngstad et al., 2018). A subgroup of fens is categorised as "critically endangered", highlighting that also fens have been affected by human destruction (Lyngstad et al., 2018). However, overall, fens are considered "intact," supporting that bogs have been most affected by land cover change the preceding decades (Figure 6) (Lyngstad et al., 2018).

According to UNEP (2022), Europe is the continent that has experienced the largest proportional peatland degradation of almost 50%. Of all terrestrial and freshwater groups, the percentage of threatened peatland habitats is the highest as 11 out of the 13 peatland habitats (85%) that the European Red List of Habitats includes are threatened to some degree (Janssen et al., 2016). Out of the 11 habitats, one is "critically endangered", three are "endangered" and seven are assessed as "vulnerable" (Janssen et al., 2016). Raised bog is one of the three peatland habitats assessed as "endangered", while poor fen is "vulnerable". This corresponds to the results of this study, with bogs being most affected by land cover change, but both peatland categories are strongly affected. The European trend of peatland degradation show a similar trend as the decline of peatlands in Trondheim.

Global estimates of degraded peatlands show the same trend to that observed in Europe and in Trondheim. UNEP (2021) estimated that 11-15% of the global peatlands have been drained for agriculture, grazing, forestry and peat mining. Vegetation removal or alteration are responsible for a further 5-10% of the global peatland degradation (UNEP, 2021). From 1850 to 2015, accessible areas in temperate and boreal regions have experienced the largest decline of peatlands globally (UNEP, 2021, 2022). This corresponds with the substantial peatland loss in the urban areas of Trondheim during the last decades.

4.2 Land Cover Change of Peatlands

The main share of the destroyed peatlands (66%) has been transformed into infrastructure, followed by 24% to agriculture and 10% to forestry. According to Statistics Norway, there has been a large population growth in Trondheim municipality the preceding century (Statistics Norway, 2001). The last decade, Trondheim had an annual population growth of 1.66%, and there has been an increasing need for residential areas and other infrastructure to tackle the population growth (Eiksund, 2014). Gundersen et al. (2017) found that Trondheim is the municipality that has had the largest reduction of agricultural land in Norway of ~2.8 km^2 between 2004 and 2015. Residential areas being responsible for the major share of the land cover change (Gundersen et al., 2017). The study by Gundersen et al. (2017) addressed land cover change from agricultural land, but shows that infrastructure development, including residential areas, is the major cause of land cover change in Trondheim. Lyngstad et al. (2018) also found that infrastructure development has caused large peatland areas to be lost the last five decades. Further, they report that land cover change to agriculture have been less common in Norway compared to a few decades ago, while ditching for forestry have decreased mainly because of the ban from 2006 (Forskrift om berekraftig skogbruk, 2006, §5; Lyngstad et al., 2018). The findings by Gundersen et al. (2017) and Lyngstad et al. (2018) emphasizes that infrastructure is a main cause of transformation of peatlands, followed by land cover change to agricultural land and forestry.

The location and elevation above sea level is a determining factor in where the peatlands are lost. This study finds that all the lost peatlands are located in the lowlands, displayed in Figure 8 and Figure 11. The main share is lost at, and close to, Heimdal/Tiller, at Byneset and in the areas surrounding the city centre of Trondheim. A map obtained from Statistics Norway, Figure 17, shows the settlement pattern in Trondheim, and thus where the human pressure on ecosystems is largest (Statistics Norway, 2001). Heimdal/Tiller and the areas surrounding the city centre are both locations with high population pressure, indicating that there has been a land cover change from peatlands to infrastructure in these areas. The establishment of Tillerbyen, previously known as Heimdalsbyen, substantiates this statement. Stugu (1991) portrays the new township, built in the 1960s and 1970s, as the city on the peatland. This is because most of the constructions were built on Heimdalsmyra, resulting in large areas being ditched and drained (Stugu, 1991).

