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Proposals for developing the monitoring of restored peatlands

Experiences gained in Hydrology LIFE project for developing general and hydrological monitoring as well as setting up monitoring by remote sensing

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Cover: Restored Soikealamminneva in Salamajärvi National Park, Kinnula. Photo: Marko Haapalehto.

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Documentation Page

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Abstract

Peatland restoration is an effective means to slow down biodiversity loss as well as to promote flow regulation, water purification and carbon sequestration. Restoration activities are increasing significantly, and thus, more applicable, fluent and efficient monitoring methods are needed to show the restoration impacts and to respond to the development needs of the methods.

On the Finnish state-owned land, peatland restoration monitoring can be divided into technical general monitoring and impact monitoring which uses a monitoring network to study the long-term changes in peatland hydrology and vegetation. Besides the conventional monitoring methods, remote sensing has a strong potential to widen the observations from single points or limited areas to the whole peatland site.

This report gathers the proposals and development recommendations from the Hydrology LIFE project. During the project, peatland restoration monitoring was developed by gathering the experiences on general monitoring and hydrological fieldwork from the restoration planners and site managers using a poll survey and workshops. Furthermore, the 10-year hydrological data from over 40 sites in the monitoring network was processed and peat and pore water samples were gathered and analysed during the project. Also, remote sensing methods were introduced using a literature review and picked methods were tested and developed at the project sites. High-resolution drone data from over 20 sites were also gathered and analysed.

Updated guidelines and regular training were emphasized in the monitoring development needs. The survey respondents wanted to keep general monitoring flexible also in the future, but observing still needs uniforming. The 10-year observation data shows that the restored water levels might be more sensitive to interannual variability than the water levels at corresponding pristine sites. Restoration produces a temporary interference in the water quality, but it diminishes during 5–10 years after the restoration. The unique data from the monitoring network should be opened for free use by all researchers.

Remote sensing was considered an appropriate tool for supplementing the ground-level observations on peatland surface moisture, vegetation, greenhouse gas emissions and peat properties, on open peatlands in particular. To enable quantitative observations, however, usually also ground truth observations are needed. Drones are a rather easy way to produce high-resolution datasets, but their more systematic use requires resources for technical development and quality control.

The results of the report can be used in the development work of the monitoring guidelines and the environmental authority's geoinformation system. Remote sensing experiences and the literature review support increasing technical monitoring of peatlands. Experiences can be applied in organizing peatland restoration monitoring also outside the state-owned protection areas.

Keywords	Peatlands, restoration, monitoring, general monitoring, hydrological monitoring, development of monitoring, guidelines, Hydrology LIFE, remote sensing, drones		
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Tekijä(t)	Lauri Ikkala ja Maarit Similä (toim.)
Julkaisun nimi	Ennallistettujen soiden seurannan kehittämisehdotukset – Hydrologia-LIFE-hankkeessa kertyneitä kokemuksia hoitoseurannan ja hydrologisen seurannan parantamiseksi ja kaukokartoitusseurannan perustamiseksi

Tiivistelmä

Soiden ennallistaminen on tehokas keino hidastaa luontokatoa sekä edistää valunnan säätelyä, vedenpuhdistusta ja hiilensidontaa. Ennallistamistoimintaa ollaan lisäämässä voimakkaasti ja siksi tarvitaan entistä soveltuvampia, sujuvampia ja tehokkaampia seurantamenetelmiä osoittamaan ennallistamisen vaikutukset ja vastaamaan menetelmien kehittämistarpeisiin.

Valtion luonnonsuojelualueilla soiden ennallistamisen seuranta jakautuu tekniseen hoitoseurantaan ja pitkän aikavälin vaikuttavuusseurantaan, jossa tutkitaan seurantaverkoston avulla muutoksia soiden hydrologiassa ja kasvillisuudessa. Perinteisten seurantamenetelmien lisäksi kaukokartoituksella on suuri potentiaali havainnoinnin laajentamiseen yksittäisistä pisteistä tai suppeilta alueilta koko ennallistettavan suon alalle.

Tähän raporttiin on koottu Hydrologia-LIFE-hankkeessa syntyneitä ehdotuksia ja kehityssuosituksia ennallistettujen soiden seurantaan liittyen. Hankkeessa soiden seurantaa kehitettiin keräämällä kyselyn ja työpajojen avulla ennallistamissuunnittelijoiden ja työmaiden ohjaajien kokemuksia hoitoseurannasta sekä hydrologisten mittausten ja näytteenoton toteuttamisesta. Lisäksi hankkeessa käsiteltiin ennallistettujen soiden seurantaverkostosta kertyneet 10-vuotisaineistot yli 40 kohteelta sekä analysoitiin hankkeessa ennallistetuilta kohteilta turve- ja huokosvesinäytteitä. Hankkeessa testattiin ja kehitettiin myös soiden seurantaan potentiaalisia kaukokartoitusmenetelmiä, joita koottiin kirjallisuuskatsauksen avulla. Lisäksi hankkeessa kuvattiin ja analysoitiin korkean resoluution drooniaineistoja yli 20 kohteelta.

