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Modelling nitrogen and phosphorus export and carbon processes in a forestry-drained peatland in eastern Finland

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Lotta Alina Jokiniemi

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Author Lotta Alina Jokiniemi

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Thesis supervisor Harri Koivusalo, professor

Thesis advisor Annamari (Ari) Laurén, professor, D.Sc (University of Eastern Finland)

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Abstract

Forestry-drainage and ditch network maintenance have been done to enhance tree-growth in peatlands. 18 % of Finnish forests were forestry-drained in 2012. Forestry-drainage of peatlands has been estimated to enhance nutrient loading of peatlands. The impact of forestry-drainage on CO_2 and CH_4 uptake or carbon storage of peatlands is still unclear. Climate change has been projected to increase precipitation and air temperature in northern peatlands, which changes soil moisture conditions and runoff generation in peatlands. Climate change is projected to alter nutrient exports and carbon balance of peatlands.

There is a gap of long-term modelling studies combining both carbon and nutrient processes under climate and drainage impact in peatlands. The objective was to evaluate modelling of nutrient exports and carbon balance via Peatland Simulator SUSI. Hydrological performance of SUSI was evaluated by comparing modelled daily and cumulative water table depth, runoff and snow water equivalent in short-term simulation to observations from Koivupuro in 2011-2013. Climate and drainage impacts on nutrient exports and carbon processes in a forestry-drained peatland were modelled for period 2006-2100. Meteorological input for long-term simulation consisted of down-scaled and bias-corrected projections from EURO-CORDEX with emission scenario 8.5. Drainage impact in 2006-2100 period was studied by simulating three ditch depth scenarios.

In the results water table deepened due to climate change and drainage, which increased nutrient exports and CO_2 uptake of the peat in Koivupuro. Climate change and drainage were projected to have negative impacts on CH_4 uptake of the peat. Carbon storage of Koivupuro was projected to increase during long-term simulation, and drainage impact on carbon balance was unclear. In the short-term simulation SUSI predicted the dynamics of water table depth, runoff and snow water equivalent similarly to observations, but under- or overestimated quantities. Increased fluctuation in modelled annual carbon balance after 2060s originate from uncertainties related to long-term modelling of biomass and stand growth, as well as changing stand mortality due to increased tree basal area in an aged forest.

Keywords SUSI, forestry-drained peatlands, hydrology, nutrient export, carbon

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Tiivistelmä

Suomessa on metsäojitettu soita puuston kasvun kiihdyttämiseksi. Vuonna 2012 18 % suomen metsistä oli metsäojitettuja soita. Metäsojituksen on arvioitu kasvattavan soiden ravinnekuormaa ja metsäojituksen vaikutus soiden CO_2 ja CH_4 vuohon sekä hiilivarastoihin on yhä epäselvä. Ilmastonmuutoksen on arvioitu lisäävän sadantaa ja ilman lämpötilaa pohjoisilla soilla, jolloin soiden kosteusoloissa ja valunnassa ilmenee muutoksia. Ilmastonmuutoksella on siten arvioitu olevan vaikutusta soiden ravinnekuormaan ja hiilitaseeseen.

Ilmastonmuutoksen ja ojituksen pitkäaikaista vaikutusta sekä suoalueiden hiilen että ravinteiden prosesseihin mallintavia tutkimuksia ei juurikaan ole. Työn tavoitteena oli arvioida SuoSimulaattorin (SUSI) ravinnekuorman ja hiilitaseen mallinnusta. Simulaattorin hydrologista mallinnusta arvioitiin vertaamalla lyhyelle ajanjaksolle 2011-2013 mallinnettua päivittäistä ja kumulatiivista valuntaa, lumen vesiarvoa ja pohjaveden pintaa Koivupurolla tehtyihin mittauksiin samalla ajanjaksolla. Ilmastonmuutoksen ja kunnostusojituksen vaikutusta metsäojitetun suon ravinnekuormaan ja hiilitaseeseen mallinnettiin ajanjaksolle 2006-2100. 95 vuotta pitkän ajanjakson mallinnukseen käytettiin EURO-CORDEXin ilmastoprojektioita päästöskenaariona RCP8.5. Kunnostusojituksen vaikutusta vuosina 2006-2100 tutkittiin mallintamalla kolmea ojan syvyyttä.

Ilmastonmuutoksen ja ojituksen vaikutuksesta pohjaveden pinnan arvioitiin laskevan, jolloin ravinnekuorma ja CO_2 vuo turpeeseen nousivat. Ilmastonmuutoksen ja ojituksen vaikutus turpeeseen kohdistuvaan CH_4 vuohon oli negatiivinen. Hiilivaraston arvioitiin kasvavan vuodesta 2006 vuoteen 2100. Ojituksen vaikutus hiilitaseeseen oli epäselvä. Lyhytaikaisessa mallinnuksessa SUSI ennusti valunnan, lumen vesiarvon ja pohjaveden pinnan vaihtelun ajoitukset mittauksia vastaavasti, mutta yli- tai aliarvioi arvoja systemaattisesti. Hiilitaseen vuosittaisessa vaihtelussa ennustettiin kasvua 2060-luvulta lähtien. Arvojen heilahtelu voi johtua biomassan ja metsikön kasvun pitkäaikaiseen mallinnukseen liittyvästä epävarmuudesta tai muutoksista ikääntyneen metsän puuston kuolleisuudessa kasvaneesta puuston pohjapinta-alasta johtuen.

Avainsanat SUSI, metsäojitetut suot, hydrologia, ravinnekuormitus, hiili

Contents

Preface

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Helsinki, 25 February 2022
Alina Jokiniemi

Symbols and abbreviations

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
DNM	Ditch network maintenance
DOC	Dissolved organic carbon
Fe	Iron
GHG	Greenhouse gas
K	Potassium
N	Nitrogen
N_2O	Nitrous oxide
NPP	Net primary productivity
OC	Organic carbon
P	Phosphorus
POC	Particulate organic carbon
SWE	Snow water equivalent
TN	Total nitrogen
TOC	Total organic carbon
TON	Total organic nitrogen
TP	Total phosphorus
WT	Water table
WTD	Water table depth

CMIP	Coupled Model Intercomparison Project
GCM	Global climate model
IPCC	Intergovernmental Panel on Climate Change
NCC	Norwegian Climate Center
RCM	Regional climate model
RCP	Representative Concentration Pathway
SMHI	Swedish Meteorological and Hydrological Institute

1 Introduction

Importance of evaluating the impacts of forestry practices on carbon and nutrient balances was highlighted in recent environmental targets: The Government Programme in Finland in 2019 set a goal of national carbon neutrality by year 2035 (VN 2019), and the European Commission adopted Water Framework Directive to reach good ecological status in surface waters of member states by year 2027 (European Commission 2019). Energy and climate strategy for 2030, updated Bioeconomy strategy, and updated National Forest Strategy among others were confirmed to enhance usability of forests in a sustainable manner.

Approximately 78 % of Finland is covered by forests (Metsäntutkimuslaitos 2012) from which 18% are forestry drained (Metsäntutkimuslaitos 2011). Forestry drainage has been observed to enhance loading of nutrients, organic carbon (OC) and suspended solids (Ahtiainen, 1991, Strack *et al.* 2008, Evans *et al.* 2016, Räike *et al.* 2019, Asmala *et al.* 2019, Nieminen *et al.* 2020, Finér *et al.* 2020, Nieminen *et al.* 2021) although also contradictory results have been reported likely due to changed pH and flow paths (Kortelainen *et al.* 1997, Åström *et al.* 2001a, Lepistö *et al.*2014). In similar incoherence, after drainage carbon dioxide (CO_2) emissions from peatlands have been reported to increase (Silvola *et al.* 1996, Kløve *et al.* 2010), stay similar to pre-drainage emissions (Evans *et al.* 2016, Lohila *et al.* 2011, Aurela *et al.* 2004), decrease (Minkkinen *et al.* 2002), or increase depending on site fertility (Couwenberg *et al.* 2011, Ojanen *et al.* 2013, Zhong *et al.* 2020).

Climate change has been projected to increase air temperature and annual precipitation in Finland. The role of peatland in climate change depends on CO_2 and methane (CH_4) efflux (Evans *et al.* 2016, Frolking & Roulet, 2007). Changes in evapotranspiration and rainfall timing affect soil moisture and runoff generation, and potential disturbances in peatland carbon dynamics due to peat moisture reduction can remarkably increase carbon emissions in waterborne or gaseous form if peatland turns from carbon sink to a carbon source (Harenda *et al.* 2018). It is under debate whether carbon content in peatland increases or decreases after drainage.

Changed soil moisture and water flow patterns in peatlands have remarkable effect on ecological status of surface waters since nitrogen (N) and phosphorus (P) loading affect the quality of receiving surface waters, and can enhance eutrophication in them (Smith 1998). In 2019, ecological status was good or excellent in the majority of inland surface waters and moderate in the majority of coastal waters of Finland (Finnish Environment Institute 2019). Exports of iron (Fe) and organic matter (OM), from which the majority is total organic carbon (TOC) (Kortelainen *et al.* 2006), causes water brownification (Kritzberg & Ekström 2012).

There is a gap of modelling studies combining the simulation of both nutrient exports and carbon processes. This study aims to investigate the current state and development of 1) nutrient exports and 2) carbon processes in forestry drained Koivupuro catchment located in Kainuu. The objective is to simulate a) a short-term and b) a long-term processes using climate data, stand and forest stand description, and soil properties, which form an input to mechanistic peatland simulator SUSI (Laurén *et al.* 2021). Both the effect of changing climate variables and ditching practices on annual and seasonal development of nutrient exports and carbon balance are investigated, and the limits of the modelling are evaluated and reported. The goal is to provide annual estimates of the development of components, and the results are evaluated based on literature values reported from other similar study sites. In the short-term simulation modelled hydrological components were compared to observations from Koivupuro in 2011-2013. Short-term simulation is driven by measured meteorological data, and long-term simulation by scenarios from EURO-CORDEX RCP8.5 regional climate model. For long-term simulation three ditch depths of i) 0.1 m ii) 0.5 m, and iii) 1.0 m are used, to be able to identify the modelled effect of intensity of drainage to nutrient exports and carbon processes.

2 Literature review

2.1 Peatlands

A peatland is considered to be an area where peat layer has accumulated naturally, and a mire is a peatland that is currently undergoing accumulation of peat. Peat forms as C accumulates to peat profile when primary production exceeds decomposition. Kortelainen *et al.* (2006) estimated that average peatland percentage in Finnish counties is 34 %. According to Räike *et al.* (2019), cover of peatlands is the highest between latitudes 63° and 66° N. In Finland peatlands are often classified to be located in the raised bog region in the south, in the aapa mire region in central and northern Finland, or in the palsa mire region in the north.

Peatland site can be an ombrotrophic bog or a more nutrient-rich fen. Ombrotrophic sites receive water and nutrients only via precipitation whereas minerotrophic sites also gain water and nutrients from surrounding areas. In bogs above-ground and below-ground biomass are higher and above-ground biomass consists mostly of shrubs and *Sphagnum* (Moore *et al.* 2002), and in fens above-ground biomass is lower and dominated by sedges, herbs and *Sphagnum* (Moore *et al.* 2002), or by *Sphagna* and brown mosses (Straková *et al.* 2011). Site and sub-site specific vegetation mapping is used to describe heterogeneity within classification from bog to fen and between sub-sites.

Straková *et al.* (2011) estimated that difference in vegetation community makes fens more minerotrophic since *Sphagna* and brown mosses have higher decomposition rates compared to more resilient bog vegetation. Typically aapa-mires are considered to be minerotrophic and raised bogs to be ombrotrophic. In an aapa-mire the lower elevation middle part of the mire is a fen and the borders have characteristics of a bog, and in a raised bog the elevated middle part resembles a bog and borders have characteristics of a fen.

Hydrology differs between peatland sites. Runoff is higher in northern catchments due to lower evapotranspiration compared to southern catchments (Kortelainen *et al.* 1997, Mattsson *et al.* 2003, Räike *et al.* 2012), and both precipitation and evapotranspiration are higher in southern areas (Mattsson *et al.* 2003). According to Kortelainen *et al.* (1997), runoff is higher in catchments with peatland coverage over 35 % compared to catchments with peatland cover less than 35 %. Nieminen *et al.* (2017) noted that minerotrophic sites have greater flow velocities, greater erosive forces, and shallower peat layers compared to ombrotrophic sites due to the more typical downslope location of minerotrophic peatlands.

Changes in water flow magnitudes and patterns in Finnish catchments have been recorded during recent decades. Räike *et al.* (2012) found that in winter the water flow in streams and rivers has increased since 1975 in northern Finland. The timing of spring thaw shifted earlier between the years 1995 and 2016, and nutrient export increased during winter since runoff decreased in spring and increased during summer, autumn and winter (Räike *et al.* 2019). Rankinen *et al*. (2016) noted at least half or majority of the Finnish catchments to have had a positive trend in late summer and early autumn temperatures and mid-winter runoff, and a negative trend in spring or early summer runoff. Veijalainen *et al*. (2010) projected potential reduction of annual floods in snowmelt-flood dominated areas.

2.1.1 Forestry-drained peatlands

Forestry drainage was started at the beginning of the 20th century. Drainage practices have been most intense in western and southern Finland but most of the drained peatlands are located in northern and western Finland where peatland proportion is the highest (Turunen 2008, Päivänen & Hånell 2012). Pine mires are the most typical sites of forestry-drained peatlands in Finland (Turunen 2008, Päivänen & Hånell 2012). Most of the drainage was implemented in the 1960s and 1970s (Päivänen & Hånell 2012). By 2000, ditch network maintenance (DNM) had replaced drainage activities practiced in pristine peatlands (Päivänen & Hånell 2012). DNM is a forest management practice that includes cleaning of old ditches, creating new ditches, or a combination of both activities. DNM has potential to lower the ground water table (WT) and enhance tree growth, especially in the early phases of stand rotation; Sikström & Hökkä (2016) reported DNM to increase tree growth by 0.5 to 1.8 m^3 $ha^{-1}yr^{-1}$ in a Scots pine forest. Sarkkola *et al.* (2012) however noted that in sites with high stand volume and relatively high water table depth (WTD) DNM might not actually enhance tree growth; DNM was the most beneficial for tree growth if pre-WTD was less than 25-30 cm.

Drainage widely changes environmental conditions in peatlands. Water level drawdown is controlled by climatic factors and transpiration, and by stand properties such as stand volume, peat layer thickness, peat type and drainage efficiency (Stenberg *et al.* 2018, Hökkä *et al.* 2021). Stenberg *et al.* (2018) included mineral soil underlying peat layer, vegetation, and site topography to model water balance in a drained peatland. Water level drawdown has been shown to have an impact on microbial communities (Jaatinen *et al.* 2007), vegetation (Minkkinen *et al.* 1999, Laiho *et al.* 2003, Jaatinen *et al.* 2007), and peat properties like pH (Minkkinen *et al.* 1999), thickness of the peat layer (Minkkinen *et al.* 1999, Price 2003, Grønlund *et al.* 2008) and hydraulic conductivity (Sikström & Hökkä 2016) . These changes have in turn effects on gross primary production (Riutta *et al.* 2007, Bridgham *et al.* 2008), carbon accumulation (Bridgham *et al.* 2008), and nutrient status of peatland (Tahvanainen 2011).

According to Zhong *et al.* (2020), drainage can cause large shifts in vegetation of peatland since the highest growth rates are observed for woody plants in dry and well-aerated environment, and for *Sphagnum* mosses in flooded conditions. Jaatinen *et al.* (2007) stated that pH and substrate type in the peat layer control changes in microbial communities after water level drawdown. Similarly, vegetation shifts differ between peatland types. Minkkinen *et al*. (1999) and Laiho *et al.* (2003) detected vegetation shift a few decades after water level drawdown from *Sphagna* and *Sphagnum* mosses and graminoids to arboreal forest vegetation in minerotrophic or southern peatlands. Similarly, Riutta *et al.* (2007) reported *Sphagnum* mosses in a fen to have higher sensitivity to moisture conditions compared to sedges and dwarf shrubs. Vegetation shifts have an effect on the quantity and quality of litterfall (Laiho *et al*. 2003, Ojanen *et al.* 2013), and on gross photosynthesis of peatland due to decreased production of *Sphagnum* mosses (Riutta *et al.* 2007, Bridgham *et al.* 2008).

Forest growth changes properties of the soil. Litter layer, diverse micro- and macro-fauna, and root system increase macroporosity, hydraulic conductivity, and infiltration rate, and decrease bulk density in the forest soil (Neary *et al.* 2009). This increases the importance of subsurface runoff and decreases the importance of surface runoff (Neary *et al.* 2009). Water level drawdown due to drainage on the other hand lowers pH (Minkkinen *et al.* 1999), reduces hydraulic conductivity of the soil (Price 2003, Sikström & Hökkä 2016), increases soil erosion (Åström *et al.* 2001a) and causes peat subsidence (Minkkinen *et al.* 1999, Price 2003, Grønlund *et al.* 2008), which is a process of gradual settling or sinking of the soil layer. Peat subsidence has been noted to be the most intensive the first years after the drainage (Grønlund *et al.* 2008), and in minerotrophic peatlands (Minkkinen *et al.*1999). Drainage has not been shown to have a remarkable impact on the discharge patterns in peatlands (Åström *et al*. 2001a, b), but as flow increases sub-surface flow has been reported to start to dominate the runoff (Dunn & Mackay, 1996).

2.2 Nutrient export

2.2.1 Methods for determining nutrient export

Watershed nutrient loading has been modelled with numerous models such as INCA (Wade *et al.* 2002), N_EXRET (Lepistö *et al.* 2006), KUSTAA (Launiainen *et al.* 2014), and VEMALA (Huttunen *et al.* 2015). Models typically simulate hydrology, nutrient processes, nutrient retention and nutrient exports in a catchment or sub-catchment based on explanatory variables including, e.g., site properties and weather data. Uncertainty of nutrient loading models typically originates from parameter and structural uncertainty (Wade *et al.* 2002). According to Nieminen *et al.* (2020) current nutrient models might use, e.g., location, peat proportion, drainage proportion and drainage age as explanatory variables and thus there is potential to improve models by addition of highly varying site description variables such as soil type, stand volume and habitat.

Nieminen *et al.* (2020) listed that the analysis of drainage effects on load generation can be based on catchment specific load calculations, comparison of pristine and drained loading, or statistical models. In this literature review the majority of represented studies cover both area specific results or statistical catchment-based results compared between catchments. Many studies compared catchments based on measurements of nutrient or carbon export (e.g. Mattsson *et al.* 2003, Laiho *et al.* 2003, Kortelainen *et al*. 2006, Rankinen *et al.* 2016), concentrations in pore waters (e.g. Åström *et al.* 2001a, Strack *et al.* 2008), concentrations in stream waters (e.g. Kortelainen *et al.* 1997, Kortelainen & Saukkonen 1998, Åström *et al.* 2001b, Mattsson *et al.* 2015, Nieminen *et al.* 2017, Asmala *et al.* 2019), or concentrations in surface waters (e.g. Lepistö *et al.* 2008, 2021, Clark *et al.* 2010).

2.2.2 Background load

Background load of nutrients is the "natural" export of nutrients occurring despite the load impact of management practices in the studied catchment. The magnitude of background loading varies between peatlands based on explanatory variables. N loading has been detected to be highest in catchments with high proportion of peatlands and in southern Finland (Kortelainen *et al.* 1997, Kortelainen & Saukkonen 1998, Mattsson *et al.* 2003, Kortelainen *et al.* 2006, Finér *et al.* 2021), and climatic factors have been stated to control N exports (Mattsson *et al.* 2003, Mattsson *et al.* 2015, Strack *et al.* 2008). P loading has been suggested to be controlled by P fertilization (Kortelainen & Saukkonen 1998, Tattari *et al.* 2017, Finér *et al.* 2021), slope (Kortelainen *et al.* 2006), stand age (Rankinen *et al.* 2016) and latitude (Mattsson *et al.* 2003, Finér *et al.* 2021).