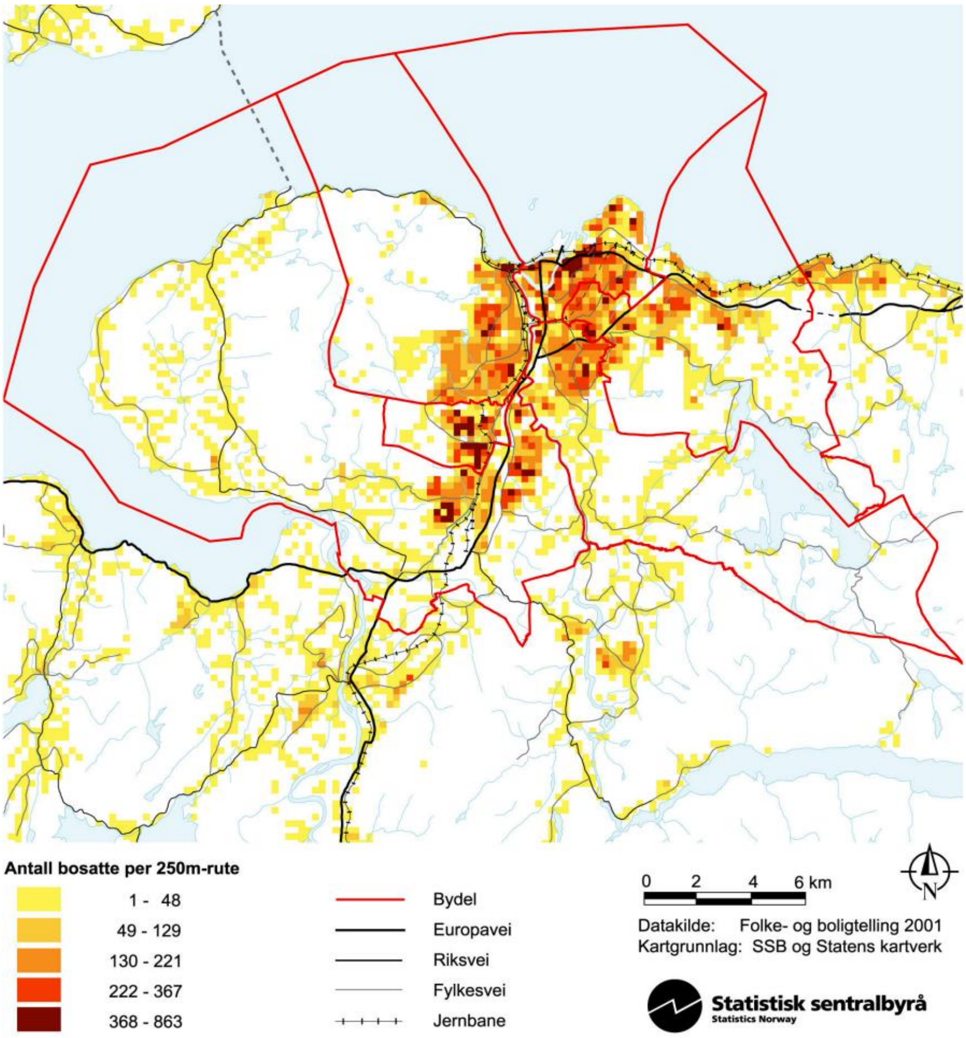

Figure 17: Settlement pattern in Trondheim showing the number of inhabitants per square of 250 metres. Obtained from Statistics Norway (2001).

The establishment of Tillerbyen represent a part of an expansion of the urban areas in Trondheim. In subsequent years to 2021, the results indicate that the urban areas have expanded to the south, west and east, displayed in Figure 8. Byplankontoret (2020) in Trondheim substantiates this statement as they describe that the urban areas around the city centre have expanded in recent years.

A share of the peatland areas is lost at Byneset with substantially lower population pressure. Thus, the loss of these peatlands are not a direct result of high population pressure or human installations. It is, however, an indirect effect of human pressure as there has been a land cover change to mainly agricultural land. As previously stated, there has been a major reduction of agricultural land in Trondheim municipality, mainly to residential areas (Gundersen et al., 2017). Since humans need food and wish to be self-sufficient for reasons such as food security, it is likely that ecosystems, such as peatlands, have been seen as substitute areas for cultivation.

The peatlands are lost in an elevation between 0 and 300 m a.s.l. (Figure 10). As the highest point in Trondheim municipality, before it was merged with Klæbu, was Storheia at 566 m a.s.l., there is a gap between 300 m a.s.l. and 566 m a.s.l. where peatlands are still intact (Kartverket, 2023). Magnussen et al. (2018), substantiates the results, as they report that peatlands in the lowlands are most exposed to human destruction, while there is less human activity in the highlands. When comparing Figure 10 and Figure 11, it is particularly interesting to observe that there are few peatlands left that are located between 0 and 100 m a.s.l. This likely reflects both a lower prevalence of peatland at low altitude, and high levels of human pressure. Further, the results show that most of the lost peatlands from 1964 to 2021 are located in an elevation interval between 100 and 200 m a.s.l. This suggests a higher prevalence of peatland area in this elevation interval than in the elevation interval between 0 and 100 m a.s.l. Further, it may indicate a trend of peatland loss occurring at increasingly higher elevations, driven by factors such as population growth and economic development (Ministry of Finance, 2021; Statistics Norway, 2022a).

4.3 Carbon Loss by Land Cover Change of Peatlands

Peat depth is a defining feature when estimating the C stock, and thus the amount of CO_2 emissions stemming from degraded peatlands (Akumu & McLaughlin, 2013). However, there is a lack of site-specific data which have resulted in extensive use of standardized values and thereby unprecise estimates (Bjørdal & Bjørkelo, 2006; Norwegian Environment Agency et al., 2022; Norwegian Public Roads Administration et al., 2022). By manual sampling, Long et al. (2022) found that peat depths of seven peatlands in Trondheim varied from 1.8 m to 6.9 m. At a national scale the Norwegian Environmental Agency (2020) report that peat depths span from 0.3 m to 10 m. Similar to these findings, the peat depths collected in this study shows large variation with mean and standard deviations of 2.9 ± 1.2 for bogs (Table 1) and 1.1 ± 0.5 for fens (Table 2). To detect differences in CO_2 emissions from degraded peatlands and thus acknowledge the importance of precise peat depth estimates, three scenarios was constructed as illustrated in Figure 14. The three bog scenarios have larger peat depths than their respective fen scenario. According to Moen et al. (2011), the peat depth of bogs tend to be larger than that of fens. Raised bog being the category with the largest peat depth of 2-5 m (Magnussen et al., 2018; Moen et al., 2011; Norwegian Environment Agency, 2020). With peat depth as a defining feature, it is likely that bogs emit larger amounts of CO_2 when degraded.

Grønlund et al. (2010) estimated that shallow peatlands contain 32 kg C m^{-2}, while deep peatlands contain 88 kg C m^{-2}. They follow the same definition of peatlands as this study, meaning an ecosystem with a minimum peat depth of 30 cm (Grønlund et al., 2010). In the C estimates they used a peat depth of 2 m for deep peatlands and 0.65 m for shallow peatlands (Grønlund et al., 2010). Bogs generally possess deeper peat layers than fens, indicating that they are more likely to correspond to deep peatlands, whereas fens are more likely to correspond to shallow peatlands (Moen et al., 2011). In scenario 1, the estimated C stock is 110.4 kg C m^{-2} for bogs and 58.4 kg C m^{-2} for fens. If, however, the peat depths are changed to 2 m for bogs and 0.65 m for fens, the C stock is 76.1 kg C m^{-2} and 34.5 kg C m^{-2}, respectively. These estimates are closely corresponding to the estimates by Grønlund et al. (2010) which substantiates their credibility. Moreover, the findings indicate that the significant difference in the C stock estimates between this study and Grønlund et al. (2010) is attributed to minor variations in peat depth. This again emphasizes the importance of precise data on peat depth.

Varying peat depths measurements between studies make it difficult to determine the most representative scenario for Trondheim. The objectives and study area can influence the peat depth measurements and their representativeness. For example, peat depths may have been collected at sites that is believed to have thick peat layers as these are more interesting objectives for conservation. This substantiates the importance of precise large-scale mapping in acquiring a comprehensive understanding of the extent and condition of peatlands.

Kasimir-Klemdtsson et al. (1997) estimated that the CO_2 efflux from cultivated peatlands in Sweden had the potential to reach a maximum of 7 kg CO_2 m^{-2} $year^{-1}$. Grønlund et al. (2006), on the other hand, estimated 2.2 kg CO_2 m^{-2} $year^{-1}$ from cultivated peat soils in Northern Norway. The disparity observed in the findings reflects the substantial variability in estimates of CO_2 emissions from peat soils. This study finds that scenarios 1, 2, and 3 emits 5.6, 2.9, and 8.5 kg CO_2 m^{-2} $year^{-1}$, respectively (Table 6). Both the values of scenario 1 and scenario 3 are close to, or higher than, the maximum estimate by Kasimir-Klemdtsson et al. (1997). However, if this study were to differentiate CO_2 emissions stemming from peatland transformation to infrastructure, agriculture and forestry, the results would most likely have been different. Joosten et al. (2015) estimated that drained peatlands emitted 3.65-3.72 kg CO_2 m^{-2} $year^{-1}$ and 0.18-1.21 kg CO_2 m^{-2} $year^{-1}$, when transitioned to cropland and forestry, respectively. In addition to ditching, soil cultivation enhances the supply of air to the soil, thereby increasing emissions from land cover change to agriculture (Joosten et al., 2015). The C content within the newly formed forest biomass partially offsets the emissions originating from the drained peatland, resulting in lower emissions from land cover change to forestry than to agriculture (Joosten et al., 2015). During the establishment of infrastructure, soil masses and vegetation are removed, and the land cover change hinder future C sequestration on the site (Norwegian Public Roads Administration et al., 2022). This causes rapid loss of peat and large annual emissions, which is in line with the results from this study.

Yearly per-capita emissions in Norway were calculated to be 7.6 tonnes of CO_2 in 2021 (Global Carbon Project, 2022). Thus, emissions from lost peatlands in Trondheim equals to yearly emissions from 302 631, 157 894, and 460 526 people, for the combined scenarios 1, 2, and 3, respectively. Considering scenario 1, the amount of emissions nearly equals a two-year consumption of the population in Trondheim (Statistics Norway, 2023). The emissions from lost peatlands also constitute a substantial share of the total CO_2 emissions in Norway in 2021 (Figure 16), while scenario 3 is closely corresponding to CO_2 emissions from domestic shipping and fishing in Norway in 2021 (Figure 15) (Statistics Norway, 2022b). In addition to direct emissions from the lost peatlands, land cover changes also hinder future C sequestration. It is important to point out that emissions from the lost peatlands are from degradation over a period of 57 years. Hence, yearly emissions would have constituted less compared to annual emissions in Norway.

4.4 Future Predictions

The period from 2021 to 2030 is proclaimed to be the Decade of Ecosystem Restoration by the UN general assembly (UNEP & FAO, 2020). The initiative may inspire decision-makers to conserve peatlands and to restore areas that have been degraded. The Norwegian Ministry of Climate and Environment (2021) report in *Norway's Climate Action Plan for 2021-2030* that peatland restoration is on the agenda and that the government is seeking to reduce peatland degradation. To fulfil the goal of restoring peatlands, the Norwegian Environmental Agency (2020) made the *Wetland restoration plan, Norway (2021-2025)*. If large-scale restoration is to be performed, the areal extent of peatlands might increase. However, it is uncertain if large-scale restoration will take place in Trondheim as large areas in the municipality is characterized by urban areas. Some restoration efforts are, however, under assessment. Lyngstad et al. (2017a) have conducted a *Pilot study on restoration of the raised bog Høstadmyra, Trondheim municipality, Norway*, which indicate that restoration efforts may be performed in the coming years.

Peatland restoration primarily involves the re-establishment of a higher water table (rewetting) (Bartlett et al., 2020). The water saturation leads to low oxygen levels and decomposition, which will prevent further C release (Joosten et al., 2015). Jäveoja et al. (2016) examined the climatic effect of restoration. They found that GHG emissions were reduced by 50% three years after rewetting, compared to unrestored peatlands (Järveoja et al., 2016). Hence, rewetting can be an effective way of mitigating negative climate impacts from degraded peatlands as it prevents prospected emissions (Järveoja et al., 2016). Beyer & Höper (2015) estimated that peatlands were likely to function as net C sinks within 30 years after the rewetting. Although local variations may influence the result, the findings by Beyer & Höper (2015) show that it takes time to restore the peatlands so that they re-establish their natural functions. This emphasizes that conserving peatlands should be prioritized with respect to GHG emissions.

To ensure the most positive mitigation effect of the restoration, it is important to restore the areas with largest climate change mitigation potential. As previously stated, Joosten et al. (2015) estimated that drained peatlands emitted 3.65-3.72 kg CO_2 m^{-2} $year^{-1}$ and 0.18-1.21 kg CO_2 m^{-2} $year^{-1}$, when transitioned to cropland and forest, respectively. The emissions are thus substantially lower when transitioned to forestry than to agriculture. Consequently, restoration of agricultural land yields a larger climate change mitigation potential, compared to forest. However, a population growth is expected in Trondheim in the coming decades, which may conflict with an increase in peatland area (Statistics Norway, 2022a). To maintain food production levels, it may be necessary to substitute the restored agricultural land (Hammervold, 2015). This action could potentially lead to deforestation, thereby resulting in supplementary emissions of CO_2 (Hammervold, 2015). To prevent such indirect emissions, dietary changes are a possible solution. Trends show that Norwegian diets are shifting to contain a larger share of meat (Norwegian Directorate of Health, 2022a). If the meat is produced locally, the need of agricultural land will increase, meaning less is available for restoration (Tangeland et al., 2017). However, if dietary advice by the Norwegian Directorate of Health (2022a) were to be followed, meaning less consumption of meat, then less agricultural land is needed which may allow peatland areas to be restored without leading to indirect emissions.