High proportion of peatlands enhances background loading of TOC (Kortelainen *et al.* 1997, 2006, Kortelainen & Saukkonen 1998, Finér *et al.* 2021). TOC export has been noticed to correlate negatively with stream water pH (Kortelainen *et al.* 1997, Asmala *et al.* 2019) and latitude (Finér *et al.* 2021), and to correlate positively with stream water C/N ratio (Kortelainen *et al.* 1997), proportion of drained peatlands (Kortelainen *et al.* 1997) and tree stand volume (Nieminen *et al.* 2021). Topography, site fertility, climatic drivers, and nutrient deposition are also related to TOC export (Kortelainen *et al.* 2006, Mattsson *et al.* 2003, 2015). Lepistö *et al.* (2014) noted deeper soil frost to reduce spring TOC fluxes, and increased precipitation and soil moisture to increase summer TOC exports. Since export is controlled by the magnitude of runoff, drought decreases and wet years increase levels of TOC export (Lepistö *et al.* 2014). Mattsson *et al.* (2015) stated that climate change is likely to change the timing of TOC and total organic nitrogen (TON) exports since the importance of spring flood on TOC and TON exports decreases along wetter and warmer years. Empirical evidence from e.g., Mattsson *et al.* (2015) and Räike *et al.* (2012) indicates that N, P and DOC exports will increase due to climate change.

According to Mattsson *et al.* (2003) the majority of TOC is exported as dissolved organic carbon (DOC). Positive trends of DOC in surface waters in Europe and North America during previous decades have been widely reported (Monteith *et al.* 2007, Lepistö *et al.* 2014, de Wit *et al.* 2016, Asmala *et al.* 2019, Finér *et al.* 2020, 2021). In long-term monitoring study Räike *et al.* (2012) found no clear trend in annual DOC exports in rivers in Finnish Baltic Sea catchment area between 1975 and 2010. Yet, de Wit *et al.* (2016) showed that OC concentrations in the majority (67 %) of streams, lakes and rivers in Finland, Sweden and Norway between 1990 and 2013 had a positive trend. de Wit *et al.* (2016) predicted an increase of 30 to 76 % of OC concentration in whole Fennoscandia except oceanic regions by year 2100 due to 10 % increase in precipitation.

Monteith et al. (2007) studied 522 lakes and streams in North America and northern Europe, and concluded that the positive trend of DOC originates from reduced deposition and concentration of atmospheric sulphates and chlorides. Similarly, de Wit *et al.* (2016) found OC trends to be associated with reduced sulfur deposition. Role of climatic factors on increasing DOC concentrations has also been discussed. Some studies conclude climatic factors to be irrelevant controllers of brownification (e.g., Monteith *et al.* 2007) whereas other studies suggest them to be important controllers (Roulet *et al.* 2007, Clark *et al.* 2010, Räike *et al.* 2012, Lepistö *et al.* 2014, 2021). Räike *et al.* (2012) stated that mild winters with precipitation falling as rain instead of snow and thus higher runoff in winter increased winter exports of DOC, but reduced snow cover decreased spring peak flow and thus spring exports of DOC. Role of precipitation as a controller of DOC export has been found to be more remarkable in drier regions (de Wit *et al.* 2016).

Vegetation community has also been suggested to control N, P and TOC exports. Mattsson *et al.* (2003) found correlation between N, P and TOC exports and stand vegetation; exports were observed to be higher in stands dominated by Norway spruce compared to Scots pine. Kortelainen *et al.* (2006) on the other hand found stem volumes or vegetation types to be irrelevant factors controlling the exports.

The level of nutrient export fluctuates seasonally. According to Åström *et al.* (2001a) TOC concentrations in stream waters increase from spring to summer, decrease towards autumn and increase again in late autumn. Most of the nutrient exports occur during high flow periods (Mattsson *et al.* 2003). Approximately half of the TOC and total nitrogen (TN) export occurred during spring in Kortelainen *et al.* (1997). Also Räike *et al.* (2019) noted the majority of nutrient export to occur during spring. Lepistö *et al.* (2021) suggested that the positive trends of TN and TOC concentrations in stream waters are caused by changes in autumn and spring exports, respectively. Mattsson *et al.* (2015) pointed out that moisture conditions affect the relative importance of spring peak on annual TOC and TON exports; during wet years the proportions of TOC and TON exports from annual exports were lower compared to drier years. In northern catchments with high peatland coverage the spring peak of TOC and TON exports were however high even in warm years (Mattsson *et al.* 2015).

TOC, TN and total phosphorus (TP) loading occur mostly in dissolved form, and organic form dominates TN and TP loading (Kortelainen *et al.* 2006). Mattsson *et al.* (2003) found strong correlation between exports of TOC and N, and thus organic N losses are likely related to humic substances. Molecular composition of TOC, TN and TP loading also varies spatially and temporally, e.g., Kortelainen *et al.* (2006) found the proportion of inorganic form to potentially dominate N exports in southern study sites where TOC/TN export ratios are typically the lowest. According to Nieminen & Penttilä (2004), in eutrophic sites Calcium-bound organic P content was four to six times higher, Calcium-bound inorganic P content two to three times higher, and Aluminium-bound inorganic P content two to three times lower compared to drained herb, tall-sedge or low-sedge dominated peatlands. Fe-bound inorganic P content was two to four times higher in herb-rich sites compared to eutrophic sites, and tall sedge and low-sedge dominated sites (Nieminen & Penttilä 2004). Molecular composition of exported DOC is affected by WTD: pore water in sites with lower WTD had higher aromatic dissolved organic molecule content and larger molecules (Hribljan *et al.* 2014, Bernard-Jannin *et al.* 2018). Bernard-Jannin *et al.* (2018) concluded that more severe WT drawdown leads to lower DOC production from top peat layer which has more easily biodegradable organic matter.

2.2.3 Forestry-drainage and nutrient exports

Lepistö *et al.* (2006) estimated that from total N loading to surface waters, agriculture contributes 38 %, forestry 9 % and background loading 27 %. According to Tattari *et al.* (2017), forestry increased N loading from forests by approximately one third. Finér *et al.* (2021) estimated that after including long-term impacts of drainage to loading determinations the proportions of loading originating from forestry practices were 17 %, 35 % and 12 % for N, P and TOC loads, respectively. The role of forestry is the most remarkable in Ostrobothnia and Kainuu (Finér *et al.* 2020). During previous decades N load from forestry has increased (Tattari *et al.* 2017, Räike *et al.* 2019, Finér *et al.* 2021) and P load decreased (Tattari *et al.* 2017, Finér *et al.* 2021). According to Nieminen *et al.* (2021), increasing wood production potentially enhances water brownification.

Former studies show incoherent results on whether or not drainage increases exports of N, P and TOC. Earlier there have been indications that drainage only has minor impact on exports of TOC, N and P (Kortelainen *et al.* 1997, Lepistö *et al.* 2014) and, in light of TOC export, even decreasing impact due to changed flow paths and immobilization of hydrogen ions and humic substances underneath the peat layer (Åström *et al.* 2001a, b). Many recent studies indicate that drainage enhances loading of TOC (Strack *et al.* 2008, Asmala *et al.* 2019), N (Räike *et al.* 2019, Nieminen *et al.* 2017, 2020) and P (Nieminen *et al.* 2017, 2020). Nieminen *et al.* (2020) suggested that when long-term impacts from drainage practices were included in the loading, N loading increased to 18-fold and P six- to seven-fold levels, and that forestry drainage is the second biggest source of anthropogenic nutrient loading in Finland. At present N, P and TOC exports from forest areas are considered to be the highest in the drained parts of forests (Finér *et al.* 2021). Due to enhanced nutrient exports after

DNM, Laurén *et al.* (2021) estimated fertilization to enhance tree growth in drained peatlands more efficiently than DNM.

The timing of increased nutrient exports after forestry-drainage practices has been under debate. Strack *et al.* (2008) estimated that one year after drainage as much as 17 % of the total carbon budget was exported as DOC from experimental peatland in Canada. Nieminen *et al.* (2017) however estimated TN and TP loads to increase with drainage age, yet noting that 20 to 30 years ago drained sites actually had similar concentrations compared to pristine sites. Currently it is widely recognized that the increase of loading from drainage practices continues longer than 10 years after drainage and that long-term impacts of drainage have been underestimated (Finér *et al.* 2020, 2021).

2.3 Carbon balance in peatlands

2.3.1 Methods for determining carbon balance

C balance and greenhouse gas (GHG) emissions have been both modelled and/or measured in experimental sites, similar to nutrient export studies covered in Section 2.2. C balance models can be either conceptual models of interacting processes, or simulation models based on conceptual models utilizing parameters mimicking the studied system (Yu *et al.* 2001). According to Yu *et al.* (2001), Clymo peat growth model is commonly used conceptual model that divides peat layer into oxic upper layer and anoxic underlying layer based on WTD and, in case of fens, additional variables, and computes decay processes for both layers. For the purposes of simulations in organic soils, Frolking *et al.* (2006) and Frolking & Roulet (2007) have used conceptual models for CO_2 and CH_4 pools, and carbon fluxes, respectively.

The majority of studies cited above cover area specific results of GHG flux or carbon emissions from catchment based on measurements from selected peat profiles (e.g., Silvola *et al.* 1996, Roulet *et al.* 2007, Turunen 2008, Couwenberg *et al.* 2011, Simola *et al.* 2012, Krüger *et al.* 2016, Pelletier *et al.* 2015). Typically C content is estimated either by measurements of ash content or radiocarbon dating (Krüger *et al.* 2016), or by peat subsidence (e.g., Grønlund *et al.* 2008, Pitkänen *et al.* 2013).

2.3.2 Carbon balance

Carbon balance is the net result of carbon uptake and carbon efflux. Turunen (2008) estimated that in 1950 C storage in aapa mire region of Finland in total was 3 298 Tg, from which forestry drained peatlands covered 125 Tg. In the raised bog region these values were 1827 Tg and 294 Tg, respectively. Continuous net ecosystem CO_2 exchange has been estimated to be the largest component in carbon balance, although CH_4 and previously discussed DOC exchanges should not be ignored (Roulet *et al.* 2007). Carbon accumulation can be determined as the recent apparent rate of C accumulation (RERCA), or as long-term apparent rate of C accumulation (LORCA).

The most important factors controlling annual carbon balance of peatlands have been suggested to be the net primary production (Minkkinen & Laine 1998), soil organic carbon age (Karhu *et al.* 2010), litterfall (Karhu *et al.* 2010), and snowmelt period (Aurela *et al.* 2004). The controlling effect of the type of the peatland has also been noted. According to Turunen *et al.* (2002) LORCA was higher in the raise-bog region compared to the aapa-mire region and in bogs compared to fens, but the aapa-mire region covers 80 % of total net C accumulation of Finnish pristine mires. In the USA, bogs were found to accumulate soil carbon and fens to lose soil carbon (Bridgham *et al.* 2008). Karhu *et al.* (2010) estimated that longer needle life span of Norway spruce compared to Scots pine increased carbon activity.

Climate change is likely to have strong impact on C balance of peatlands since the controlling factors of C balance such as primary production, decomposition, and runoff are affected by meteorological variables. Aurela *et al.* (2004) estimated that climate warming may lengthen the growing season and thus increase C storage in peatlands. Karhu *et al.* (2010) however stated that with constant C input the C content decreases by 30-45 % due to climate warming. Minkkinen *et al.* (2007) noted that in northern sites temperature response was stronger compared to southern sites.

2.3.3 CH_4 and CO_2

Climate radiative forcing of peatland is dependent on the net results of CO_2 uptake and storage, and CH_4 emissions (Frolking & Roulet 2007). Northern peatlands were concluded to be sources of CH_4 and sinks of CO_2 in Frolking & Roulet (2007). They estimated the net radiative forcing of northern peatlands to be at present, and to have been in the past 8 000 - 11 000 years, cooling. According to Frolking *et al.* (2006) peatland acts as net warmer after its formation for several hundred to several thousand years, and the peak of net warming is reached when the peatland is 50 years old. After several hundred to several thousand years, peatland starts to act as net cooler.

The controlling factors of seasonal CO_2 uptake are soil respiration in winter and ecosystem respiration in the growing season (Aurela *et al.* 2004). Peat respiration is the most important component of ecosystem respiration (Riutta *et al.* 2007). In winter peatland emits CO_2 and in summer peatland gains CO_2 (Roulet *et al.* 2007). According to Pelletier *et al.* (2015), maximum net ecosystem CO_2 uptake occurs in September. Mäkiranta *et al.* (2009) estimated that at depth of 5 cm in the peat, decomposition is positively related to peat temperature. After severe water level drawdown, phospholipid fatty acid composition however changes, which limits the potential increase of decomposition (Mäkiranta *et al.* 2009).

CO_2 emissions have been estimated to correlate positively with air temperature (Silvola *et al.* 1996), soil temperature (Mäkiranta *et al.* 2009, Kløve *et al.* 2010, Ojanen *et al.* 2010) and site fertility (Minkkinen *et al.* 2007), and negatively with C/N ratio (Couwenberg *et al.* 2011) and WTD (Zhong *et al.* 2020). Vegetation was found by Couwenberg *et al.* (2011) to alter long-term water level and GHG emissions by changing the supply of assimilates. Of pristine sites in Silvola *et al.* (1996), the lowest CO_2 emissions originated from ombrotrophic sites with vegetation dominated by *Sphagnum fuscum*, and the highest fluxes from ombrotrophic sites with no understory vegetation. The highest total C sink of peatlands in Finland was detected by Turunen *et al.* (2002) to be in dwarf-shrub pine bogs, cottongrass pine bogs, *Sphagnum fuscum* pine bogs, ridge-hollow pine bogs, and low-sedge *Sphagnum papillosum* pine fens located in the raised-bog region.

CH_4 emissions have been estimated to be related to C/N ratio (Maljanen *et al.* 2010), peat layer thickness, WTD, and age of the peatland (Leppälä *et al.* 2011). Leppälä *et al.* (2011) found that CH_4 emissions increased along age as peatland successes from sedge-dominated fens to bog stage.

2.3.4 Drained peatlands

According to Turunen (2008) the most remarkable anthropogenic C losses since 1950 are related to cultivation of peatlands, water reservoirs and DOC losses from forestry drainage. Average WTD, nutrient level, and climate affect the role of drained peatland as sink or source of carbon (Mäkiranta *et al.* 2010). Fens have been estimated to be more sensitive to WT changes compared to bogs (Zhong *et al.* 2020). Ojanen *et al.* (2013) predicted that drainage leads to carbon losses in fertile sites unless tree biomass is collected and stored. Carbon content of managed minerotrophic peatlands has in fact been noted to have decreased (Krüger *et al.* 2016), but in ombrotrophic drained sites the trend is less clear. Krüger *et al.* (2016) indicated that C profiles are affected by drainage in both upper and deeper layers of minerotrophic peat profile but only in upper layers of ombrotrophic peat profile. Minkkinen *et al.* (1999) estimated that in Lakkasuo mire drained 30 years ago, the carbon storage had decreased in minerotrophic sites but actually increased in ombrotrophic sites. Decreasing C balance in minerotrophic sites was however compensated by increasing tree stand volume (Minkkinen *et al.* 1999).

Greenhouse gas emissions in drained peatlands have been stated to be higher (Kløve *et al.* 2010, Evans *et al.* 2016, Zhong *et al.* 2020) or lower (Ojanen *et al.* 2010, Maljanen *et al.* 2010) compared to pristine ones, but potential C losses might be compensated by increased plant production (Minkkinen *et al.* 1999, Zhong *et al.* 2020). According to Evans *et al.* (2016), two major processes of GHG emissions originating from ditching are CH_4 emissions from drained peat and CO_2 emissions from photo- and/or biodegradation of exported DOC and particulate organic carbon (POC) in downstream waters.

2.4 Climate projections

Global climate models (GCMs) project the future climate changes. Coupled Model Intercomparison Project (CMIP) is a climate model archive that is updated roughly every six years as reports of the Intergovernmental Panel on Climate Change (IPCC) are published (Ruosteenoja *et al.* 2016). Representative Concentration Pathways (RCPs) are trajectories of greenhouse gas concentrations based on IPCC publications (IPCC 2013).

Regional climate models (RCMs) are used to produce downscaled, regional outputs from GCMs. In historical scenarios of RCMs there often occurs systematic errors in output meteorological variables when compared against observations (Jacob *et al.* 2007). Common correction methods of climate model results to fix these biases include delta method utilizing change factor, and nudging utilizing bias correction (Hawkins *et al.* 2013). Delta method was found by Hawkins *et al*. (2013) to more frequently perform better compared to nudging, but case-specific selection of method is still emphasized.

According to RCP 8.5, increase of greenhouse gas emissions would continue for the whole 21st century, and in 2100 CO_2 concentration would reach 1000 ppm (Ruosteenoja *et al.* 2016). Other RCP scenarios project reducing global emissions during the 21st century. Based on CMIP5 GCMs, the surface air temperature in winter will increase by 2 to 7 C^o, in summer by 1 to 4 C^o, and precipitation by 4 to 30 % in Finland in 30-50 years compared to the period of 1981-2010 (Ruosteenoja *et al.* 2016). Net primary productivity (NPP) has been projected to increase strongly in northern Europe (Olesen *et al.* 2007).

EURO-CORDEX (EURO-CORDEX 2022), the European branch of the Coordinated Regional Climate Downscaling Experiment (CORDEX), is an initiative funded by the World Climate Research Program (WRCP). EURO-CORDEX provides RCMs based on RCPs in CMIP5 publication (IPCC 2013).

2.5 Research gaps

Recent modelling studies and empirical analyses have focused on determination of either nutrient and organic C loading, C balance, or GHG efflux, and driving factors behind them in pristine or drained peatlands. Monitoring of nutrients, C and GHGs is important in light of detecting trends in their long-term development, and in light of model building and evaluation. Research on the driving factors is important in terms of further improvements of models. Launiainen *et al*. (2014) and Nieminen *et al*. (2020) emphasized research on controlling factors behind nutrient retention in soils to be important in analysis of observed positive trends in nutrient exports from forestry-drained peatlands. According to Arheimer *et al.* (2012), there is an urgent need for improvements in specific validation of nutrient loading models, especially concerning change of nutrient storage in soil profile during a long simulation period. Comparison of nutrient loading models would enlighten the structural uncertainty of models (Wade *et al.* 2002).

Further analysis of C balance in forestry-drained peatlands is needed to determine the role of forestry-drained peatlands as C sink or source (Krüger *et al.* 2016). According to Pelletier *et al*. (2015), higher resolution models are needed for modelling C dynamics and pools in peatlands, and DOC losses and methane efflux should be included in future C balance modelling. Salas-Eljatib & Weiskittel (2020) emphasized the evaluation of underlying assumptions behind long-term simulation of ecosystem dynamics, such as simulation of tree mortality.