The urban development strategy for Trondheim towards 2050 indicates a densification and expansion of urban areas in the east, west and south (Byplankontoret, 2020). Infrastructure development on peatlands is explicitly mentioned in the report. Hence, the ecosystems are threatened despite national plans for restoration and conservation of peatlands. Laws and regulations may, however, decrease the magnitude of peatland degradation in Trondheim in the coming years, relative to the preceding decades. Ditching for forestry and cultivation for agriculture was forbidden from 2006 and 2020, respectively (Forskrift om berekraftig skogbruk, 2006, §5; Forskrift om nydyrking, 2020, § 5a). Although exceptions may occur, it is reasonable to assume that the legislation may result in less peatlands being transformed into forestry and agricultural land. It is, however, a paradox that it is in line with laws and regulations to disturb peatlands for infrastructure purposes, while the reduction of peatlands for agricultural land and forestry is contrary to legislation. As land cover change to infrastructure is the main cause of peatland degradation in Trondheim municipality, laws and regulations should be implemented to safeguard the areas from their major threat. The legislation has created debate and a proposal to repeal the ban has been initiated (Endringslov til jordlova (oppheve forbudet mot nydyrking av myr), 2021, § 11). Hence, laws and regulations are only protecting peatland areas to some extent.

With projected urban expansions in the east, west and south, the surrounding hill areas with intact peatlands, shown as pink polygons in Figure 8, are in danger of becoming more influenced by humans (Byplankontoret, 2020). Bymarka Nature Reserve is protected from human destruction through legislation, but it only includes parts of the areas west of Trondheim city centre (Andersen, 2010; Forskrift om Bymarka naturreservat, 2005, § 3). Regulations in *Kommuneplanens arealdel Trondheim 2012-2024* also provide a certain degree of protection to areas in the highland, but the areas are not protected in the same manner as Bymarka Nature Reserve, which makes them more exposed to human intervention, and thus peatland loss (Trondheim municipality, 2012).

What peatland category that will be most affected by future human intervention is uncertain as both bogs and fens are present in Trondheim. As a greater number of bogs have been lost between 1964 and 2021 compared to fens, there is potentially a higher proportion of fens remaining in Trondheim. However, Øien et al. (2015) reports that nutrient-rich fens were drained earlier than nutrient-poor bogs due to their suitability for cultivation. As a result, a greater number of fens were lost before 1964 compared to bogs. Given that fens experienced most of the destruction prior to 1964, while bogs were primarily affected after 1964, it can be inferred that the representation of peatland categories is relatively balanced in Trondheim at present. Meaning both bogs and fens are exposed to future land cover changes.

In terms of emissions, future destruction of peatlands in the highlands indicate that the CO_2 emissions will decrease. This is because peat accumulation occurs at a slower rate in higher elevations due to lower temperatures, resulting in smaller C stocks (Lyngstad et al., 2012). However, it is uncertain how much the emissions will decrease based on the projected expansion of Trondheim.

According to Lyngstad et al. (2018), climate change will have an impact on the formation of peatlands. Precipitation is projected to increase in intensity and frequency which promotes soil moisture and thereby better conditions for peatland formation (Lyngstad et al., 2018; IPCC, 2022). However, the projected rise in temperatures can result in drier conditions as more water will evaporate (Lyngstad et al., 2018; IPCC, 2022). Despite drier conditions, it is uncertain how an increase in temperature will influence peat formation as it will enhance both organic matter production and decomposition (Lyngstad et al., 2018). Hence, to which extent climate change will better or worse the conditions of peatland ecosystems in Norway is uncertain.

4.5 Limitations and Strengths of the Study

4.5.1 Classification of Peatlands

Although the most comprehensive classification of peatlands in Trondheim is found to be given in AR5 and DMK, it has some limitations. Peatland areas usable for cultivation and forest production that are larger than 2-5 acres is the only ones included in the DMK map layer (NIBIO, n.d.). Consequently, the map is limited from functioning as a complete information source for peatlands present in Trondheim. Further, it classifies the peatlands based on vegetation which aligns to the classification in NiNs typification system, described in Appendix 1. According to Halvorsen et al. (2015), a combination of the typification system and the attribute system is required for a complete description of the variation in Norwegian nature. Thus, the classification in DMK and AR5 is limited in scope.

NiNs classification system includes nine peatland ecosystems, whereas the classification in AR5 and DMK only aligns with V3 Bog, V1 Open fen, V2 Mire and swamp forest and V8 Tidal and alluvial forest (Lyngstad et al., 2022b). Consequently, five peatland ecosystems are not considered in the classification in AR5 and DMK. The presence of the remaining five peatland ecosystems, namely V4 Spring, V9 Semi-natural fen, V11 Peat quarry, V12 Drained peatland and V13 Artificial wetland, included in NiNs classification system, needs to be evaluated to assess the reliability of the classification in AR5 and DMK. According to Moen (1983), the coverage of springs is small, and Lyngstad et al. (2012) found that the prevalence of semi-natural fens is relatively low in Trondheim. Søgaard et al. (2017) found no active peat quarries in Trondheim, except for a former extraction site (Høstadmyra). However, Øien et al. (2017) argue that the method used by Søgaard et al. (2017) may not capture all peat quarries as they find a larger number of active peat quarries in Norway. These are, however, located outside of Trondheim which emphasises the credibility of the findings by Søgaard et al. (2017) for the scope of this study. Further, the coverage of artificial wetlands is usually small (Norwegian Biodiversity Information Centre, n.d.-b). In contrast to the four peatland ecosystems described, drained peatlands are reported to have a large areal extent in Norway (Joosten et al., 2015). Moen (1983) reported that several areas are drained in his assessment of peatlands in Sør-Trøndelag, which substantiates that peatland areas in Trondheim are degraded. This study emphasizes that peatlands have been degraded in Trondheim in recent decades (Table 5).

To achieve a comprehensive understanding of the peatlands in Trondheim, all peatland ecosystems included in NiNs classification system should be considered. However, the limited occurrence of the majority of the peatland ecosystems partly validates the classification in AR5 and DMK.

4.5.2 Mapping of Peatlands

Determining whether an area is a peatland just by analysing aerial photos is not optimal. One could have obtained more precise mapping if manual sampling was supplemented to the analysis. The peat depth is an element of uncertainty as one cannot obtain this information from the aerial photos. Consequently, polygons may be constructed in areas that do not meet the required peat depth of 30 cm. Further, differentiating between bog and fen is also a challenging task just by analysing aerial photos. As vegetation is a determining factor when categorising bog and fen, field work would optimize the precision of the analysis (Lyngstad et al., 2022b). Also, stereo (3D) interpretation of aerial photo projects increases the possibility of correct classification (Lyngstad & Davidsen, 2021). Another limitation of the study is related to the centroids that was made to obtain the elevation of the centrum of each polygon. As topography may vary within a peatland, this method of obtaining the elevation may be insufficient. On the other hand, the use of supplementary map layers and sources to validate the work strengthens the reliability of the mapping in QGIS.

4.5.3 Carbon Loss Estimates

As there is a lack of information on peat depths in Trondheim municipality, as discussed in section 4.3, the data collection was supplemented with peat depths from Western Norway to get a wider range of depths. Climatic and hydrologic conditions are quite similar in Trøndelag and western Norway (Norwegian Centre for Climate Services, 2016, 2021). Moreover, all peatlands assessed are located in the lowlands. Thus, one may argue that the formation process in peatlands in Western Norway and in Trondheim municipality is quite similar. However, relatively small differences in climatic and hydrologic conditions may affect important factors for plant growth and thus accumulation of peat. Hence, using peat depths obtained from Western Norway represent a source of uncertainty in the estimates.

The amount of collected peat depths is small, especially for fens, which may limit the estimates from being representative for Trondheim municipality. A small amount of collected peat depths place greater demands on each individual value to be representative. As there are a lack of measured peat depths in Trondheim municipality, a proportion of the obtained peat depths are from other locations. For fens, all the values are from outside Trondheim municipality (Table 2). Hence, a greater amount of measured peat depths at several locations in Trondheim municipality would have increased the chance of obtaining more representative and precise C stock estimates. Thus, the small amount of collected peat depths represent a limitation in this study.

4.5.4 General Limitations of the Study

This study only considers C storage, whereas peatlands provide a series of ecosystem services such as habitat provision for wildlife, water regulation and purification, and erosion protection (Bonn et al., 2016). Further, the ecosystem is of global importance because it supports unique biodiversity (Ramsar Convention, 2015). When assessing the value of peatlands, these should also be included. Given that the world is facing both a climate crisis and a nature crisis, it is important to give equal priority to biodiversity and greenhouse gas emissions.

Social and economic factors are not considered which are important factors in the overall assessment of peatlands. Peatland mapping and monitoring, conservation and restoration are costly processes, which substantiates that economic aspects should be considered. Social aspects are important to incorporate in decision-making as safeguarding peatlands may conflict with other land-use purposes.

4.6 Future Research

Partly because of diverse use of definitions, in addition to imprecise and low coverage mapping, statistics on peatlands are varying widely (Joosten et al., 2015). Terms like "bog", "mire" and "peatland" is in many cases referring to the same ecosystem. Employing a consistent terminology and implementing a standardized ecosystem definition would have facilitated the comparative analysis of studies conducted across national borders. Additionally, future research incorporating mapping techniques such as remote sensing presents the potential for large-scale mapping (Bakkestuen et al., 2023). To validate the accuracy of remote sensing, ground truthing should be conducted as an additional measure. Ground truthing is based on field observations and measurements that can provide more precise peat depth measurements and a better selection of peatland category. Combining remote sensing and ground truthing in future research can thus provide precise large-scale mapping of peatlands.

5 Conclusion

Trondheim municipality has experienced a substantial decline in peatland coverage, mirroring global trends observed over the past decades. From 1964 to 2021, 16% of the peatland area in Trondheim has been lost. The lost peatlands are located in lowland areas, where the majority has undergone a transformation to infrastructure followed by agricultural land and forestry.

The results have revealed that large amounts of CO_2 have been emitted from lost peatlands in Trondheim municipality from 1964 to 2021. To detect differences in CO_2 emissions from degraded peatlands and thus acknowledge the importance of precise peat depth estimates, three scenarios was constructed for each of the peatland categories bog and fen. Scenario 1, constitute a mean of the measured peat depths, while scenario 2 constitute 50% more shallow peat and scenario 3 constitute 50% deeper peat. The scenarios for bogs showed higher values than their respective fen scenario which is reasonable as they tend to have thicker peat layers. With peat depths, as a defining feature, the results show that more CO_2 is emitted from bogs than fens. The combined bog and fen scenarios 1, 2, and 3 equals 2.3, 1.2, and 3.5 million tonnes of CO_2 emissions, respectively. Considering scenario 1, the amount of emissions nearly equals a two-year consumption of the population in Trondheim. The differences in emissions between the scenarios highlights the need for accurate measurements of peat depth. Therefore, future research should combine remote sensing and ground truthing to achieve precise large-scale mapping of peatlands.