Nieminen *et al.* (2020) stated that research on means to reduce especially C and N losses from forestry-drained peatlands is required for reducing GHG-emissions and nutrient loading. Combination of analyses of both nutrient loading and C balance in pristine or drained peatlands is rare, but not completely non-existent; e.g., Kløve *et al.* (2010) measured nutrient leaching and GHG emissions in cultivated peatlands. Long-term modelling of both drainage and climate impacts on nutrient loading and C balance of peatlands is also lacking, although the effects of drainage and climate variables on nutrient exports or C balance have been noted in analyses based on empirical evidence (e.g., Kløve *et al.* 2010, Mäkiranta *et al.* 2010, Räike *et al.* 2019, Asmala *et al.* 2019). This study aims to provide a new approach to analysis of forestry-drained peatlands by combining nutrient exports and C balance in long-term modelling of a forestry-drained peatland.

3 Materials and methods

3.1 The study site

Modelling work was implemented for Koivupuro catchment (Figure 1), which is located in Sotkamo in the region of Kainuu in mid-Eastern Finland (63°53′ N, 28°40′ E). Koivupuro is located in a far upstream reach of the catchment of Bay of Bothnia (Räike *et al.* 2019), and the Koivupuro catchment is a part of the middle boreal coniferous forest zone and aapa mire zone. The catchment area is 113 ha (Haahti *et al.* 2014) and peat area covers 57 % of the catchment (Ahtiainen 1991). Cover of forested peatlands, forested upland soils, and open pristine mires was 21 %, 47 %, and 32 % of the Koivupuro catchment area, respectively (Stenberg *et al.* 2015). 24 % of the Koivupuro catchment is drained for forestry.

Koivupuro catchment was pristine until winter 1983, when the average stand volume was 71 m^3 ha^{-1}. Norway spruce, Scots pine, and Silver and Downy birch covered 49 %, 40 %, and 11 % of stand volume, respectively (Kortelainen *et al.* 2006). Average site fertility class was 2.8.

In winter and spring 1983 a clear-cutting was performed in an area of 6 ha (Ahtiainen 1991). In summer 1983, an area of 32 ha was drained with a total length of ditches of 11 km. In 1986, an additional 4 ha area was drained. Ditch spacing was 35 m, ditch depth 1 m, and ditch width 2 m (Stenberg *et al.* 2015). In 1986, seeding of Scots pine was performed (Ahtiainen 1991). In 2011, 27 ha area with 9.1 km of ditches were cleaned (Stenberg *et al.* 2015).

In this study, a 5.2 ha sub-catchment area (Figure 1) of Koivupuro catchment was studied. The same sub-catchment has been studied previously by Haahti *et al.* (2014, 2016), and Stenberg *et al.* (2015). Soil type was mostly woody *Sphagnum* peat or woody *Sphagnum-carex* peat (Haahti *et al.* 2014). In 2011, 20 % of ditches in the sub-catchment reached mineral soil of mostly silt or till after DNM (Haahti *et al.* 2016). Peat layer was from 0 to 4 m deep and the degree of decomposition ranged from 3 to 8 in the von Post scale (Haahti *et al.* 2014).

Scots pine was the dominating tree species in the sub-catchment, but also Norway spruce and birches grow in the area (Haahti *et al.* 2014, Stenberg *et al.* 2015). In 2012, the stand volume was 89 m^3 ha^{-1}. There occurs variation of *Vaccinium myrtillu*s swamp or tall sedge pine fen, *Vaccinium vitis-idaea* swamp or low sedge fens, and dwarf shrub pine bogs in the sub-catchment (Luke 2019). In site fertility classification these habitats correspond to classes two, three and four, respectively. The most common class in the sub-catchment was 4.

Mean annual air temperature and mean annual precipitation in 1981-2010 in Koivupuro were 2.3 °C and 591 mm, respectively (Haahti *et al.* 2016). Snow cover period continued typically from late October to April. In spring the ditch flow, and in summer the bank erosion were found to be the most important erosion processes in Koivupuro (Haahti *et al.* 2016). According to Haahti *et al.* (2014) the risk of erosion in Koivupuro is the highest during snowmelt in segments, where the slope is relatively steep and upstream area is relatively large. First years after ditch cleaning runoff and sediment loads were found to be elevated, especially during spring (Stenberg *et al.* 2015).

Liuhapuro (63°80′ N, 28°50′ E) and Kivipuro (63°90′ N, 28°70′ E) catchments (Figure 1) were selected to be the reference study sites for modelled N, P and DOC exports. Both reference catchments are included in MetsäInfo monitoring study by Luke (2022). Monitored annual exports of total N, total P, and TOC in 2014-2019 from Liuhapuro and Kivipuro were compared to modelled annual mean exports of N, P and DOC in Koivupuro in 2011-2013 and in 2006-2024. Liuhapuro and Kivipuro are located in Kainuu approximately 50-70 km from Koivupuro. In Liuhapuro peatland covers 58 %, and drained peatland covers 3 % of the catchment area (Lepistö *et al.* 2021). In Kivipuro corresponding values are 34 % and 0 %, respectively.

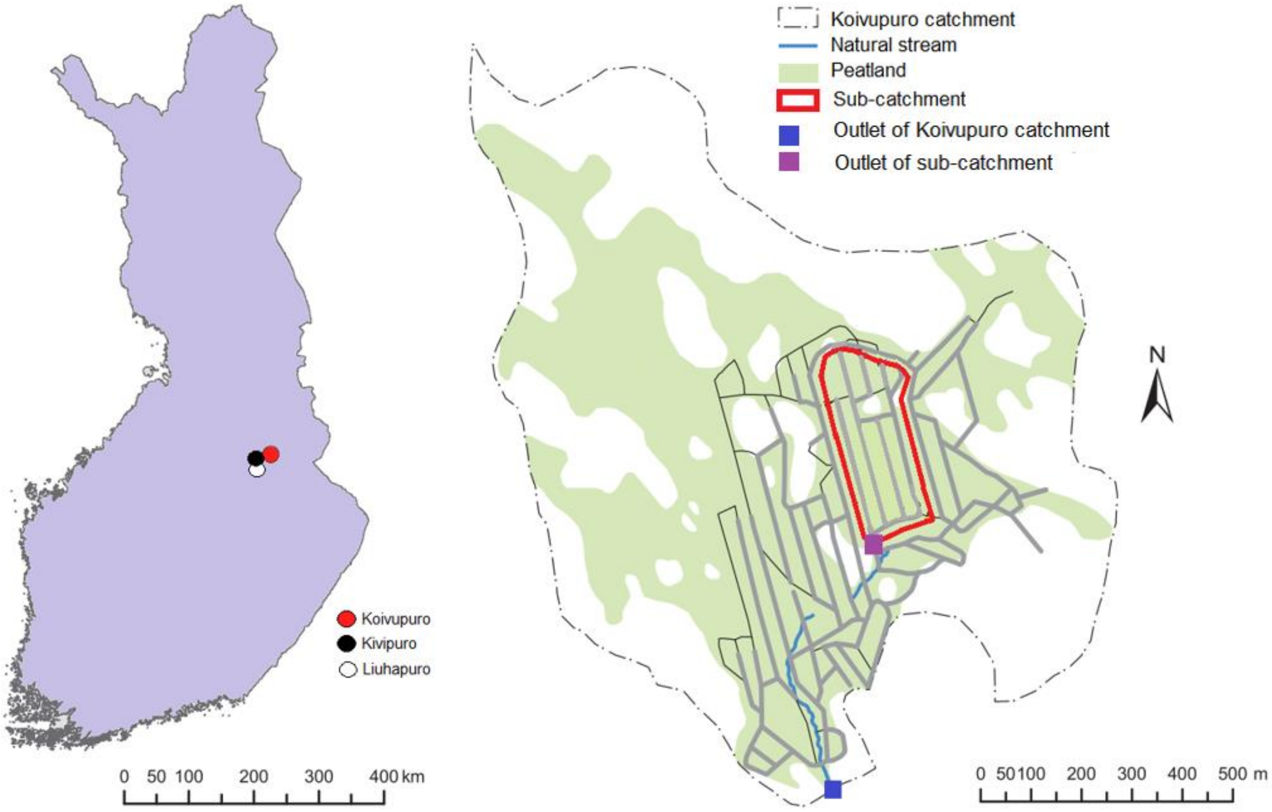

Figure 1 *Location of Koivupuro, Kivipuro, and Liuhapuro catchments, and sub-catchment in Koivupuro, modified from Haahti et al. (2014).*

3.2 Data

Meteorological variables covering 20-minute interval records of precipitation (Figure 2), air temperature (Figure 3), global radiation and relative humidity from 2011 to 2013 were measured by the Finnish Forest Research Institute in Iso-Kauhea weather station located 3 km from Koivupuro catchment (Haahti *et al.* 2014). From 2011 to 2013, the annual mean air temperature was 2.8 °C and the mean annual precipitation was 759 mm.

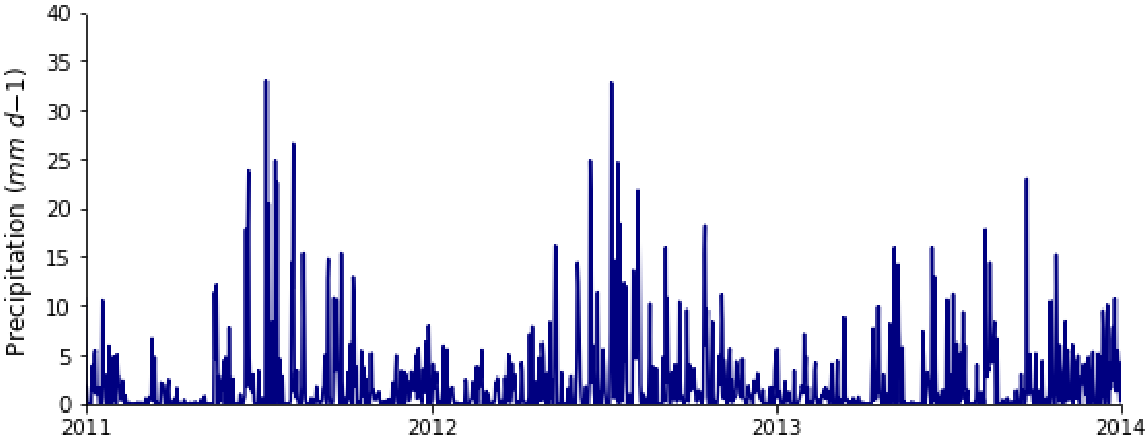

Figure 2 *Measured precipitation (mm d*$^{-1}$*) in Koivupuro in 2011-2013.*

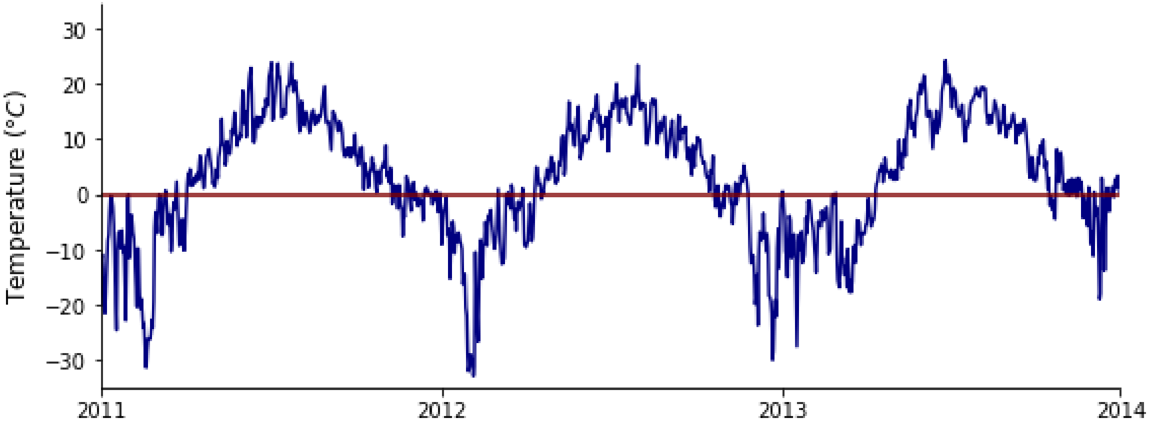

Figure 3 *Measured air temperature (°C) in Koivupuro in 2011-2013.*

From 2011 to 2013, WTD, runoff and snow water equivalent (SWE) were measured in the sub-catchment of Koivupuro by Haahti *et al.* (2014). During frost free periods from August 2011 onwards, WTD was measured at two locations with 1 mm resolution and 15 min interval using automatic Trutrack WT-HR Water Height loggers. Measurements of discharge were implemented with a 15 min interval in the outlet of sub-catchment and outlet of the whole Koivupuro catchment using pressure sensors, and the following equation was used to compute discharge at the outlet (Haahti *et al.* 2014):

$$Q = 1.381(h - h_{weir})^{2.5} \quad (1)$$

where Q is the discharge (m^3 s^{-1}), h is flow depth at the weir (m), and h_{weir} is distance between bottom of the ditch and bottom of V-notch (m).

Initial state of the tree stand was collected from standard stand-wise forest inventory data for Joensuu in yield model Motti, available in repository for source code for SUSI and test input data: https://github.com/annamarilauren (accessed on 20.1.2022). Motti-file for Joensuu was seen as adequate to describe the stand growth in Koivupuro since it had the same dominating tree species (Scots pine), same initial stand volume (89 m^3 ha^{-1}), and similar stand age.

The climate scenarios for Koivupuro in time periods 2006-2100 from EURO-CORDEX are based on CMIP5 publication and the high-emission RCP 8.5. forcing scenario. Projection had been run for the period of 2006 to 2100 at a spatial resolution of EUR-11, which is approximately 12.5 km. Temporal resolution had been 1 h for precipitation and 3 h for air temperature, relative humidity and global radiation. Scenarios were extracted as average values from nine climate model cells (3x3). More detailed description of the used EURO-CORDEX data is listed in Table 1.

Table 1 *Global and regional climate models of the EURO-CORDEX climate scenario used in the current study.*

Global Climate Model (GCM)		**Regional Climate Model (RMC)**	
Institute	Norwegian Climate Center (NCC)	**Institute**	Swedish Meteorological and Hydrological Institute (SMHI)
Model	NoeESM1-M	**Model**	RCA4
Model run	r1i1p1	**Resolution**	EUR-11

RCM output was bias-corrected with weather data of period 2006-2020 from Valtimo weather station located 26 km from Koivupuro. Weather data from Valtimo by the Finnish Meteorological Institute was interpolated for Koivupuro (Stenberg *et al.* 2015). Meteorological variables included daily precipitation, air temperature, relative humidity and global radiation.

3.3 Modelling

3.3.1 Climate model results

Precipitation and air temperature from the climate scenario were bias-corrected by comparing daily values to observations made in Valtimo in the period 2006-2020.

Precipitation data was bias-corrected with following equation:

$$P_{ds} = \frac{P_{sumMeas}}{P_{sumScen}} P_{Scen} \qquad (2)$$

where P_{ds} is downscaled daily precipitation (mm d^{-1}), P_{scen} is daily precipitation from scenario (mm d^{-1}), $P_{sumMeas}$ is the sum of observed precipitation for 2006-2020 (mm yr^{-1}), and $P_{sumScen}$ is the sum of precipitation from scenario for 2006-2020 (mm yr^{-1}). Projected precipitation was 60 % higher than measured precipitation.

Air temperature data was corrected with equation:

$$T_{ads} = \frac{T_{meanMeas}}{T_{meanaScen}} + T_{aScen} \qquad (3)$$

where T_{ads} is the downscaled daily air temperature (°C), T_{aScen} is the daily temperature from scenario (°C), $T_{MeanMeas}$ is the mean of observed temperature for 2006-2020 (°C), and $T_{MeanScen}$ is the mean of temperature from scenario for 2006-2020 (°C). Measured daily air temperature was on average 2.4 °C higher than projected daily air temperature.

The quantities of daily precipitation were underestimated in the climate scenario before bias-correction (Figure 4). Climate scenario overestimated number of days with precipitation less than 2 mm d^{-1}, and underestimated number of days with higher precipitation than 2 mm d^{-1}

(Figure 5). Climate scenario under- or overestimated some of the annual maximum or minimum temperatures, respectively, before bias-correction (Figure 6). Number of days with daily maximum temperature near 0 °C was overestimated and number of days with daily maximum temperature over 20 °C was underestimated in the climate scenario (Figure 7).

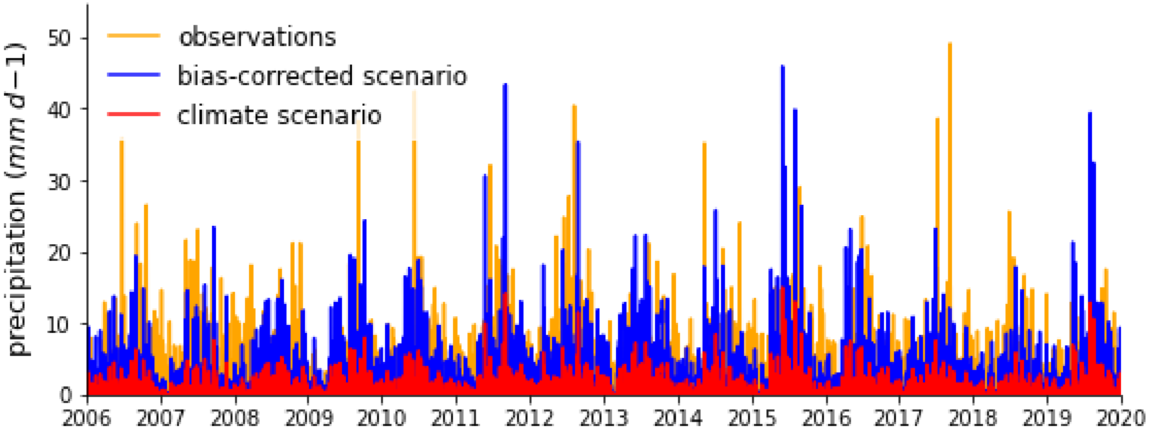

Figure 4 *Daily precipitation of observed, bias-corrected and non-corrected climate scenario data in period 2006-2020.*

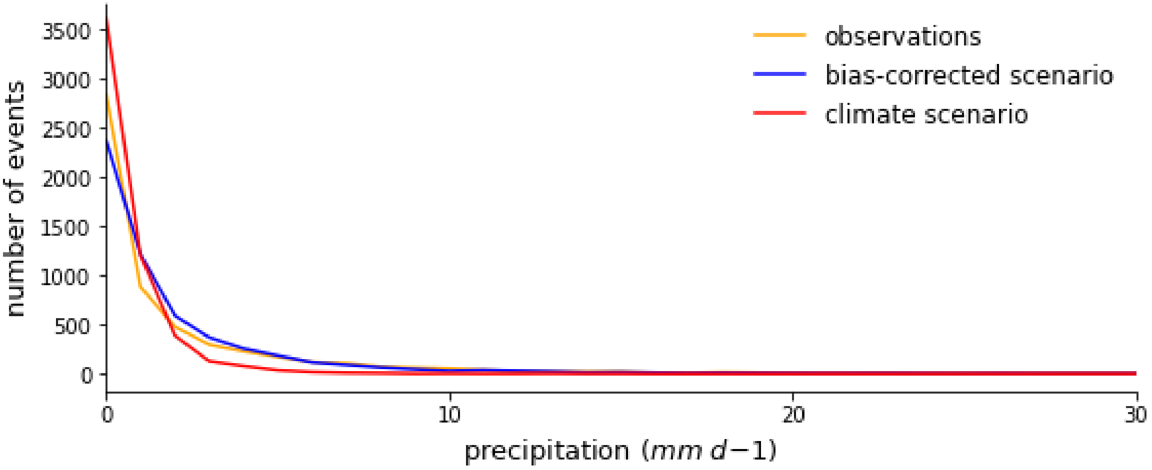

Figure 5 *Frequency-magnitude plot of precipitation of observed, bias-corrected and non-corrected climate scenario data in period 2006-2020.*

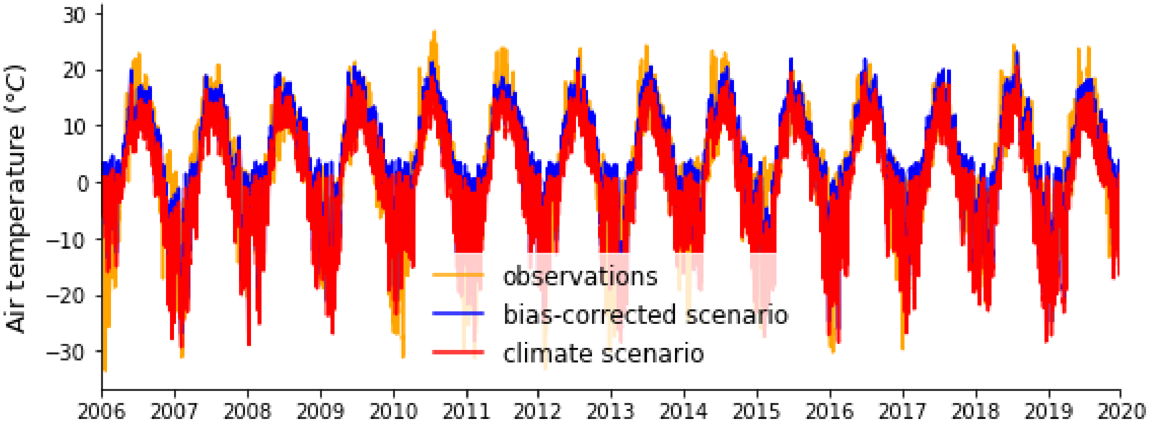

Figure 6 *Daily air temperature of observed, bias-corrected and non-corrected climate scenario data in period 2006-2020.*

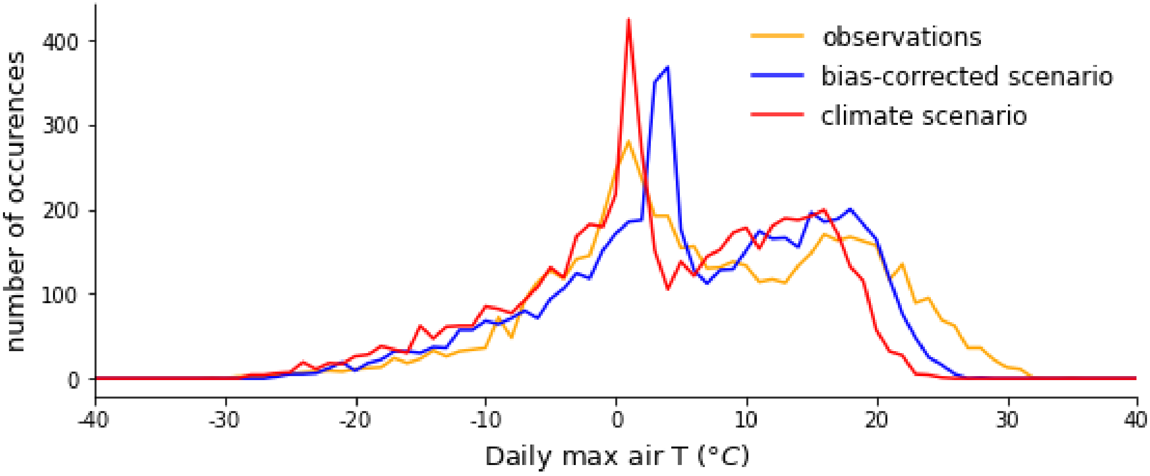

Figure 7 *Frequency-magnitude plot of daily maximum air temperature of observed, bias-corrected and non-corrected climate scenario data in period 2006-2020.*

From 2006 to 2100 in the bias-corrected climate projections, mean of annual sum of rainfall was 775 mm and mean of annual mean temperature was 5.2 °C and. Bias-corrected mean annual air temperature and annual precipitation, and relative humidity had positive trends from 2006 to 2100 (Figures 8, 9 and 10). Mean annual global radiation had a negative trend (Figure 11), potentially due to increased precipitation and cloudiness. Highest mean annual air temperature was projected for year 2091 and highest annual precipitation for year 2054.

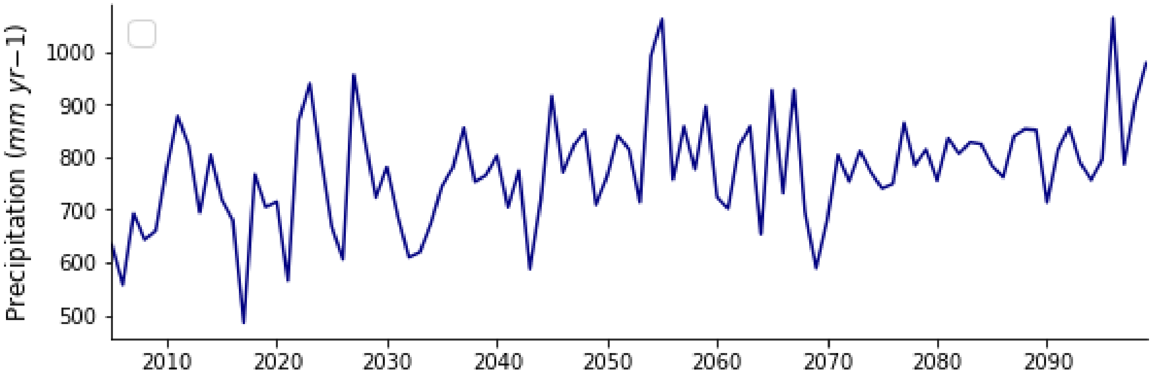

Figure 8 *Bias-corrected projected annual precipitation (mm yr^{-1}) in Koivupuro in 2006-2100.*

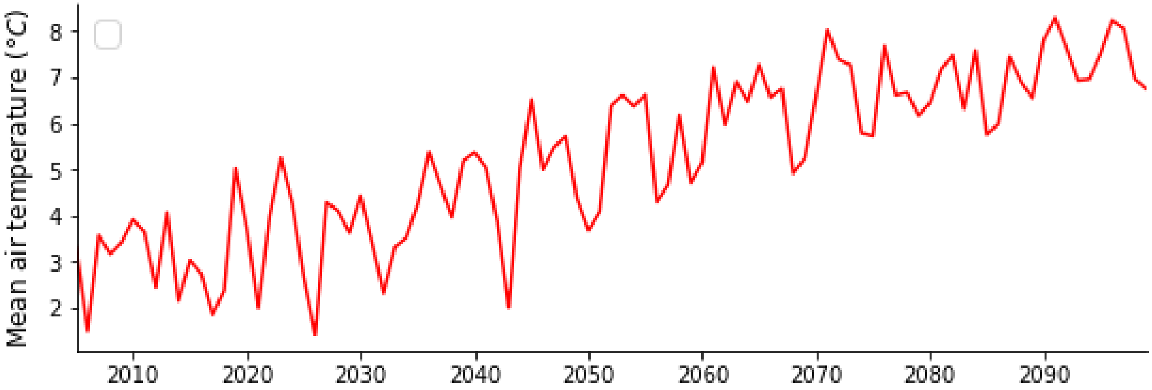

Figure 9 *Bias-corrected projected mean annual air temperature (°C) in Koivupuro in 2006-2100.*

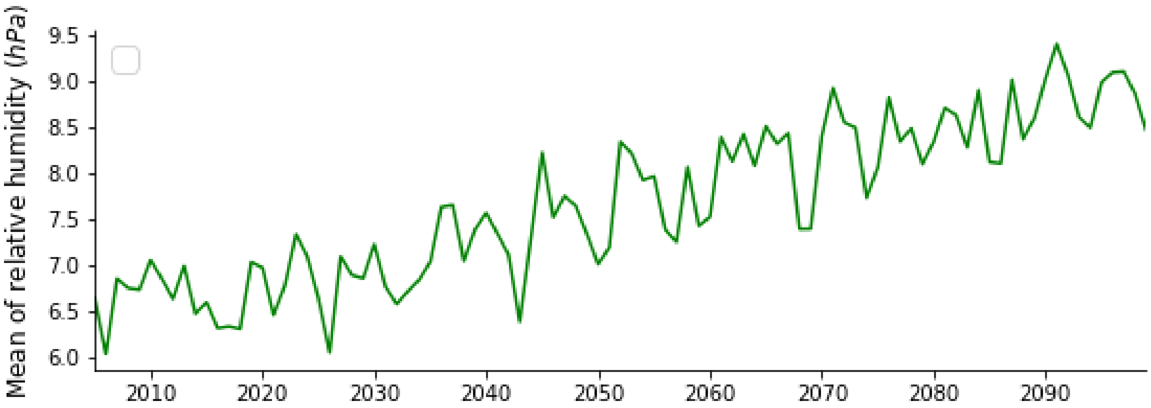

Figure 10 *Mean annual relative air humidity (hPa) in Koivupuro in 2006-2100.*

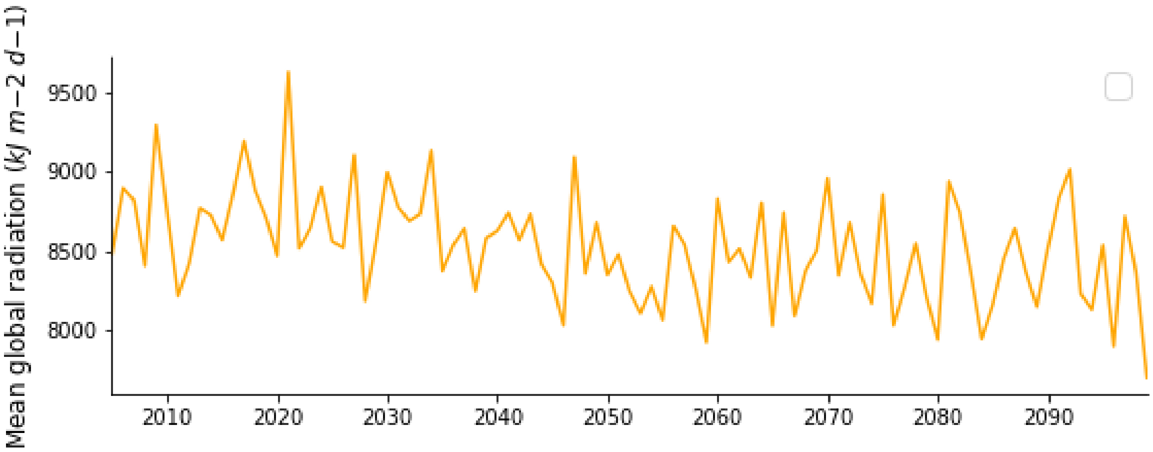

Figure 11 *Mean annual global radiation (kJ m^{-2} d^{-1}) in Koivupuro in 2006-2100.*

3.3.2 SUSI

A detailed description of Peatland Simulator SUSI (SuoSimulaattori) is given in Laurén *et al*. (2021). In SUSI, the studied domain is the 2D cross-section between two parallel ditches. Hydrology, biogeochemical processes and stand growth are computed for 16 points between the ditches, including the two ditches. SUSI contains functional modules of soil hydrology, peat temperature, stand and allometry, above-ground and moss hydrology, NPP, decomposition, ground vegetation, nutrient, and stand growth. Required input data of SUSI consist of drainage design including the strip width and ditch depth, site description including information of the peat type and nutrient content, tree stand, and daily meteorological data.

Hydrological part of SUSI includes modules for aboveground hydrology and snow, and belowground hydrology (Figure 12). Components in aboveground hydrology module include precipitation, evapotranspiration and interception through canopy and moss/litter layer, rain and snowfall through the canopy, and infiltration to the belowground water storage. Water fluxes going out of the water storage are transpiration and outflow to ditch. Assumption is that WT reaches hydraulic equilibrium immediately after water flux changes. Horizontal water movement in the hydrology modules are solved by implicit solution of diffusion equation. Peat column is divided to 0.05 m layers, and peat is assumed to reach impermeable bottom at a depth of 1.5 m. Sink or source term of the water storage in peat is solved from relation of infiltration and evapotranspiration by SpaFHy model, where infiltration is solved from bucket approach and evapotranspiration from the Penman-Monteith equation.

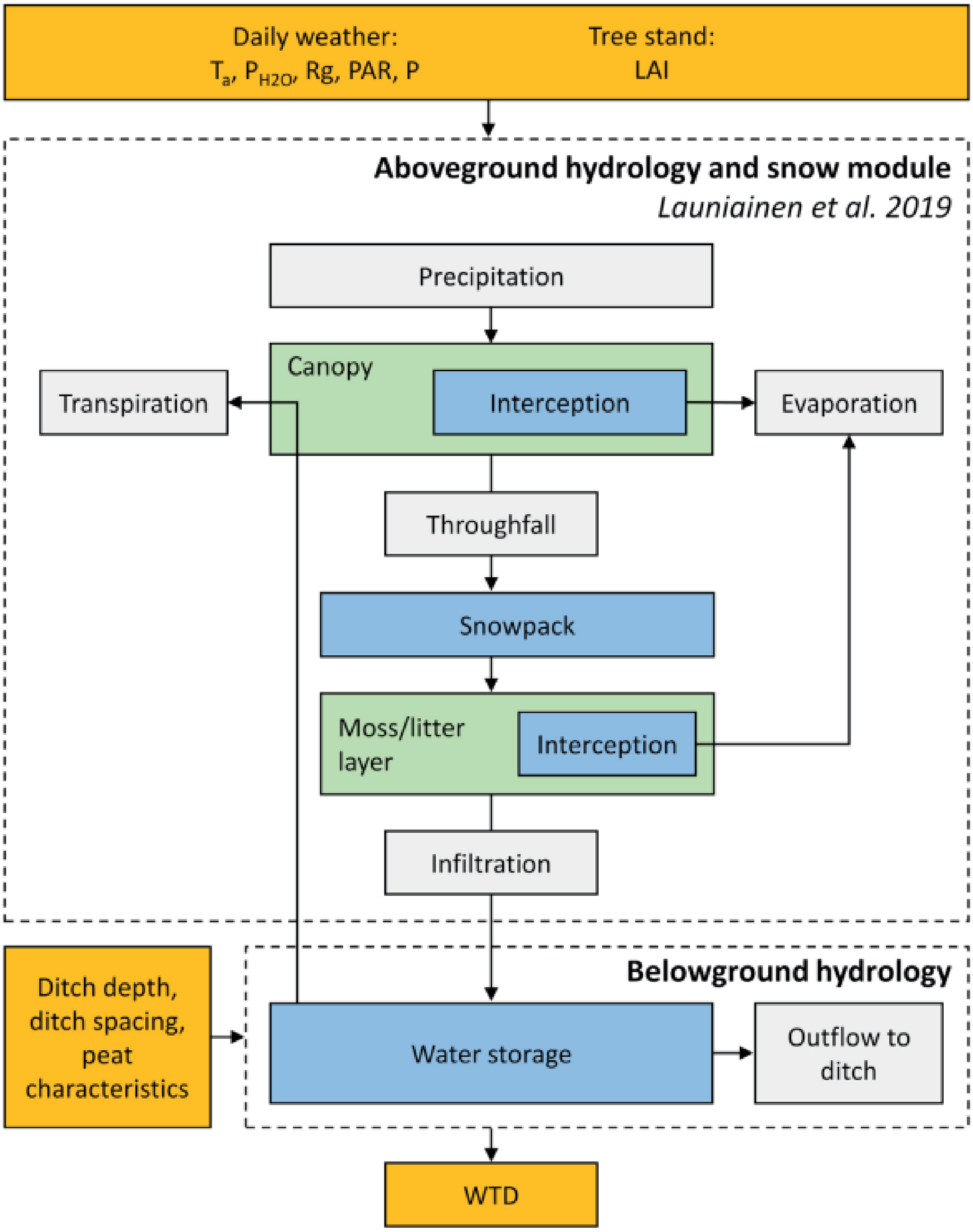

Figure 12 *Hydrological modules of SUSI (Hökkä et al. 2021).*

Outputs of SUSI for this study are computed from a large variety of modules (Figure 13). Runoff, SWE, and WTD are computed from the above-ground and moss hydrology module, and the peat hydrology module. Decomposition is computed from the daily soil temperature, stand volume, growing season mean WTD and peat bulk density described by Ojanen *et al.* (2010). Peat temperature is solved by explicit solution of heat equation. Released nutrients and further the maximum potential stand growth are computed from decomposition, stand volume, biomass, and nutrient uptake demand from the ground vegetation module. Nutrients that are released below the rooting zone are subject to exports. Annual peat C balance is computed by subtracting CO_2-C emissions from the C input to the peat in the total litterfall. The total litterfall includes C in stand and ground vegetation leaf, branch and root litter, and the C in the dead trees died during the time interval. Annual C balance of the stand is solved by adding the C in the stand biomass growth to the C balance of the peat. Positive C balance means that the peat or stand gains C. Computation for heterotrophic respiration requires reference value for respiration, bulk density of the peat, stand volume, WTD during the growing season, and daily peat temperature. CH_4 uptake of the peat is computed from WTD in the peat hydrology module, and DOC export are derived from frost free WTD in peat temperature and peat hydrology modules. Computed DOC export was selected to be the high molecular weight (hmw) DOC. NPP is computed in daily timestep based on Mäkelä *et al.* (2008). Stand growth is computed from nutrient release through Liebig's law of minimum, and NPP module. Annual growth values are updated to the stand description.

Lowered WT increases the aeration and decomposition of OM in the peat. In dry conditions WT controls stand growth in a daily timestep through availability of water, and in wet conditions through availability of O_2.

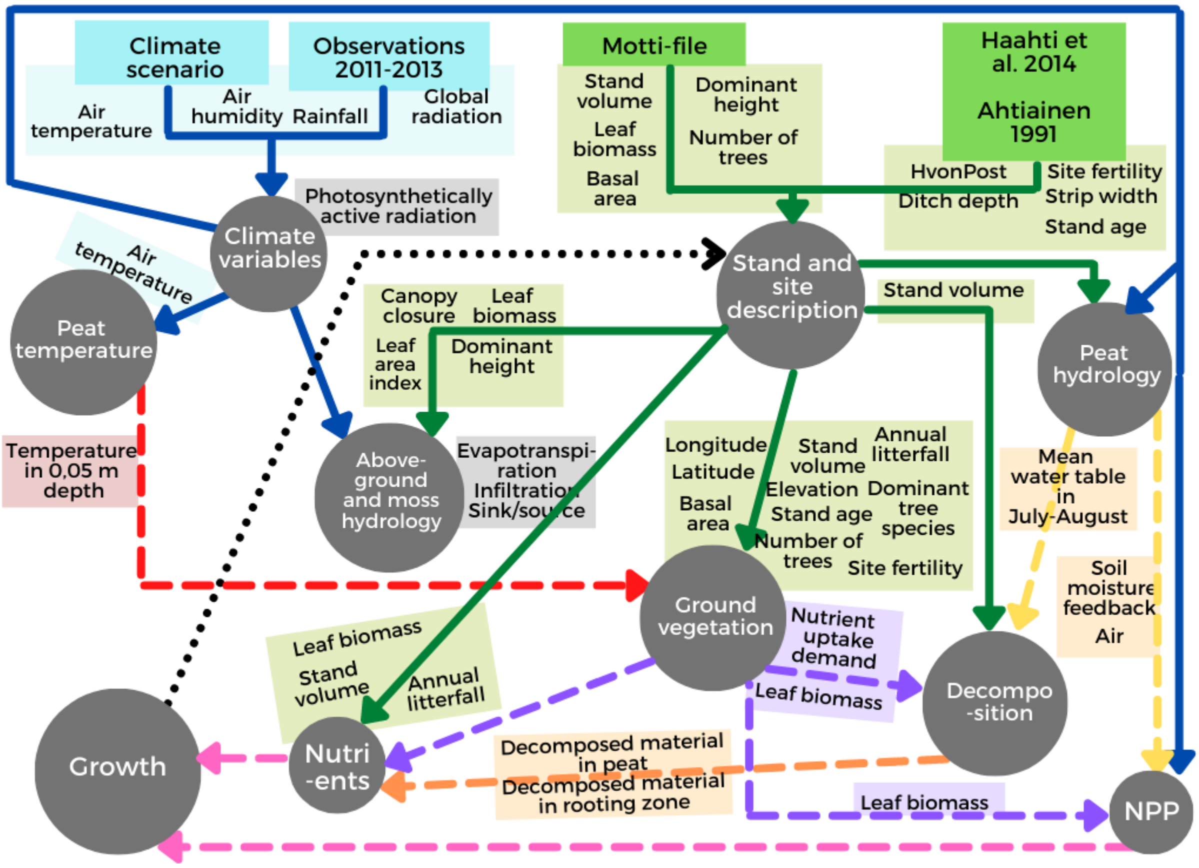

Figure 13 *Descriptive chart of information flow in SUSI, modified from Laurén et al. (2021).*

3.3.3 Modelling framework

Nutrient exports and C balance of Koivupuro sub-catchment were modelled with SUSI. Short-term measurements in 2011-2013 and climate scenarios in 2006-2100 were used for short-term and long-term simulations, respectively. Long-term simulation was divided to four simulation periods S1, S2, S3 and S4 (Table 2).