While efforts to restore and conserve peatlands through national regulations and initiatives provide some level of protection against peatland loss, the expansion of urban areas in Trondheim municipality poses a continued threat to these valuable ecosystems. The surrounding hills in the urban areas suggest that future destruction is likely to impact primarily the peatlands in highland areas. These peatlands have thinner peat layers compared to those in lowland areas due to slower peat accumulation rates caused by lower temperatures, resulting in smaller carbon stocks. Nature areas in the highlands are also regulated which may counteract the loss of peatlands. Consequently, it is anticipated that peatland loss in Trondheim municipality will result in lower emissions. However, if not new practises are implemented to safeguard the peatlands, emissions will continue to contribute to climate change.

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Appendix

Appendix 1: Classification of Peatlands

Appendix 1: Classification of Peatlands

Appendix 1 comprises a section that is derived from the project thesis by Ekerholt (2022).

The EcoSyst Framework

The EcoSyst Framework (NiN) is a classification system developed by experts on behalf of the Norwegian Biodiversity Information Centre to describe the variation in Norwegian nature (Halvorsen et al., 2015). The first edition of NiN 1.0 was launched in 2009, and it was revised and upgraded to NiN 2.0 in 2015 (Halvorsen et al., 2015). To provide a complete description of the variation in Norwegian nature, NiN uses a combination of a typification system and an attribute system (Halvorsen et al., 2015).

Typification System

The classification in the typification system is based on vegetation and is evaluated by the turnover of plant species along ecological gradients (Lyngstad et al., 2022b). It comprises a three-level hierarchy that includes main ecosystems, ecosystem types, and ecological gradients (Norwegian Biodiversity Information Centre, 2014). The main ecosystem, "Wetland systems," is further classified into 13 ecosystem types, with nine of them being peatland ecosystems (Lyngstad et al., 2022b). These nine peatland ecosystems are V1 Open fen, V2 Mire and swamp forest, V3 Bog, V4 Spring, V8 Tidal and alluvial swamp forest, V9 Semi-natural fen, V11 Peat quarry, V12 Drained peatland, and V13 Artificial wetland (Lyngstad et al., 2022b).

Natural Ecosystem Types

Peatlands that develop naturally without human interference are known as natural peatlands. The peat layer accumulates as plant material decomposes, causing the vegetation to become increasingly isolated from mineral groundwater (Rydin & Jeglum, 2013). When the peatland's surface is completely separated from groundwater, it only receives water from precipitation (Rydin & Jeglum, 2013). Peatlands that receive nutrients from groundwater are called minerotrophic, while those that receive nutrients from precipitation are called ombrotrophic (Rydin & Jeglum, 2013). In the NiN system, minerogenous peatlands correspond to natural ecosystem types V1 Open fen, V2 Mire and swamp forest, V4 Spring, and V8 Tidal and alluvial swamp forest, while ombrogenous peatlands correspond to V3 Bog. V2 Mire and swamp forest and V8 Tidal and alluvial swamp forest are wooded fens, while wooded bogs are included in V3 Bog due to differences in vegetation caused by differences in nutrient access. While fens have varying, sometimes species-rich vegetation, only a few species can survive in bogs due to their low pH (Lyngstad et al., 2022b).

At the most specific level of the typification system, ecological gradients are based on the variation in vegetation along ecological gradients (Lyngstad et al., 2022b). The different ecosystem types are characterized by a combination of multiple ecological gradients. The main ecological gradients in mire vegetation are poor-rich, hollow-hummock, and mire margin-mire expanse.

Ecosystem Types Characterized by Human Interference

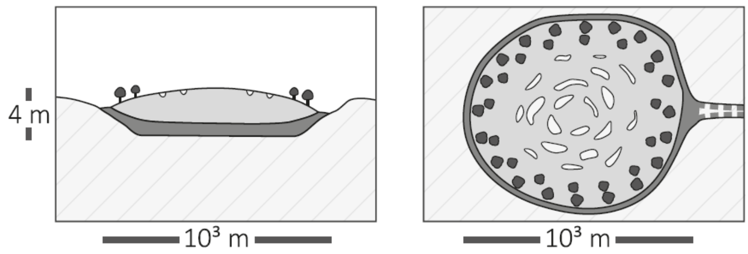
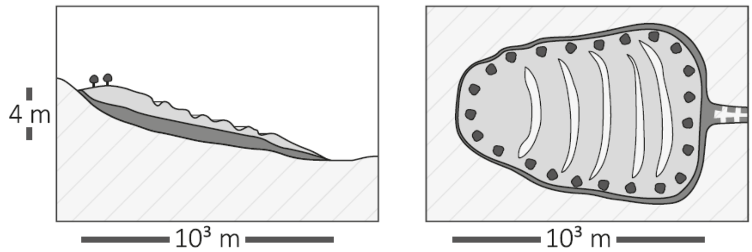
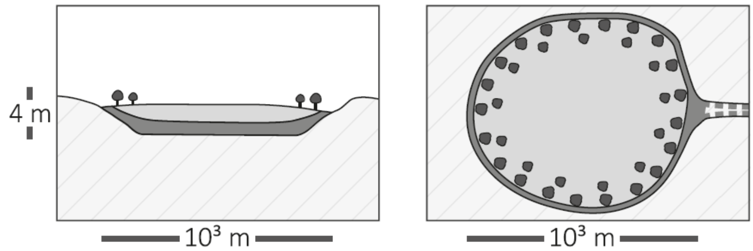
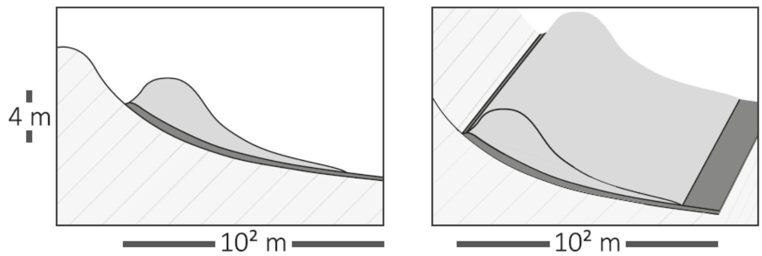
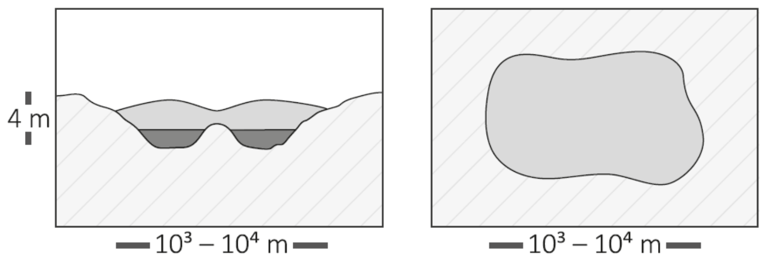
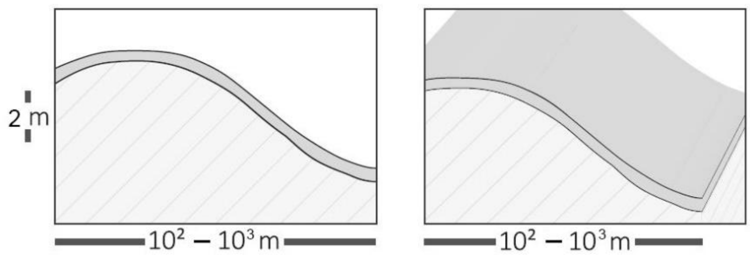
The NiN ecosystem types that have been impacted by human activity are V9 Semi-natural fen, V11 Peat quarry, V12 Drained peatland, and V13 Artificial wetland. Semi-natural fens have been subjected to extensive mowing or grazing, resulting in a different plant species ratio than other peatlands (Lyngstad et al., 2022b). Peat quarries, drained peatlands, and artificial wetlands have all undergone significant human intervention. Peat has been extracted from peat quarries for use as i.e. fuel or fiber material, resulting in highly modified ecosystems (Lillesund et al., 2018). Ditching has lowered the water level in drained peatlands, changing the vegetation composition and peat properties (Lyngstad et al., 2022b). Lastly, artificial wetlands are created through human interventions, resulting in the creation of new wetland areas (Lyngstad et al., 2022b). Since peat accumulation is a slow process, V13 Artificial wetland areas are generally not classified as peatlands.