Table 2 *Short-term and log-term simulations*

	Reference period	**Long-term simulation**			
Name	**Short-term simulation**	**S1**	**S2**	**S3**	**S4**
Years	2011 - 2013	2006 - 2024	2025 - 2049	2050 - 2074	2075 - 2100

For SUSI the 20-minute interval data by Haahti *et al.* (2014) and 1 or 3 h interval climate scenarios were transformed to daily sum of precipitation, daily mean air temperature, daily sum of global radiation, and daily mean of relative humidity. Precipitation was estimated to fall in the form of snow above threshold temperature of 1 °C.

Three ditch depth scenarios were utilized in the simulation: 0.1 m, 0.5 m, and 1.0 m ditch depths, from which the 1 m ditch depth scenario was the control ditch depth scenario and the 0.1 m ditch depth scenario was selected to represent minimal drainage practices. In the simulation settings, stand age was counted to begin from year 1986. Peat layer was divided to top and bottom layers. Bottom peat column was set to be *Carex* type and other peat layers to be *Sphagnum* type. Bottom layer was set to be decomposed in class 8 on von Post scale. Top layer was divided to eight 5 cm sublayers which were set to have values 3, 3, 3, 4, 4, 5, 6, and 7 in von Post classification from top towards bottom.

Hydrological performance of SUSI was evaluated in the short-term simulation by comparing the modelled daily results against measured daily runoff, SWE and WTD. Modelled cumulative runoff was compared to observed cumulative runoff in 2011-2013. Root mean squared error (RMSE) and Pearson correlation coefficient were computed for daily runoff, SWE and WTD.

RMSE was computed from differences between daily modelled values and observations:

$$RMSE\ (y, \hat{y}) = \sqrt{\frac{1}{n_{samples}} \sum_{i=1}^{n_{samples}} (y_i - \hat{y}_i)} \tag{4}$$

where $\hat{y}_i$ is the modelled value of sample number i, y_i is the corresponding observation, and $n_{samples}$ is the number of samples.

Pearson correlation coefficient was:

$$\rho_{y\,\hat{y}} = \frac{\frac{i}{n_{samples}} \sum_{i=1}^{n_{samples}} (y_i - E[y_i])(\hat{y}_i - E[\hat{y}_i])}{\sqrt{(E[y_i^2] - E[y_i]^2)(E[\hat{y}_i^2] - E[\hat{y}_i]^2)}} \tag{5}$$

where $\rho_{y\,\hat{y}}$ is the Pearson correlation coefficient between the modelled and observed values, $\hat{y}_i$, is the modelled value of sample number i, and y_i is the corresponding observation, $n_{samples}$ is the number of samples, $E[\hat{y}_i]$ is mean of $\hat{y}_i$ and $E[y_i]$ mean of y_i.

In short-term simulation modelled annual mean of N, P and DOC exports were compared to monitored exports in MetsäInfo monitoring of Liuhapuro and Kivipuro (Luke 2022). Modelled C balance, and CO_2 and CH_4 uptake of the peat were compared to literature values.

The long-term simulation was performed to analyze the future climatic development of annual and seasonal N, P, potassium (K) and DOC exports, C balance, and CO_2 and CH_4 uptake of the peat in Koivupuro sub-catchment. Seasonal variation of nutrient exports was concluded from seasonal variation of WTD. Annual mean of WTD in late summer (July to August) was modelled to demonstrate released nutrients for the next growing season.

Water balance for the whole system was checked in the long-term simulation. Water balance included precipitation, evapotranspiration and runoff. Cumulative precipitation, evapotranspiration, interception and runoff were computed.

Computational mass balance errors for the modelling of canopy and moss layer hydrology were computed from changes in water storage and water fluxes in the canopy or the moss layer over the simulation period. Mass balance error is 0, when solution is correct.

4 Results

This Section presents the outcomes from the short- and long-term simulations for Koivupuro. First, hydrological results from the short-term simulation are presented, to describe the hydrological performance of SUSI. The level of C balance and nutrient exports in 2011-2013 period are also presented to check the level of the studied components during the reference time period. Secondly, the development of C processes and nutrient exports in ditch depth scenarios along changing climate in the long-term simulation are presented.

4.1 The short-term simulation

4.1.1 Hydrological performance in the short-term simulation

Hydrological performance in the short-term simulation was evaluated by comparing observed daily and cumulative runoff, and observed SWE and WTD to the corresponding simulation results for reference period 2011-2013. The timings of modelled daily runoff were mostly similar to the observations in Koivupuro in 2011-2013 (Figure 14). There occurred some notable differences between modelled and observed daily runoff peaks, e.g., the highest observed daily runoff peak in the end of April and the beginning of May in 2012 was clearly underestimated in the simulation (Figure 14). Correspondence of modelled runoff to observed runoff was the highest in 2013 (Figure 14). Modelled cumulative runoff was lower compared to the observed cumulative runoff in the end of reference period (Figure 15). The peak runoff in spring 2012 caused higher increasing slope in the observed cumulative runoff compared to modelled one (Figure 15). The modelled cumulative runoff exceeded the observed discontinuous cumulative runoff on average by 100 mm in the end of the period (Figure 15).

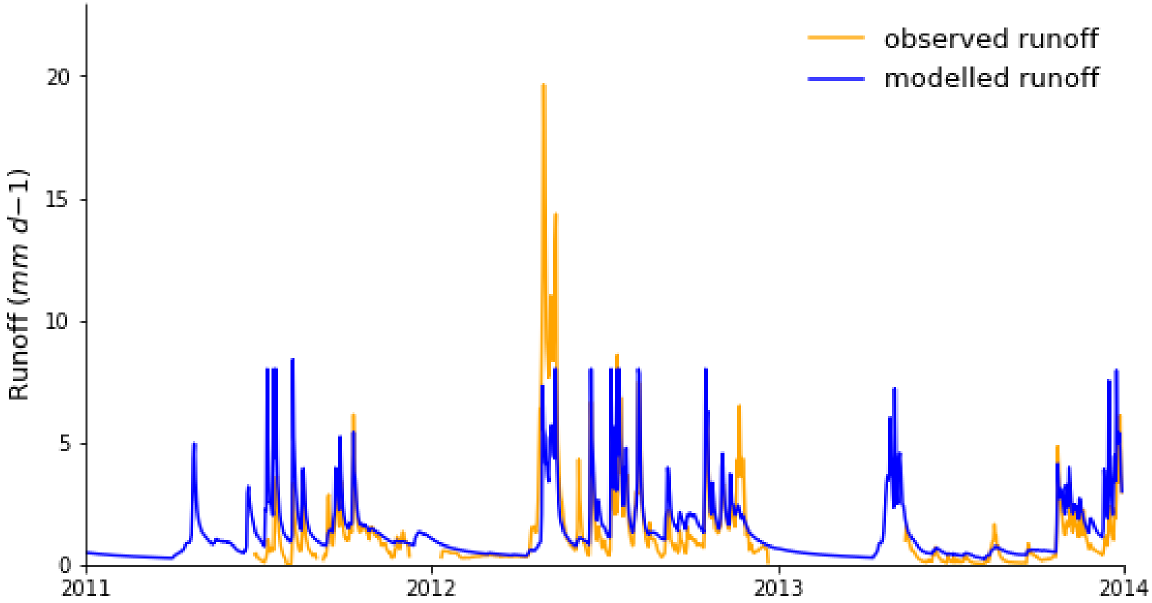

Figure 14 *Observed and modelled runoff (mm d^{-1}) in Koivupuro in 2011-2013.*

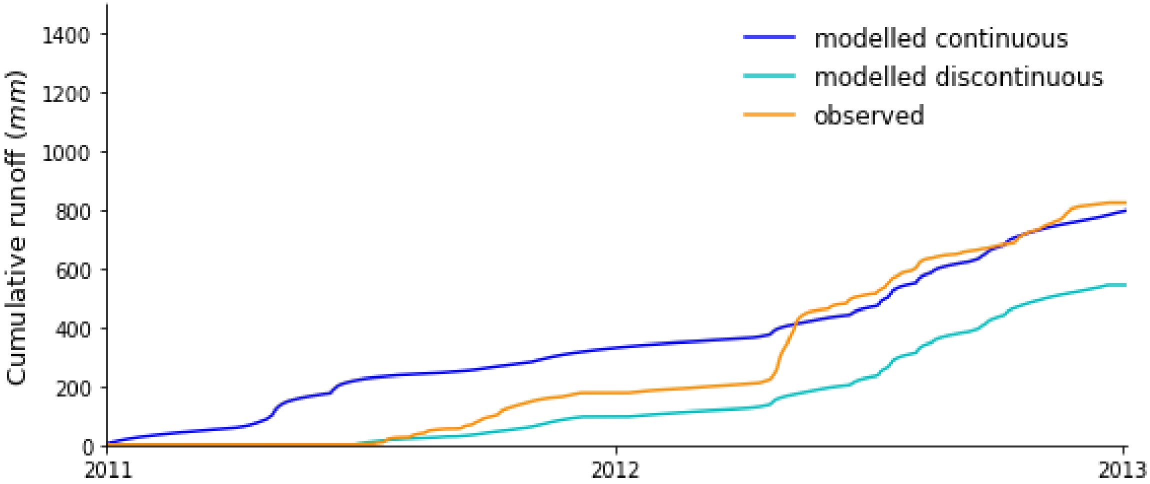

Figure 15 *Observed, modelled continuous, and modelled discontinuous cumulative runoff (mm) in Koivupuro in 2011-2013. In modelled discontinuous cumulative runoff, runoff cumulates only on days where there exists an observation of daily runoff, and in modelled continuous cumulative runoff modelled runoff cumulates every day in 2011-2013.*

The timings of modelled snow cover followed the timings of observations in Koivupuro in 2011-2013 (Figure 16). Modelled SWE was lower compared to observed SWE, especially in 2012 (Figure 16). Modelled SWE was on average 27 mm lower compared to the observed SWE.

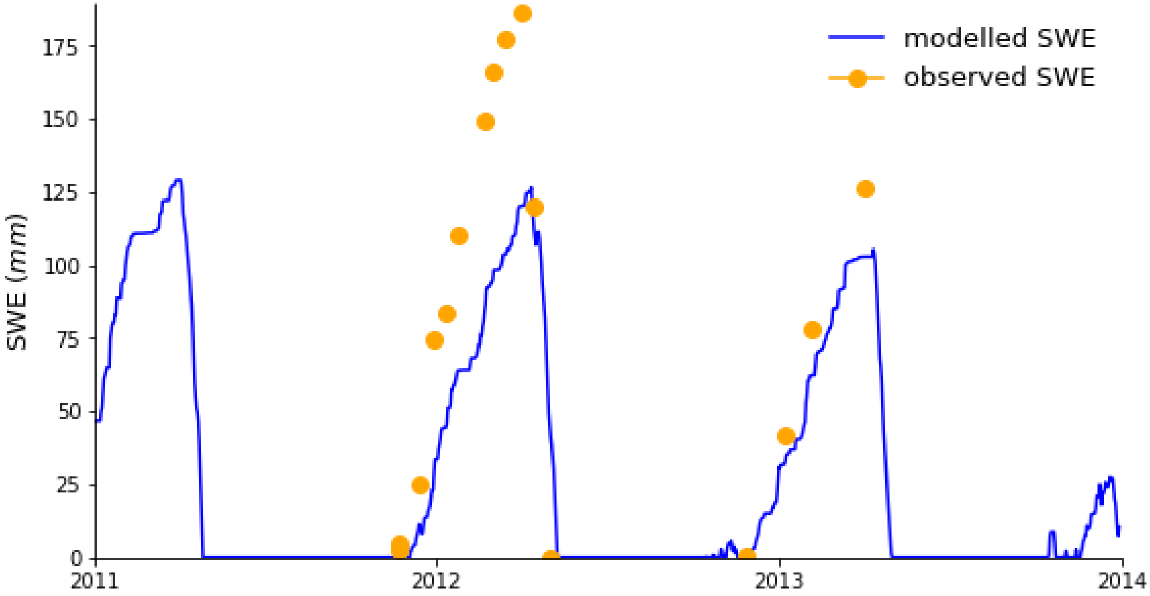

Figure 16 *Observed and modelled SWE (mm) in Koivupuro in 2011-2013.*

Modelled dynamics of WTD were similar to observed WTD in Koivupuro in 2011-2013 (Figure 17). Modelled WTD dynamics corresponded to the observations especially during wet years (Figure 17). Modelled WTD was mostly higher compared to observations in 2011 and 2012, but in 2013 observed WTD exceeded simulated WTD (Figure 17).

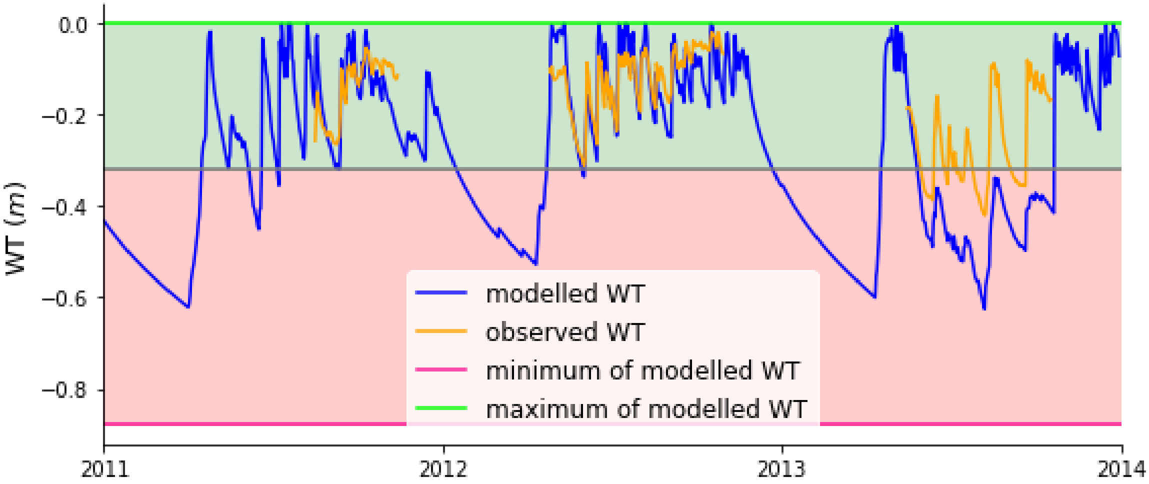

Figure 17 *Observed and modelled mean daily WT (m), and modelled maximum and minimum WT (m) between two ditches in Koivupuro in 2011-2013. Light pink and light green area represent the difference between median and minimum, and between maximum and median of daily WT in 2011-2013, respectively.*

RMSE of runoff, SWE and WTD predictions were 1.43 mm d^{-1}, 41.8 mm and 0.12 m, respectively (Figure 18). Correlations of modelled runoff, SWE or WTD against the observations are shown in Table 3.

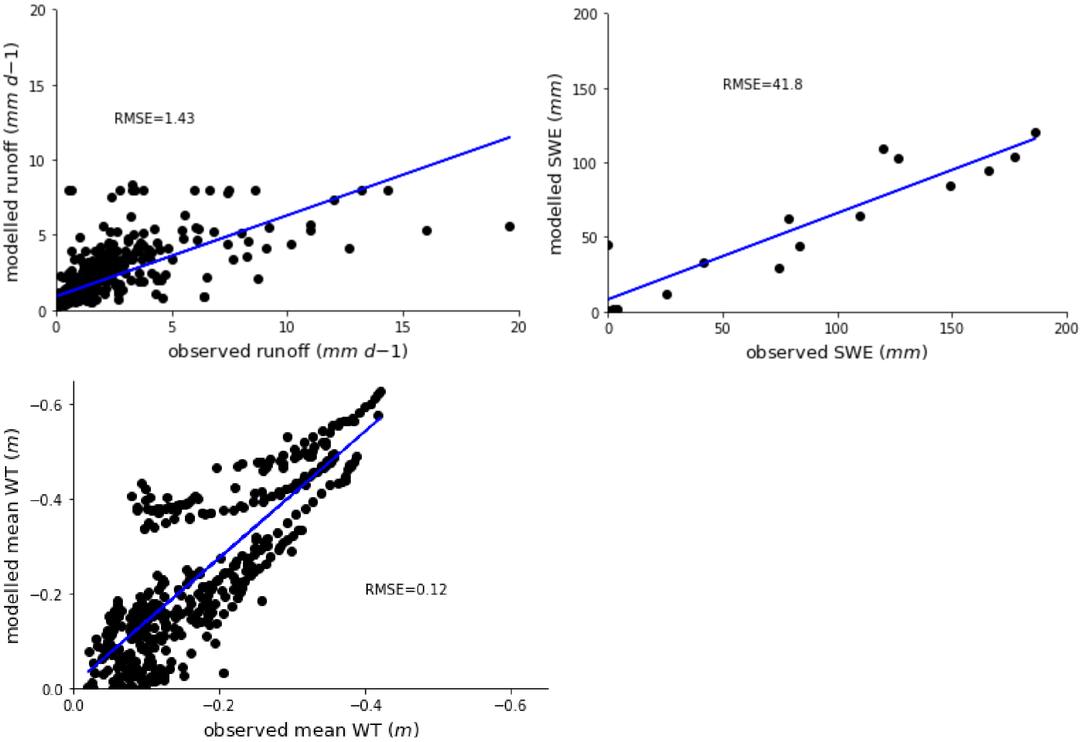

Figure 18 *Observed and modelled runoff (mm d^{-1}), observed and modelled SWE (mm), and observed and modelled WT (m) in Koivupuro in 2011-2013. Blue lines represent the least squares polynomial fit curves between observation and simulations.*

Table 3 *Pearson correlation coefficients between modelled and observed runoff, SWE and WTD.*

	Runoff	**SWE**	**WTD**
Pearson correlation coefficient	0.71	0.92	0.83

4.1.2 Level of nutrient exports and carbon balance in 2011-2013

The mean of annual nutrient exports in the control ditch depth scenario in 2011-2013 period were 0.90 kg ha^{-1} yr^{-1}, 0.06 kg ha^{-1} yr^{-1}, and 14.48 kg ha^{-1} yr^{-1} for N, P, and DOC exports, respectively. Annual CH_4 and CO_2 uptake of the peat were positive in 2011-2013 in Koivupuro. Mean C balance of the peat was -1087 kg ha^{-1} yr^{-1} and of the stand 54 kg ha^{-1} yr^{-1}. The sub-catchment of Koivupuro was therefore a C sink, even though the peat was a C source.

4.2 The long-term simulation

4.2.1 Water balance

Water balance was unclosed in the long-term simulation; during 95 simulation years annually on average 1.8 mm of total precipitation exceeded sum of total evapotranspiration and runoff. Mean annual sum of evapotranspiration in 2006-2100 was 286 mm yr^{-1} in the control ditch depth scenario, and 292 mm yr^{-1} in all of the ditch depth scenarios, and mean annual sum of runoff was 486 mm yr^{-1} in the control ditch depth scenario, and 418 mm yr^{-1} in all of the ditch depth scenarios. Mean annual runoff covered approximately 63 % of mean annual precipitation in the control ditch depth scenario and approximately 54 % in all of the ditch depth scenarios in 2006-2100. The difference between cumulative runoff and cumulative evapotranspiration was highest in spring (Figure 19). In all of the ditch depth scenarios, both the water balance of SWE and interception in the canopy, and the water balance of interception in the moss layer included mean computational mass balance errors of $<10^{-16}$ mm annually.

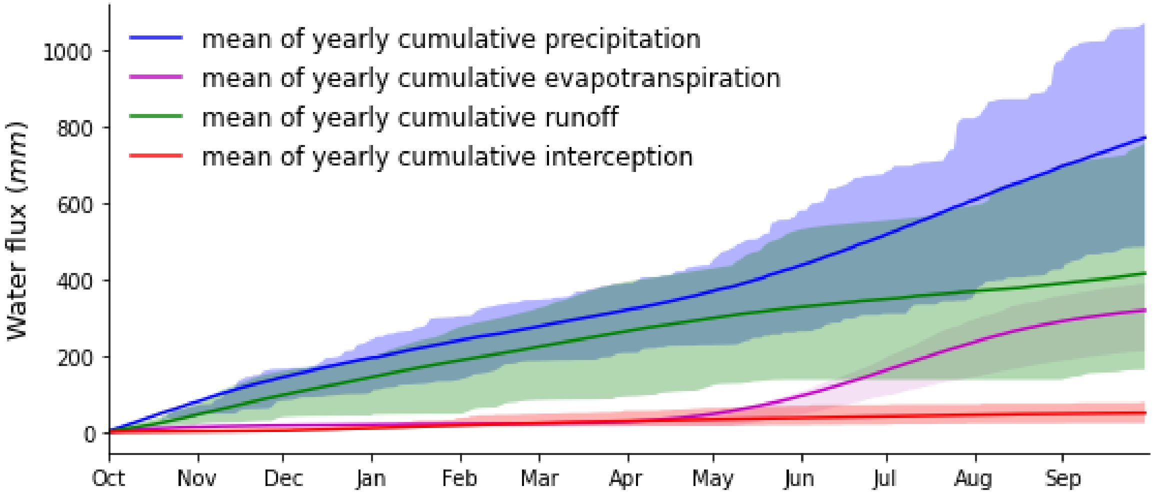

Figure 19 *Mean of annual cumulative evapotranspiration (mm), runoff (mm), interception (mm), and precipitation (mm) in 2006-2100. Light blue, light plum, light green, and light red areas represent the range between the highest and the lowest annual cumulative precipitation, evapotranspiration, runoff, and interception, respectively, in 2006-2100.*

4.2.2 WTD, nutrient exports and carbon processes

Modelled annual mean WT in late summer was the deepest in the control ditch depth scenario and the shallowest in the 0.1 m ditch depth scenario throughout the climate scenario simulation. In the control ditch depth scenario, the annual mean WTD in late summer fluctuated between -0.88 m and -0.13 m throughout the climate scenario simulation. Similar minimum and maximum values of annual mean WTDs in late summer in 2006-2100 were -0.65 m and -0.03 m, respectively, for the 0.1 m ditch depth scenario, and -0.78 m and -0.09 m for the 0.5 m ditch depth scenario. Simulated annual mean WT in late summer was the deepest in decades 2060 and 2070 in all of the ditch depth scenarios (Figure 20).

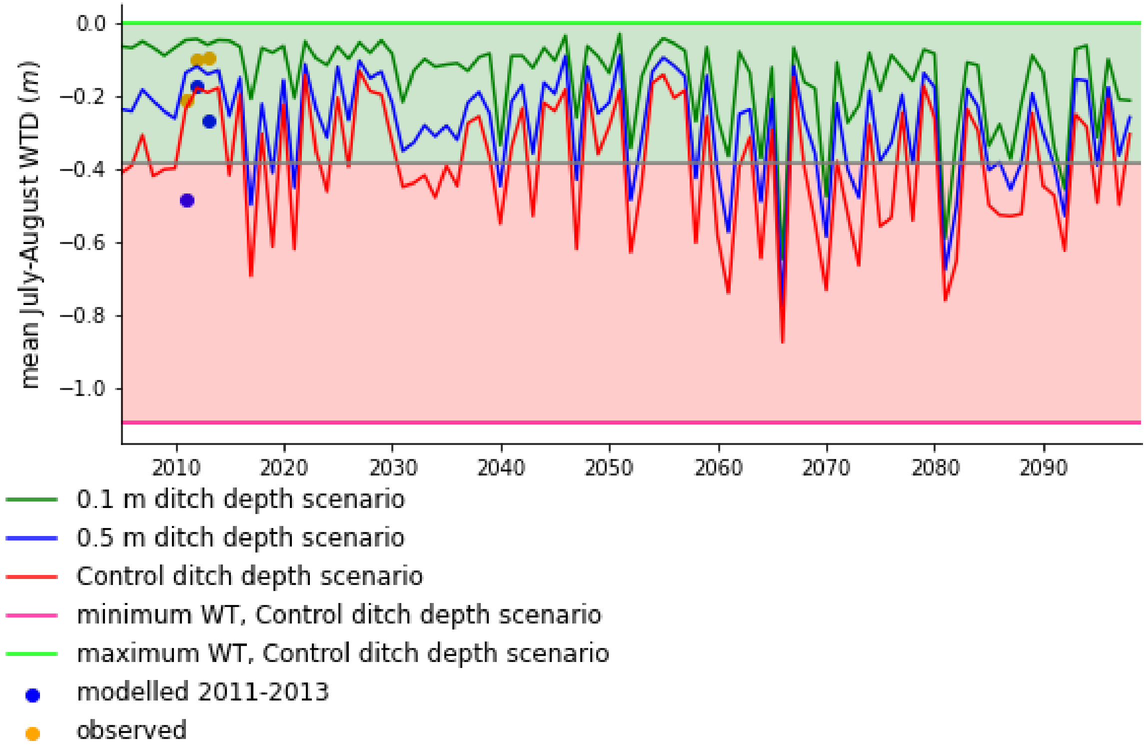

Figure 20 *Modelled mean of late summer WTD (m) in ditch depth scenarios and in the short-term simulation in 2011-2013, and observed mean of late summer WTD (m) in 2011-2013. Light green area represents the range from median to maximum of late summer WTD (m), and light pink area the range from median to minimum late summer WTD (m) in the control ditch depth scenario.*

Mean daily WT in 2006-2100 was relatively high from October to late spring in all ditch depth scenarios (Figure 21). From May onwards WT decreased, and the lowest WT was simulated for August (Figure 21). WT in August was deeper in S3-S4 compared to S1-S2 (Figure 21).

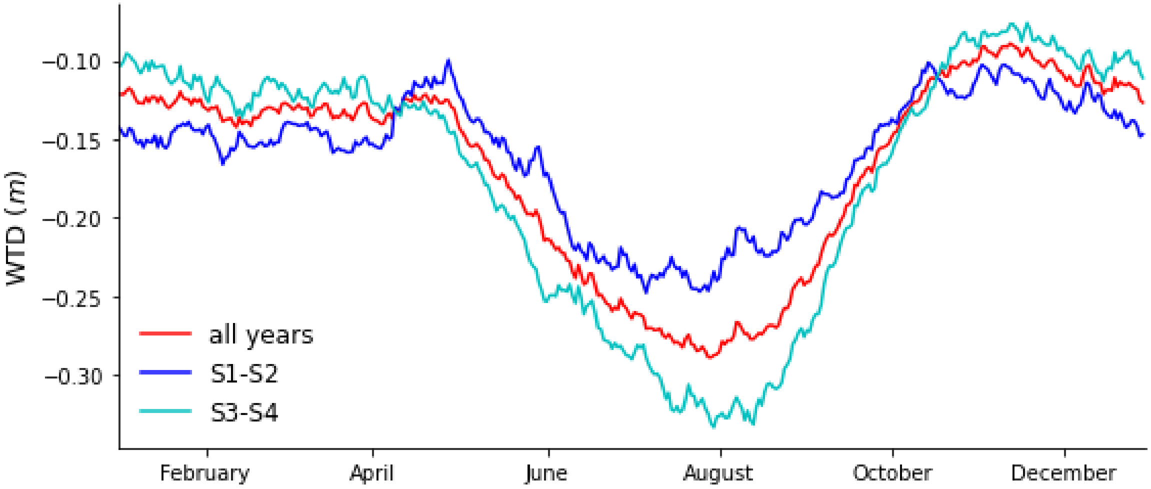

Figure 21 *Modelled daily WTD (m) in 2006-2100 (all years), S1-S2 and S3-S4 in Koivupuro.*

In 2006-2100, the modelled annual mean exports of N, P, K and DOC were consistently higher in the control ditch depth scenario compared to the 0.1 m and the 0.5 m ditch depth scenarios (Figures 22, 23, 24 and 25). N, P and K exports in the control ditch depth scenario were on average 1234 % higher compared to the 0.5 m ditch depth scenario, and clearly higher compared to the nutrient exports in the 0.1 m ditch depth scenario. DOC exports in the control ditch depth scenario were on average 269 % higher compared to the 0.1 m ditch depth scenario, and on average 27 % higher compared to the 0.5 m ditch depth scenario.

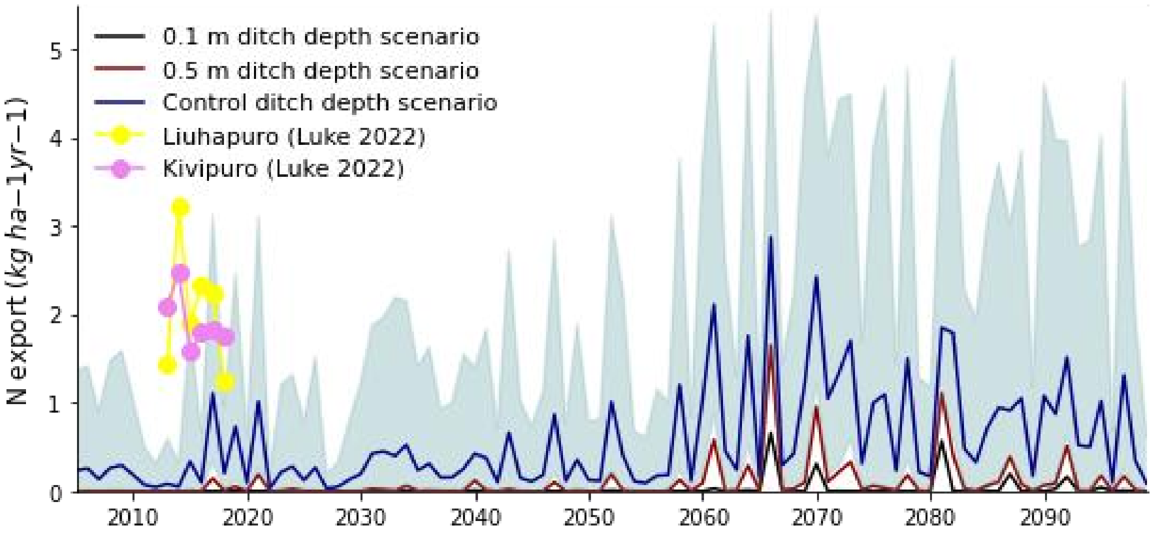

Figure 22 *Annual mean N export (kg ha^{-1} yr^{-1}) in Koivupuro in ditch depth scenarios, and annual mean N export in Liuhapuro (Luke 2022) and in Kivipuro (Luke 2022). Light blue area represents the range of annual maximum to minimum N export in the control ditch depth scenario.*

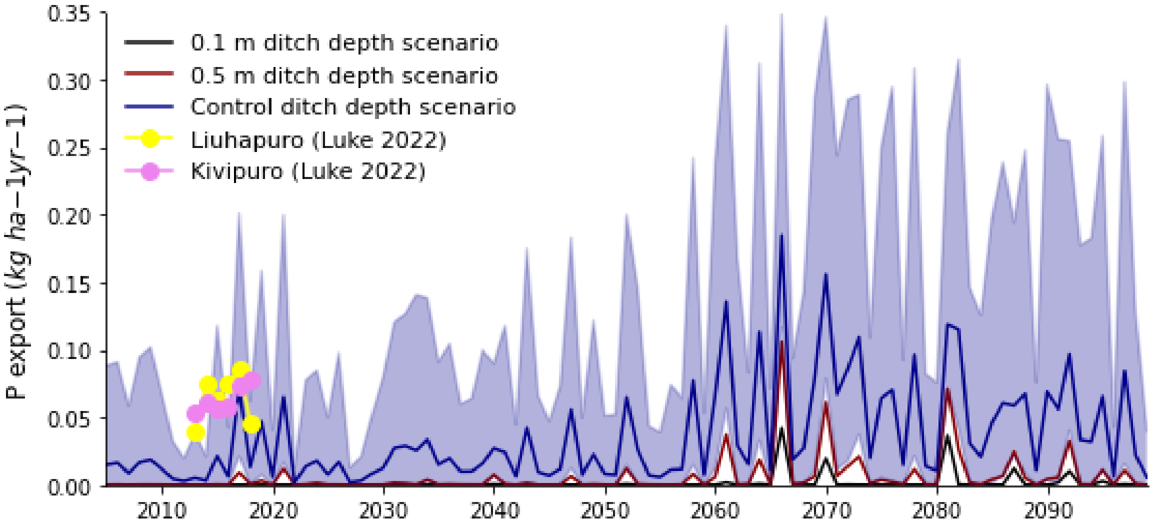

Figure 23 *Annual mean P export (kg ha^{-1} yr^{-1}) in Koivupuro in ditch depth scenarios, and annual mean P export in Liuhapuro (Luke 2022) and in Kivipuro (Luke 2022). Light slateblue area represents the range of annual maximum to minimum P export in the control ditch depth scenario.*

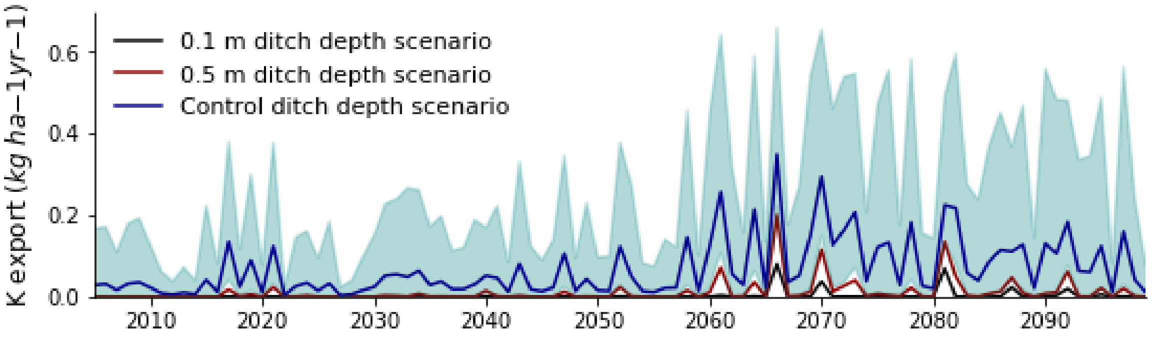

Figure 24 *Annual mean K export (kg ha^{-1} yr^{-1}) in Koivupuro in ditch depth scenarios. Light blue area represents the range of annual maximum to minimum K export in the control ditch depth scenario***.**

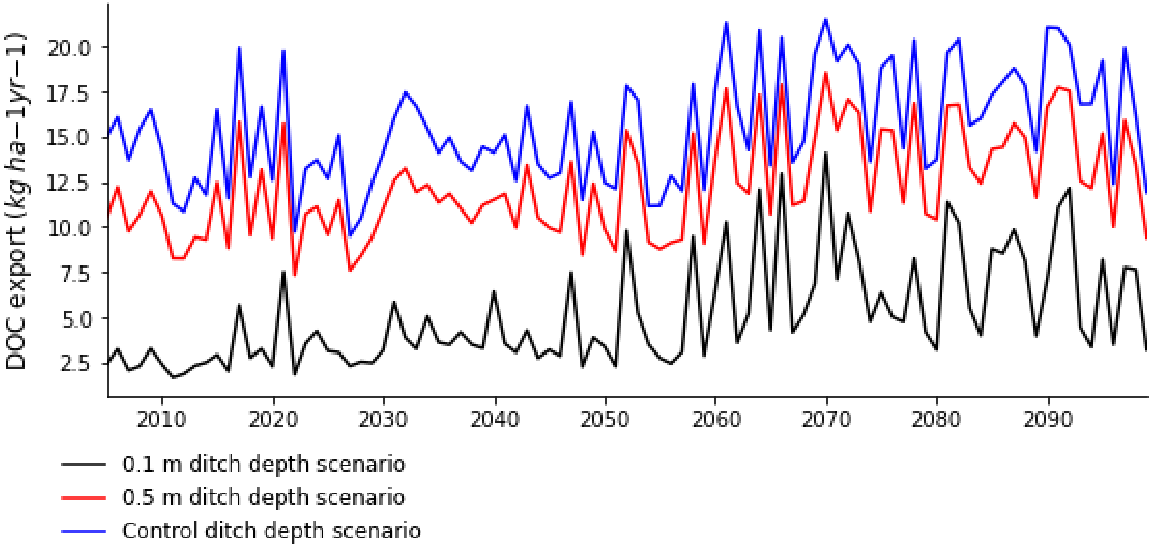

Figure 25 *DOC export (kg ha^{-1} yr^{-1}) in ditch depth scenarios in Koivupuro in 2006-2100.*

Minimum and maximum of mean annual N, P, K, and DOC exports were higher in the control ditch depth scenario compared to other two ditch depth scenarios (Table 4).

Table 4 *Minimum, maximum and mean of modelled mean annual N, P, K and DOC exports in 2006-2100.*

Component	Ditch depth scenario	Minimum	Maximum	Mean
N	0.1 m ditch depth scenario	<0.001	0.68	0.02
	0.5 m ditch depth scenario	0.04	1.77	0.17
	Control ditch depth scenario	0.67	3.85	1.53
P	0.1 m ditch depth scenario	<0.001	0.04	0.001
	0.5 m ditch depth scenario	0.003	0.11	0.01
	Control ditch depth scenario	0.04	0.25	0.1
K	0.1 m ditch depth scenario	<0.001	0.08	0.003
	0.5 m ditch depth scenario	0.005	0.21	0.02
	Control ditch depth scenario	0.08	0.47	0.19
DOC	0.1 m ditch depth scenario	2	14	5
	0.5 m ditch depth scenario	7	19	12
	Control ditch depth scenario	10	22	15

The highest modelled mean N, P, and K exports occurred in S3 and S4 in the 0.1 m ditch depth scenario, in S4 in the control ditch depth scenario, and in S3 in the 0.5 m ditch depth scenario (Table 5). N, P, and K exports increased from S1 to S4 in the control ditch depth scenario by 124 %, and in the 0.5 m ditch depth scenario by 243 % (Table 5). In S1 and S2 in the 0.1 m ditch depth scenario nutrient exports were very low (Table 5). DOC export increased from S1 to S4 approximately by 20 % in the control ditch depth scenario, by 131 % in the 0.1 m ditch depth scenario, and by 31 % in the 0.5 m ditch depth scenario (Table 5).