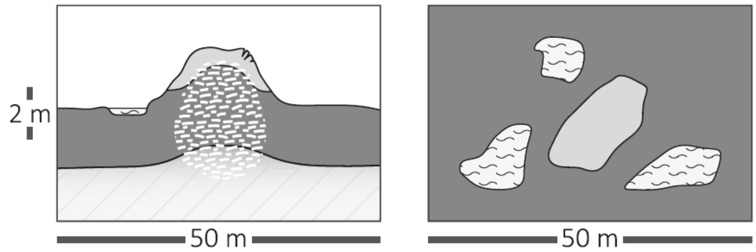
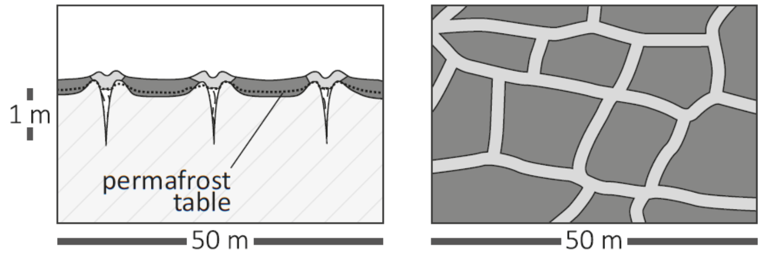
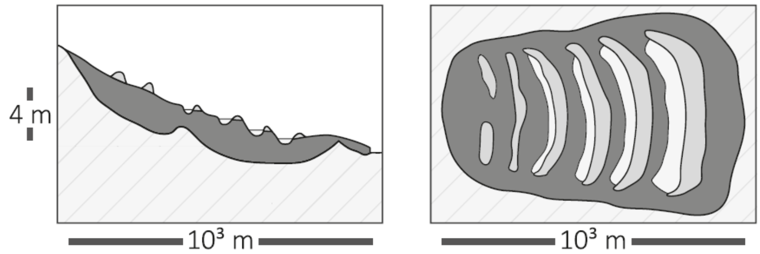
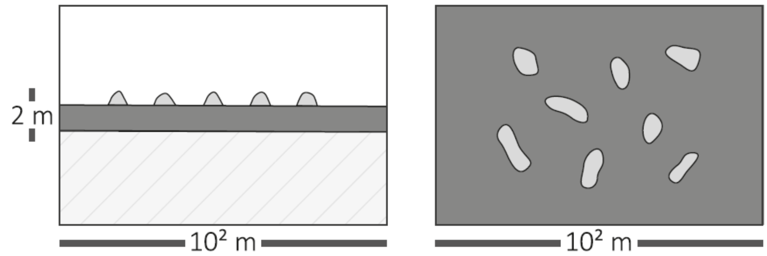
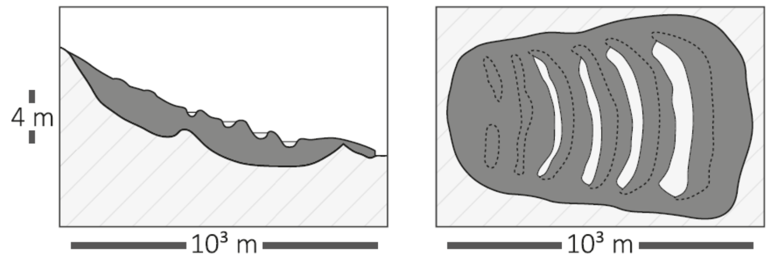
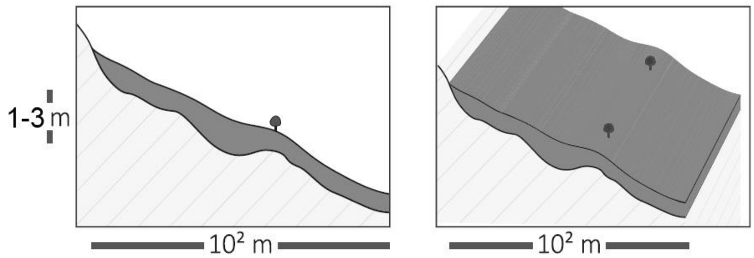
Attribute System