Table 5 *N, P, K and DOC export (kg ha^{-1} yr^{-1}) in Koivupuro in four simulation periods.*

Ditch depth	N	P	K	DOC
0.1 m ditch depth scenario				
S1	<0.01	<0.001	<0.001	2.9
S2	<0.01	<0.001	<0.001	3.7
S3	0.04	0.003	0.005	6.4
S4	0.04	0.003	0.005	6.7
0.5 m ditch depth scenario				
S1	0.07	0.004	0.008	10.7
S2	0.08	0.005	0.009	10.9
S3	0.27	0.018	0.033	13.1
S4	0.24	0.015	0.029	14.0
Control ditch depth scenario				
S1	0.92	0.059	0.112	14.2
S2	1.09	0.070	0.132	14.0
S3	1.89	0.122	0.230	16.2
S4	2.06	0.132	0.250	17.0

Modelled mean annual C balance of the peat was negative in all ditch depth scenarios until decade 2060 (Figure 26). In all ditch depth scenarios modelled mean annual C balance of the stand was mostly positive (Figure 27). Occasional negative peaks in C balance of the stand occurred in the decade of 2090 (Figure 27). After 2060 C balance of the peat and stand increased unsteadily (Figures 26-27). Maximum values of C balance of the peat and the stand were technically possible, but were unrealistic due to high oscillation between annual values (Figures 26-27). Unrealistic values and oscillation likely originated from long simulation period, since stand age and stand volume approached the interpolation limits of biomass functions in SUSI.

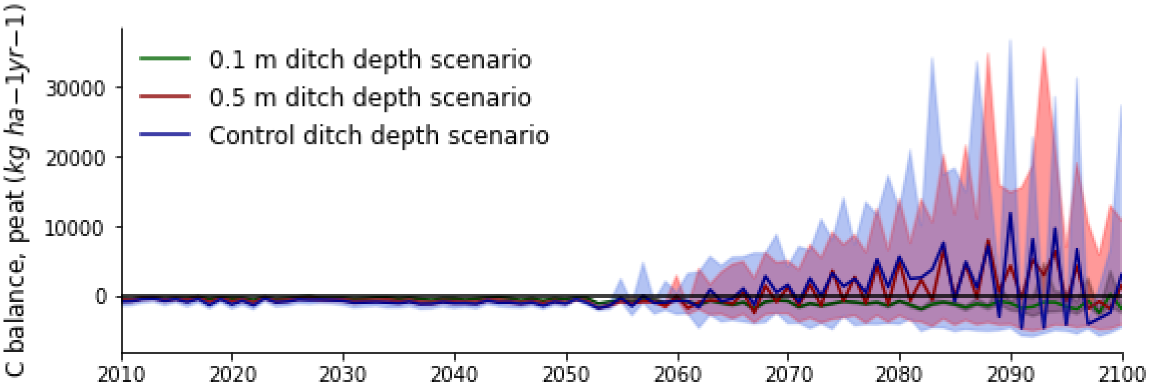

Figure 26 *Carbon (C) balance (kg ha^{-1} yr^{-1}) of the peat in ditch depth scenarios in Koivupuro in 2006-2100. Light blue, red and green areas represent range of annual maximum to minimum C balance (peat) in the control ditch depth scenario, in the 0.5 m ditch depth scenario, and in the 0.1 m ditch depth scenario, respectively*. *Positive values mean that the peat gains C.*

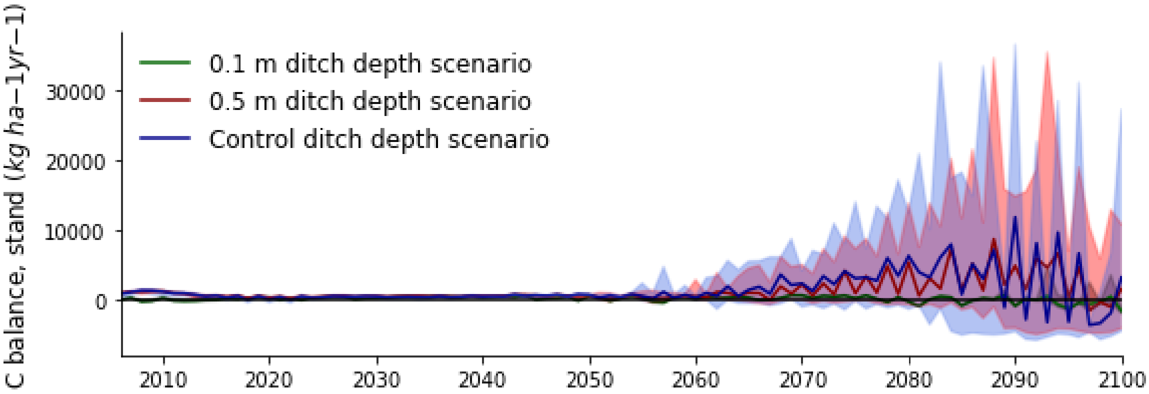

Figure 27 *Carbon (C) balance (kg ha^{-1} yr^{-1}) of the stand in ditch depth scenarios in Koivupuro in 2006-2100. Light blue, red and green areas represent range of annual maximum to minimum C balance (stand) in the control ditch depth scenario, in the 0.5 m ditch depth scenario, and in the 0.1 m ditch depth scenario, respectively*. *Positive values mean that the stand gains C.*

Modelled annual mean CO_2 uptake of the peat increased in all of the ditch depth scenarios from 2006 to 2100 (Figure 28). Annual mean CO_2 uptake in the control ditch depth scenario was on average 58 % higher compared to the 0.1 m ditch depth scenario, and on average 13 % higher compared to the 0.5 m ditch depth scenario. Modelled annual mean CH_4 uptake of the peat fluctuated greatly in 2006-2100 (Figure 29). Annual mean CH_4 uptake in the control ditch depth scenario was on average 96 % lower compared to the 0.1 m ditch depth scenario, and on average 59 % lower compared to the 0.5 m ditch depth scenario. Sum of transformed CO_2 and CH_4 uptake to CO_2 equivalents was positive in all of the ditch depth scenarios in 2006-2100. In the control ditch depth scenario, sum of CO_2 equivalent uptake of the peat was 86 % lower compared to the 0.1 m ditch depth scenario, and 49 % lower compared to the 0.5 m ditch depth scenario.

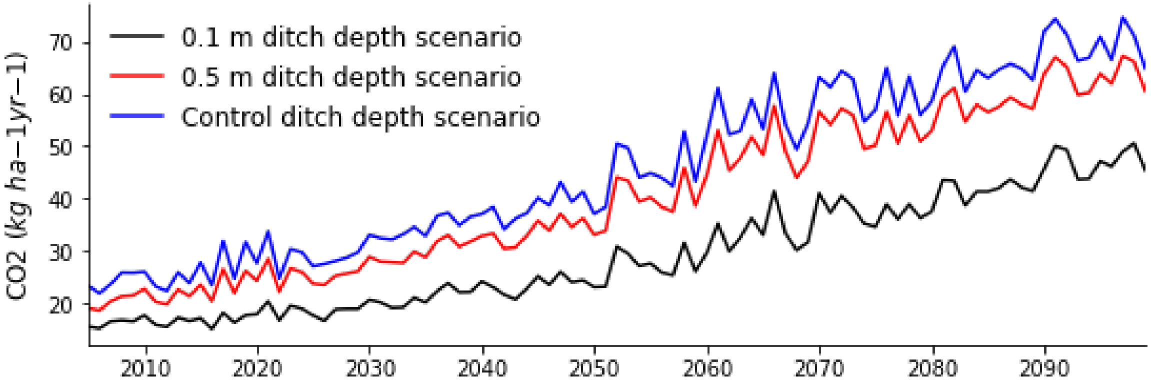

Figure 28 *CO_2 uptake (kg ha^{-1} yr^{-1}) of the peat in ditch depth scenarios in Koivupuro in 2006-2100. Positive values mean that the peat gains CO_2.*

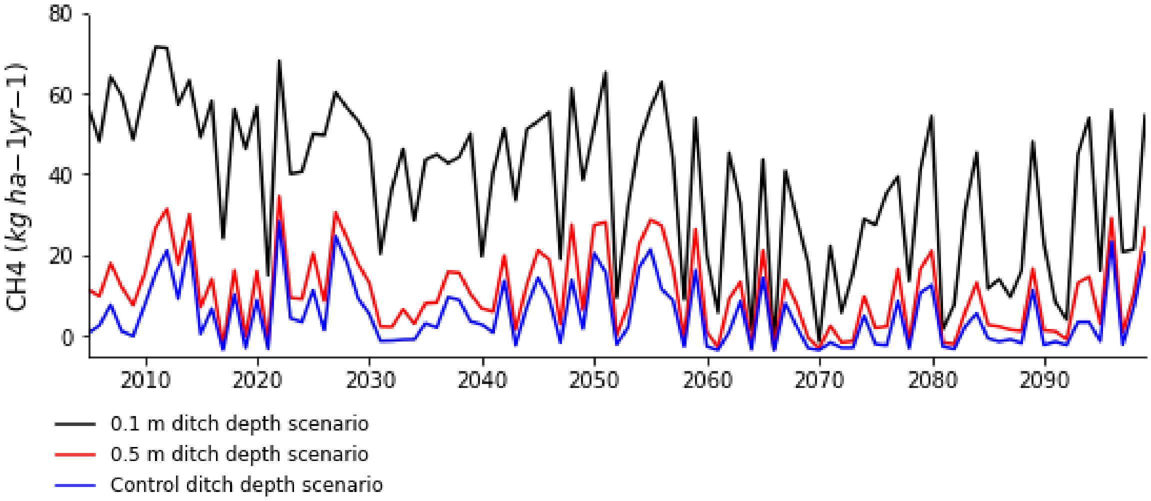

Figure 29 *CH_4 uptake (kg ha^{-1} yr^{-1}) of the peat in ditch depth scenarios in Koivupuro in 2006-2100. Positive values mean that the peat gains CH_4.*

Minimum and maximum of mean annual CO_2 uptake were higher in the control ditch depth scenario compared to other two ditch depth scenarios (Table 6). Minimum and maximum of mean annual CH_4 uptake were lower in the control ditch depth scenario compared to the 0.1 m and the 0.5 m ditch depth scenarios (Table 6).

Table 6 *Minimum, maximum and mean of modelled mean annual CO_2 and CH_4 uptake in 2006-2100.*

Component	Ditch depth scenario	Minimum	Maximum	Mean
CO_2	0.1 m ditch depth scenario	15	51	29
	0.5 m ditch depth scenario	19	68	40
	Control ditch depth scenario	22	76	45
CH_4	0.1 m ditch depth scenario	-2	67	36
	0.5 m ditch depth scenario	-3	30	9
	Control ditch depth scenario	-4	25	4

Modelled mean CO_2 uptake of the peat was growing in all of the scenarios from S1 to S4 (Table 7). From S1 to S4, CO_2 uptake increased approximately by 100 % in the control ditch depth scenario, by 86 % in the 0.1 m ditch depth scenario, and by 106 % in the 0.5 m ditch depth scenario (Table 7). CH_4 uptake was lowest in S4 in all of the ditch depth scenarios (Table 7). CH_4 uptake decreased approximately by 58 % in the control ditch depth scenario, by 47 % in the 0.1 m ditch depth scenario, and by 46 % in the 0.5 m ditch depth scenario from S1 to S4 (Table 7). Computational mean C balance of the stand increased by 456 % and by 285 % from S1 to S4 in the control ditch depth scenario and in the 0.5 m ditch depth scenario, respectively (Table 7). In the 0.1 m ditch depth scenario C balance of the stand was 22 % lower in S4 compared to S1 (Table 7).

Table 7 *C balance (kg ha^{-1} yr^{-1}) of the peat and the stand, and CO_2 and CH_4 uptake of the peat (kg ha^{-1} yr^{-1}) in Koivupuro in four simulation periods. Positive values mean that the peat or stand gains C, CO_2 or CH_4.*

Ditch depth	C balance, peat	C balance, stand	CO_2	CH_4
0.1 m ditch depth scenario				
S1	-382	96	16.4	50.4
S2	-387	378	20.7	41.8
S3	-886	254	25.4	28.3
S4	-992	75	30.5	26.6
0.5 m ditch depth scenario				
S1	-645	670	20.8	12.3
S2	-786	541	29.2	10.6
S3	-361	1 095	36.3	8.2
S4	1 629	2 580	42.8	6.6
Control ditch depth scenario				
S1	-966	492	24.2	6.0
S2	-1 115	356	33.5	5.0
S3	-226	1 243	41.3	3.7
S4	1 879	2 734	48.2	2.5

Annual mean of forest stand volume increased from 2006 to 2100 in all ditch depth scenarios (Figure 30). From 2080 onwards maximum of annual stand volume in the control and in the 0.5 m ditch depth scenarios were constant (Figure 30). Stand growth was the highest in the control ditch depth scenario and the lowest in the 0.1 m ditch depth scenario (Figure 30). Mean annual stand volume in the control ditch depth scenario was on average 8 % and 93 % higher compared to the the 0.5 m ditch depth scenario and the 0.1 m ditch depth scenario, respectively.

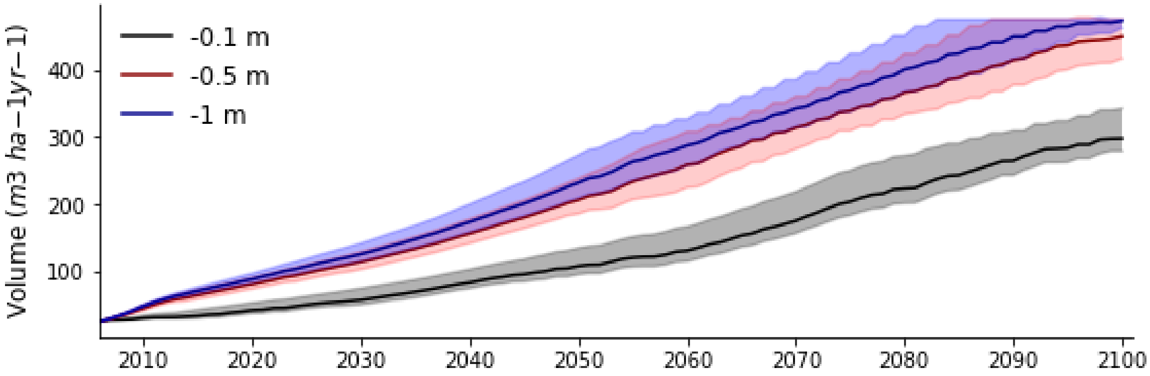

Figure 30 *Mean stand volume (m3 ha^{-1} yr^{-1}) in ditch depth scenarios in Koivupuro in 2006-2100.*

5 Discussion

In this Section, the results from the short-term and long-term simulations presented in the Section 4 are discussed and evaluated in the light of literature values. Limitations and uncertainties of the study are discussed, and methodologies are evaluated. Improvements for further research are presented, and finally, potential recommendations for peatland management are suggested.

5.1 The short-term simulation

SUSI succeeded in modelling most of the timings of runoff, SWE, and WT in the short-term simulation. SUSI generated accurate predictions of WT dynamics especially during wet years. The quantities of runoff and WT were often over- or underestimated, and SWE was systematically underestimated. Underestimated SWE in winter 2012 explained underestimation of runoff in spring 2012. Modelled cumulative runoff was underestimated in 2011-2013. RMSE of WT prediction in this work was lower compared to RMSE of 0.15 m in Laurén *et al.* (2021).

Laurén *et al.* (2021) found physical growth restrictions, e.g. O_2 stress, to be typically higher in *Sphagnum* peat, where WT was higher. In this study, the peat column was assumed to consist of *Sphagnum* peat in eight top layers, and of *Carex* peat in the bottom layer. SUSI likely, therefore, simulated higher WT compared to simulation set up with dominating *Carex* peat.

Modelled mean of annual P export in the control ditch depth scenario in Koivupuro in 2011-2013 was within measured range of annual P exports in Liuhapuro and Kivipuro in 2014-2019 (Luke 2022). Modelled mean of annual N and DOC exports in the control ditch depth scenario in Koivupuro in 2011-2013 were 28-72 % and 80-93 % lower compared to annual N and TOC exports in Liuhapuro and Kivipuro in 2014-2019, respectively (Luke 2022). The study likely underestimated N and DOC exports due to initial state of site fertility in Koivupuro, since modelled N, P, and K exports were also found to be lower in this study compared to modelled exports in Laurén *et al.* (2021).

Model uncertainty is related to the inputs, parameters and structure of the model (Refsgaard *et al.* 2007). Due to the lack of measurements of nutrient exports or C balance in Koivupuro site, SUSI was not calibrated. Calibration and validation was earlier done in Laurén *et al.* (2021), but the low magnitude of modelled nutrient exports in Koivupuro compared to exports in Laurén *et al.* (2021) might have been fixed by recalibration.

Koivupuro was found to be a sink of C in 2011-2013, which was in line with Lohila *et al.* (2011), but opposite to Simola *et al.* (2012) who studied C losses in peatlands in southern and middle Finland that have been forestry-drained in the 1980s.

5.2 Nutrient exports and C processes in the long-term simulation

In the simulation DNM was conducted in sub-catchment of Koivupuro, which was initially drained more than 20 years ago. The peatland had thus already been forested and the properties of the peat and stand had changed due to the initial drainage, e.g. nutrient uptake was likely more efficient in Koivupuro compared to pristine peatlands due to higher initial forest stand volume. DNM growth response was found to be the smallest in less fertile sites in SUSI (Laurén *et al.* 2021). In 2006-2100, modelled growth response of drainage in mid-fertile Koivupuro was approximately 5 m^3 ha^{-1} yr^{-1} in the control ditch depth scenario, approximately 4.7 m^3 ha^{-1} yr^{-1} in the 0.5 m ditch depth scenario, and approximately 3 m^3 ha^{-1} yr^{-1} in the 0.1 m ditch depth scenario.

N, P and K exports were projected to increase along the long-term simulation and along deeper ditch depth. Results of positive drainage impact on N, P and DOC exports were in line with e.g., Strack *et al.* (2008), Nieminen *et al.* (2017, 2020), Asmala *et al.* (2019) and Räike *et al.* (2019). According to review by Evans *et al.* (2016), DOC export increases in peatlands by approximately 60 % due to drainage. In the long-term simulation, DOC export however increased approximately by as much as 269 % as the ditch depth was changed from 0.1 m to 1 m. Nieminen *et al.* (2017) estimated, that loading of TN and TP increase with drainage age, which can also be seen in the simulation results of this study, even if the increasing exports are in fact a combination of ageing stand and changing weather conditions. Simulation results agree with the predominant understanding, that nutrient loading increases in peatlands longer than 10 years after drainage (Finér *et al.* 2020, 2021).

Kortelainen *et al.* (2006) estimated that TOC, TN and TP exports from Koivupuro catchment in period 1979-1982 were 70, 1.2 and 0.04 kg $ha^{-1}yr^{-1}$, respectively. Based on these estimates and modelled nutrient exports from long-term simulation in the control ditch depth scenario, N had decreased by 33 % and P export had increased by 28 % until year 2006. Similarly, N and P export would increase by 25 % and 150 % until year 2100, respectively. TOC export had decreased by more than 79 % until year 2006, and would decrease by more than 83 % until year 2100. Both projected increase in N and P exports, and decrease in TOC exports were likely originating from increasing decomposition of OM due to increasing temperature and deepening WT.

The frequency of relatively high peaks of annual mean nutrient exports increased from late 2050s onwards. The highest nutrient export peaks were simulated to occur in 2060s and 2070s, simultaneously to the relatively low simulated mean annual WTs in late summer. Low WTs in late summer in 2060s and 2070s were likely related to concurrent increase in C balance of the stand.

Due to the seasonal dynamics of WTD, the highest peaks of average daily nutrient exports were simulated for late summer and autumn, and spring snowmelt was simulated to have a smaller role in nutrient exports. This is contradictory to studies highlighting the importance of spring flood such as Kortelainen *et al.* (1997) on forested catchments and Räike *et al.* (2019) on drained peatlands, and in accordance with e.g. Strack *et al.* (2008) and Lepistö *et al.* (2021) on drained peatlands in Canada and in Finland, respectively. From the beginning towards the end of the long-term simulation, the late summer and early autumn peak of nutrient export was projected to increase due to deepening WT.

Modelled mean of annual N, P and DOC exports in all ditch depth scenarios in S1 were mostly lower compared to literature values on N, P and TOC exports from drained peatlands (Table 8). Modelled mean of annual N export in S1 in the control ditch depth scenario was from 26 to 72 % lower, and simulated mean of annual DOC export from 80 to 91 % lower compared to monitored N and TOC exports from Liuhapuro and Kivipuro, respectively (Luke 2022). Modelled N and P exports in S1 and S4 in 0.1 m and 0.5 m ditch depth scenarios were very low compared to literature values on nutrient exports from drained or pristine peatlands (Table 8). Modelled DOC exports in all ditch depth scenarios in S4 were 94 to 98 % lower compared to Billet *et al.* (2004) for drained peatlands (Table 8). Modelled N and P exports were clearly lower compared to literature values on nutrient exports from agriculture (Table 8), e.g. N and P exports form the control ditch depth scenario in S1 were 87 to 95 % and 74 to 96 % lower compared to agricultural N and P exports, respectively, reported in Rankinen *et al.* (2016), Tattari *et al.* (2017), and Räty *et al.* (2020).

Table 8 *Literature values and simulation results for N, P and TOC/DOC export (kg ha^{-1} yr^{-1}).*

Publication	N	P	TOC
PRISTINE PEATLANDS			
(Kortelainen & Saukkonen 1998)	1…2.9	0.04…0.2	26…88
(Mattsson *et al.* 2003)	1.4	0.05	30…100
(Kortelainen *et al.* 2006)	0.29...2.3	0.02....0.15	9.4…140
(Mattsson *et al.* 2015)			6.1…133
DRAINED			
(Billet *et al.* 2004)			304 ± 62
(Nieminen *et al.* 2020)	1...1.8	0.01...0.05	
AGRICULTURE			
(Rankinen *et al.* 2016)	13.4	0.83	
(Tattari *et al.* 2017)	8.2...16.1	0.23...1.34	
(Räty *et al.* 2020)	19 ± 7.2	1 ± 0.37	
FORESTS			
(Kortelainen *et al.* 1997)	0.83...3		
MODELLED EXPORT			
S1			
0.1 m ditch depth scenario	<0.01	<0.001	2.9
0.5 m ditch depth scenario	0.07	0.004	10.7
Control ditch depth scenario	0.92	0.059	14.2
S4			
0.1 m ditch depth scenario	0.04	0.003	6.7
0.5 m ditch depth scenario	0.24	0.015	14.0
Control ditch depth scenario	2.06	0.132	17.0
REFERENCE CATCHMENTS			
(Luke 2022)			
Liuhapuro	1.25...3.23	0.04...0.09	72…208
Kivipuro	1.58...2.47	0.05...0.08	94…161

Minkkinen *et al.* (2007) estimated northern peatlands to more likely to undergo C losses after drainage, since decomposition is not as efficiently compensated by stand growth compared to southern sites. Modelled C balance of the peat and the stand in ditch depth scenarios increased unsteadily along the long-term simulation, and reached the highest peaks in S4. Fluctuation from negative to positive peaks of C balance increased in S4. Positive trend in modelled C balance is in line with Aurela *et al.* (2004), who noted that climate warming lengthens the growing season and thus increases C storage in peatlands. This temperature response has been predicted to be stronger in northern peatlands compared to southern sites (Minkkinen *et al.* 2007). Projections of drainage impact on C content in mid-fertile Koivupuro was unclear between the 0.5 m and the control ditch depth scenarios, which is in accordance with Krüger *et al.* (2016) estimating negative drainage impact on C content in minerotrophic peatlands and unclear impact in ombrotrophic peatlands.

Modelled annual CO_2 and CH_4 uptake of the peat were mostly positive, which was in line with Maljanen *et al.* (2003), Lohila *et al.* (2011) and Ojanen *et al.* (2013), but in contrast to Minkkinen *et al.* (2007). Modelled negative drainage impact on CO_2 and CH_4 uptake of the peat was in correspondence with Ojanen *et al.* (2010) and Maljanen *et al.* (2010). In accordance with Pelletier *et al.* (2015), modelled daily CO_2 uptake of the peat tended to be relatively high from April to October.

Changes in C balance can be explained by changes in biomass and CO_2 efflux. Fluctuating CH_4 uptake of the peat was directly derived from WT, and steadily increasing CO_2 uptake of the peat followed increasing annual mean air temperatures. In SUSI, the direct effect of drainage decreases as stand growth increases, since the level of evapotranspiration is elevated in high volume stand. Stand growth was steady throughout the long-term simulation, and ranged from 0 to 10 m^3 ha^{-1} yr^{-1} in all of the ditch depth scenarios. From the ditch depth scenarios, the direct effect of drainage was the lowest in the control ditch depth scenario, where stand growth was the highest.

Mean of annual computational C source in the peat in S1 in all ditch depth scenarios were lower compared to the estimates for drained peatlands by Simola *et al.* (2012) and Pitkänen *et al.* (2013), but higher compared to estimates by Minkkinen *et al.* (1998). In correspondence with Lohila *et al.* (2011), Koivupuro stand was estimated to be a computational C sink in all ditch depth scenarios in most of the simulation years. C content of Koivupuro catchment located in the aapa-mire region can be assumed to be relatively low compared to peatlands located in the raise-bog region, since Turunen *et al.* (2002) estimated LORCA to be higher in the raise-bog region. Modelled mean of annual C balance in S4 was very high in the control ditch depth scenario and in the 0.5 m ditch depth scenario compared to literature values on C balance of pristine or drained peatlands or agricultural fields (Table 9).

Table 9 *Literature values and simulation results for C balance (kg ha^{-1} yr^{-1}) of the peat and the stand. Positive values mean that the peat or stand gains C.*

Publication	peat	stand
PRISTINE PEATLANDS		
(Turunen *et al.* 2002)	151...218	
(Roulet *et al.* 2007)		215 ± 390
DRAINED		
(Minkkinen *et al.* 1998)	983 ± 2400	
(Tahvanainen 2011)		1006
(Lohila *et al.* 2011)	650	
(Simola *et al.* 2012)	-1500	
(Pitkänen *et al.* 2013)	-1310 ± 280	
AGRICULTURE		
(Ceschia *et al.* 2010)		1380 ± 2390
(Heimsch *et al.* 2021)		570 ± 100… 860 ± 120
MODELLED C BALANCE		
S1		
0.1 m ditch depth scenario	-382	96
0.5 m ditch depth scenario	-645	670
Control ditch depth scenario	-966	492
S4		
0.1 m ditch depth scenario	-992	75
0.5 m ditch depth scenario	1 629	2850
Control ditch depth scenario	1 879	2374

5.3 Limitations in the long-term simulation and recommendations for future

According to author's knowledge, there are not many studies combining modelling of both C processes and nutrient exports in drained peatlands. SUSI provided tool for this kind of analysis, and hence in this study modelling of these components were combined. The study included many sources of uncertainties due to needed simplifications of complex relations between variables in the model.

According to Olesen *et al.* (2007), simulations of climate change impacts on terrestrial ecosystems typically include uncertainties related to emission scenarios, climate models, impact models, and local soil and climatic conditions of the study site. Jacob *et al.* (2007) stated that typically RCM's include coupled biases of warm bias and wet bias or cold bias and dry bias in the winter, and warm bias and dry bias in the summer. In climate model calibration the period compared against the measurements was chosen to be 15 years, so it can be assumed, that the calibration period covered quite extensively the natural variability of the weather. In the period 2006-2020 in Koivupuro, the selected climate scenario (RCP 8.5 W m^{-2}) was underestimating precipitation and summer air temperatures, and overestimating winter air temperatures, and thus the used climate scenario likely included coupled biases of cold bias and dry bias in the summer, and warm bias and dry bias in the winter.

Benestad *et al.* (2021) recommended use of an ensemble climate projections due to scenario uncertainty, internal climate variability, and model uncertainty. This study included scenario uncertainty since only a high forcing scenario was included in the study. Currently it can be assumed that the long-term simulation results provide pessimistic predictions, but the level of average or minimum results can only be hypothesized. Model uncertainty or internal climate variability were not assessed in this study, since only one climate model and one initialisation state were used. Comparison of climate models and climate scenarios would provide more information of uncertainties from a single climate model and climate scenario, and use of several initialisation states would have provided multiple climate evolutions instead of one. It is important to note that the results of climate impact modelling studies should be considered as directional guidelines, and not as precise and accurate results. Average values of nutrient export and C balance in four periods were more emphasized in the interpretation of results, than individual annual values in aim to separate natural variability from climate impact. Some potential climate responses of Koivupuro were not included in the study, such as changing peat hydraulic properties. It is however worth to note that additional predictor variables do not necessarily improve the model performance, but the addition of variables increases the noise in the simulation.

According to Hökkä *et al.* (2021), the main limitation of SUSI was uncertainty in hydrological modelling due to hydrological characteristics of peat. Sood & Smakhtin (2015) summarized that uncertainties in hydrological models originate from model inputs, the structure of the model, used parameters, and available measurements. Similarly to underestimations of SWE and runoff in the short-term simulation, it is possible that quantities of runoff were underestimated in the long-term simulation. Evapotranspiration also included uncertainty, since the data describing the initial state of the forest stand and ground vegetation likewise included uncertainty. Further in the model, potential overestimations of WT originating from underestimated runoff and evapotranspiration would lead to underestimations of nutrient exports and C losses and overestimations of CH_4 uptake of the peat, and vice versa. Based on the short-term simulation, modelled WTD dynamics corresponded more to observed WTD during wet years compared to dry years. WT computations could be specified further with the addition of new WT controllers, such as site topography and mineral soil under the peat layer (Stenberg *et al.* 2018), but it seems more important to concentrate on the computations behind WT, such as the computations of drainage impacts and evapotranspiration controlled by the forest stand. More detailed knowledge of the initial state of the stand and the forest stand would thus improve the hydrological computations and their most important output, WT. Potential under- and overestimations of runoff were not reflected to the water balance of SUSI in the long-term simulation; error of computed water balance for the whole system was on average 1.8 mm annually, and computational error of modelling both canopy and moss layer hydrology on average $<10^{-16}$ mm annually.

From 2060 onwards the computational C sink of the stand increased, but the role of stand as a C sink was highly dependent on the conditions of stand volume and biomass. Modelling biomass in long time periods is challenging due to the unpredictable nature of tree mortality (Wilson *et al.* 2019, Salas-Eljatib & Weskittel 2020). According to Wilson *et al.* (2019), often the largest uncertainty in long-term simulation of forest growth is related to the tree-level mortality. Great fluctuation in C balance of the peat and the stand in the latter half of long-term simulation (Figures 26-27) was not realistic and might originate from fluctuating stand mortality due to large basal area in nearly 140 years old Koivupuro stand, or from noise in the modelling. The noise in modelled C balance partly originated as interpolation limits of the volume growth and biomass production were approached after the stand volume exceeded 400-450 m^3 ha^{-1}. In the end of long-term simulation all new biomass was lost in litterfall, because maximum stand volume stayed constant.

N, P, and DOC exports were likely somewhat underestimated in the modelling work, since the effect of runoff was underestimated in the simulation of the exports. In Koivupuro, increased runoff due to snowmelt or rainfall was found to be an important erosion process, and neglecting erosion and eroding material in computations of nutrient and C losses might have led to underestimations in nutrient exports. Haahti *et al.* (2014) and Stenberg *et al.* (2015) estimated the highest erosion and sediment loads to occur during spring snowmelt.

Validation of trends in the nutrient storage of the soil is difficult, and future research of long-term development of nutrient storage in soil is essential (Arheimer *et al.* 2012). In long-term modelling the nutrient storage in soil profile tends to increase over time, which causes systematically increasing error in nutrient exports. Error of accumulating nutrient storage in the soil was not assessed in this study, since only one nutrient model was included in the work, and the development of nutrient exports was modelled for a long continuous time period instead of simulating time slices as, e.g., in Arheimer *et al.* (2012).

In summary, representativeness of the results would increase by including ensemble climate projections, continuous hydrological observations and empirical evidence of nutrient load and C processes in the study site, and several study sites in the work. In future research there is a need for long-term modelling of nutrient and C processes in forestry-drained peatlands based on ensemble climate projections and several simulators. Great fluctuation in C balance of the peat and stand in the latter half of long-term simulation could be solved by updating interpolation limits in biomass and volume growth functions. Demand for continuing monitoring of nutrient and C processes, further research on driving factors behind them, and revision of models in terms of long-term modelling is also high.

5.4 Drainage design and environmental impacts

The chosen and most dominating site fertility class of Koivupuro sub-catchment is the second most typical site fertility class on mineral soils and peatlands on forest land in Finland; approximately 29 % of Finnish mineral soils and peatlands on forest land are classified to be sub-xeric forests or dwarf shrub pine bogs (Metsäntutkimuslaitos 2012). In total 94 % of mineral soils and peatlands on forest land in Finland have site fertility class of two to four (Metsäntutkimuslaitos 2012), which were the site fertility classes present in Koivupuro catchment. Simulation results could thus be applied to represent an example of forested peatland in Finland, and utilized in the process of planning protective measures for future climate change feedback mechanisms.

The results highlighted, that the current ditch depth of 1 m is likely too deep for the Koivupuro sub-catchment. Simulated growth response in the control ditch depth scenario was close to the growth response in the 0.5 m ditch depth scenario, whereas nutrient exports and CO_2 uptake of the peat were clearly lower in the 0.5 m ditch depth scenario. CH_4 uptake of the peat was however higher in the 0.5 m ditch depth scenario compared to the control ditch depth scenario. Drainage impact on the C balance of the stand was unclear, but mostly C content was estimated to be highest in the control ditch depth scenario. Ditch depth scenarios cannot therefore be straightforwardly put in order based on environmental impacts, since lower ditch depth scenario has lower nutrient and DOC exports, but also smaller C storage. In the light of restoration of drained peatlands, it could be argued that less extreme anthropogenic changes in peatlands are more natural and hence seen as better compared to more extreme actions, even if implemented to increase C storage of peatlands. Regardless, the results highlighted the importance of modelling ditch depth scenarios before DNM, since in the case of Koivupuro, the extreme ditch depth of 1 m was not estimated to be necessary in light of enhancing the tree growth.

6 Conclusions

The aim of this study was to simulate the development of C balance and nutrient exports in the sub-catchment of Koivupuro in a long-term simulation from 2006 to 2100, and to evaluate the modelling. In the simulation, the effect of climate change was simulated by using downscaled and bias-corrected climate projections from EURO-CORDEX based on RCP 8.5 forcing in the simulation, and the effect of DNM was simulated by three ditch depth scenarios. Model performance was evaluated by comparing results from the short-term simulation to hydrological observations measured in Koivupuro in 2011-2013, and by estimating the credibility of simulation results of C balance and nutrient exports in the light of literature values.

Simulated N, P, and DOC exports at the beginning of the 21st century were lower compared to literature values. Concurrent levels of nutrient exports in 2011-2013 were low in the light of observations from reference study sites. Koivupuro was estimated to be a computational carbon sink in 2011-2013 and in the first simulation periods of the long-term simulation. Estimates of carbon balance of drained peatlands have a high variability in literature values, and thus the accuracy of simulation results pointing towards Koivupuro acting as a C sink was uncertain.

From 2006 to 2100 WT was simulated to be relatively high in spring and winter, and relatively low in summer and autumn. WT in late autumn was deeper in the end of long-term simulation, and thus nutrient exports and CH_4 uptake of the peat in autumn were simulated to increase towards the end of long-term simulation. Annual nutrient exports and CO_2 uptake of the peat were predicted to increase due to increasing mean annual air temperature in 2006-2100. The highest magnitudes and fluctuation of annual C balance were modelled to occur from 2060 onwards. The C balance fluctuation increased to overly high range in the end of the simulation. Dynamics of CH_4 uptake and C balance of the stand were predicted to fluctuate from negative to positive, but overall CH_4 uptake of the peat was predicted to decrease and C content of the stand to increase. Climate change feedback of the mid-fertile Koivupuro site in 2006-2100 was estimated to be neutral or negative on CO_2 equivalent sum of CO_2 and CH_4 uptake of the peat, and positive on C storage of the stand and potential eutrophication of the Koivupuro stream.

Uncertainties of modelling are related to hydrological modelling, climate modelling, and long-term modelling of development of biomass, carbon and nutrients. Total precipitation exceeded sum of total evapotranspiration and runoff in the long-term simulation, but mass balance errors for whole system, canopy and moss layers were small. In terms of comparison of modelled runoff, SWE and WTD against measurements in Koivupuro in 2011-2013, SUSI succeeded to simulate the timings, but systematically under- or overestimated the quantities. The representativeness of climate modelling would be improved by ensemble climate projections with several climate scenarios, climate models and initialisation states. Long-term modelling of biomass and carbon accumulation included uncertainty due to unpredictable nature of stand mortality, and due to biomass modelling within the limits of biomass interpolation in SUSI. Long-term modelling of nutrient exports include uncertainty due to uncertainty of change of nutrient storage in soil. The modelling work has potential for improvements by addition of several study sites and new controlling factors to the modelling, e.g., nutrient exports could be updated by addition of eroding material. Site-specific information includes uncertainty since some of the information is based on remote sensing data, and the historical reporting of environmental factors in Koivupuro is not continuous. Addition of other management practices, such as biomass collection or fertilization, to the modelling work would enable comparison between peatland managements.

Simulated results emphasized, that neither of the ditch depths of 0.5 or 1 m was absolutely better and that the best ditch depth might also be between them. From the ditch depth scenarios, the ditch depth of 1 m had the highest level of stand growth, CO_2 uptake of the peat and during most years the highest C storage, but the highest nutrient and DOC exports and the lowest CH_4 uptake of the peat. The ditch depth of 0.5 m was related to relatively good stand growth, low nutrient exports, and high CH_4 uptake.

In drainage impact research the choice of the best ditch depth in the light of enhanced tree growth and minimized environmental impacts is not straightforward and calls for more modelling work and prioritization of environmental impacts. Modelling studies combining both C balance and nutrient exports in drained peatlands is, according to the author's knowledge, still at its infancy, and thus further similar modelling studies utilizing SUSI and other peatland simulators are encouraged.

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