The attribute system encompasses variables that are not accounted for in the typification system, namely those that are not determined by the diversity in plant life along ecological gradients (Norwegian Biodiversity Information Centre, 2015). The classification of peatlands in the attribute system is determined by hydromorphology (Norwegian Biodiversity Information Centre, n.d.-a). Hydromorphological characteristics are used to classify peatland areas into five geographical levels (Lyngstad et al., 2022b):

1. Mire microstructure: The smallest units of uniform peat and vegetation (Norwegian Biodiversity Information Centre, n.d.-a). I.e. hummocks.
2. Mire structure: The combination of mire microstructures (Norwegian Biodiversity Information Centre, n.d.-a). I.e. a string.
3. Mire segment: An area with a relatively uniform composition of mire structures, such as an open mire expanse.
4. Mire massif: An area with a characteristic combination of mire segments that form a hydromorphological massif, which serves as the basis for defining hydromorphological peatland categories such as raised bogs (Norwegian Biodiversity Information Centre, n.d.-a).
5. Mire complex: A geographically circumscribed mire area that often consists of several mire massifs (Norwegian Biodiversity Information Centre, n.d.-a).

The geographic level referred to as "mire massif" yields the hydromorphological peatland categories (Lyngstad et al., 2022b). These categories can be classified into three groups, namely, those that are dominated by ombrogenous peatlands (bogs), those that are a combination of ombrogenous and minerogenous peatlands, and those where minerogenous peatlands (fens) dominate (Lyngstad et al., 2022b). There are seventeen hydromorphological peatland categories included in NiN version 2.3, as shown in Figure 18.

1	*Concentric raised bog*	
2	*Eccentric raised bog*	
3	*Plateau raised bog*	
4	*Ridge raised bog*	
5	*Atlantic bog*	
6	Blanket bog	

7	*Palsa fen*	
8	*Polygon fen*	
9	*String mixed mire*	
10	*Islet mixed mire*	
11	*String fen*	
12	*Sloping fen*	

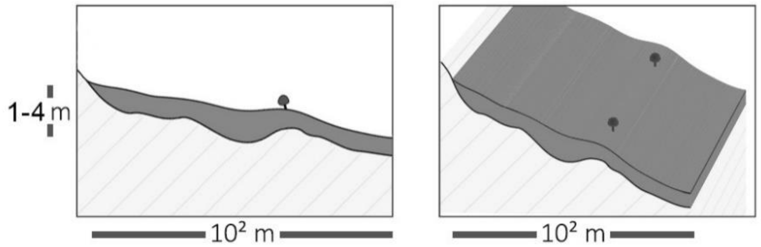
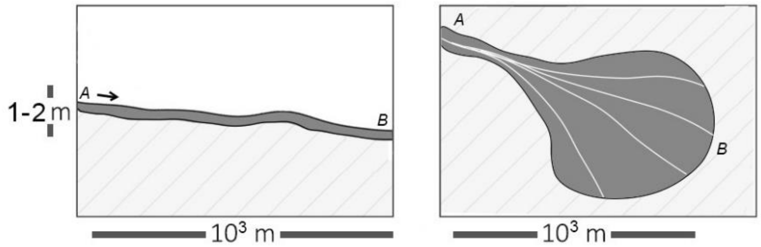
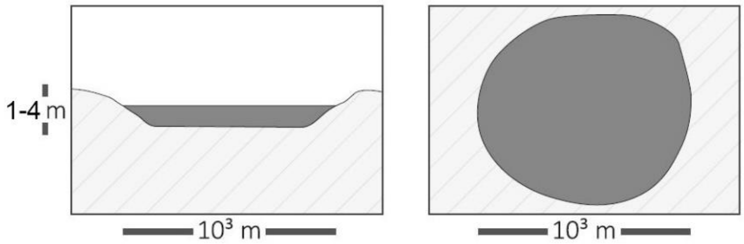
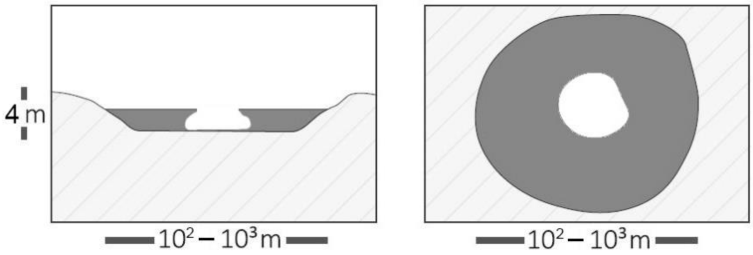
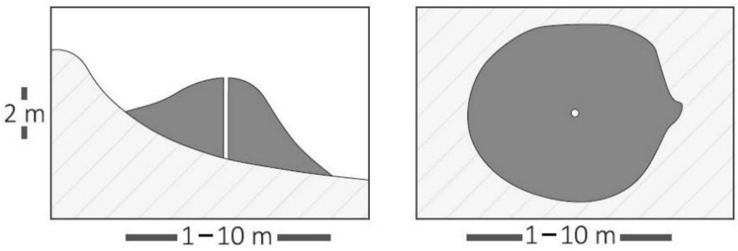
13	*Percolation mire*	
14	*Transgression mire*	
15	*Flat fen*	
16	*Terrestrialisation fen*	
17	*Spring fen*	

Figure 18: Peatland categories included in NiN version 2.3. The profile is shown to the left in the illustration, while peatlands from above is shown to the right in the illustration. Typical extent is given in the x-axis, while the typical peat depth is given in the y-axis. The illustration is obtained from Lyngstad et al. (2022) and Joosten et al. (2017).

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