Seurantojen kehittämisessä korostuivat ohjeistuksen päivittämisen ja jatkuvan kouluttamisen tarpeellisuus. Hoitoseurannat haluttiin jatkossakin pitää joustavana menetelmänä, mutta havainnoimisen yhdenmukaistamiselle koettiin silti tarvetta. Suoseurantaverkoston hydrologisten 10-vuotishavaintosarjojen perusteella ennallistettujen soiden vedenkorkeus saattaa olla herkempi vuosien väliselle vaihteluille kuin vastaavilla luonnontilaisilla kohteilla. Ennallistaminen aiheuttaa vedenlaatuun tilapäisen häiriön, joka tasoittuu 5–10 vuodessa ennallistamisen jälkeen. Verkoston ainutlaatuiset aineistot olisi syytä avata kaikkien tutkijoiden vapaaseen käyttöön.

Kaukokartoitus katsottiin hyväksi, maanpinnalta tehtävää seurantaa täydentäväksi työkaluksi esimerkiksi suon pintakosteuden, kasvillisuuden, kasvihuonekaasutaseiden ja turpeen ominaisuuksien seurantaan, erityisesti avoimilla soilla. Kvantitatiivisten havaintojen muodostamiseksi tarvitaan kuitenkin yleensä myös suon pinnalta kerättäviä tukiaineistoja. Drooneilla on mahdollista tuottaa melko helposti korkean resoluution aineistoja, mutta niiden systemaattisempi käyttö vaatii aktiivista panostusta tekniseen kehitystyöhön ja laadunhallintaan.

Raportin tietoja voidaan käyttää tulevassa seurantaohjeistuksen päivitystyössä ja ympäristöhallinnon paikkatietojärjestelmiä uudistettaessa. Kaukokartoituskokemukset ja kirjallisuuskatsaus tukevat soiden teknisen seurannan lisäämistä. Kokemuksia voidaan soveltaa soiden ennallistamisen seurannan järjestämiseen muuallakin kuin valtion suojelualueilla.

Avainsanat	suot, ennallistaminen, seuranta, hoitoseuranta, hydrologinen seuranta, seurannan kehittäminen, ohjeistus, Hydrologia-LIFE, kaukokartoitus, droonit		
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Författare	Lauri Ikkala och Maarit Similä (red.)
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Sammandrag

Restaurering av myrar är ett effektivt sätt att bromsa förlusten av biologisk mångfald och främja flödesreglering, vattenrening och kolbindning. Restaureringsverksamheten utökas kraftigt och därför behövs allt lämpligare, smidigare och effektivare uppföljningsmetoder för att påvisa restaureringens effekter och svara på metodernas utvecklingsbehov.

Uppföljningen av restaureringen av myrar i statens naturskyddsområden indelas i teknisk skötseluppföljning och långsiktig effektivitetsuppföljning, där man med hjälp av ett uppföljningsnätverk undersöker förändringar i myrarnas hydrologi och vegetation. Utöver de traditionella uppföljningsmetoderna har fjärranalys stor potential att utvidga observationen från enskilda punkter eller begränsade områden till hela den myr som restaureras.

I denna rapport ingår förslag och utvecklingsrekommendationer som uppkommit inom projektet Hydrologi-LIFE i anslutning till uppföljningen av restaurerade myrar. Inom projektet utvecklades uppföljningen av myrar genom att med hjälp av en enkät och workshoppar samla in erfarenheter av skötseluppföljning och genomförande av hydrologiska mätningar och provtagningar från dem som planerat restaureringarna och dem som lett arbetet på plats. I projektet behandlades dessutom material från uppföljningsnätverket för restaurerade myrar på över 40 platser under 10 års tid och det gjordes analyser av torv- och porvattenprover från de restaurerade myrar som ingick i projektet. Inom projektet testades och utvecklades också potentiella fjärranalysmetoder för uppföljning av myrar. Metoderna sammanställdes med hjälp av en litteraturöversikt. I projektet beskrevs och analyserades dessutom drönarmaterial med hög upplösning från över 20 platser.

I utvecklingen av uppföljningarna betonades behovet av uppdaterade anvisningar och kontinuerlig utbildning. Man ville fortsätta betrakta skötseluppföljningar som en flexibel metod, men upplevde ändå ett behov av att förenhetliga observationerna. Utifrån myrövervakningsnätverkets hydrologiska observationsserier som täcker 10 år kan vattenståndet i restaurerade myrar vara känsligare för variationer från år till år än i motsvarande orörda myrar. Restaureringen orsakar en tillfällig störning i vattenkvaliteten, som utjämnas inom 5–10 år efter restaureringen. Nätverkets unika material borde göras tillgängligt för alla forskare.

Fjärranalys ansågs vara ett bra verktyg som kompletterar uppföljningen på markytan, till exempel för att följa upp myrens ytfukt, vegetation, växthusgasbalans och torvens egenskaper, särskilt på öppna myrar. För att skapa kvantitativa observationer behövs dock i allmänhet också stödmaterial som samlas in från myrens yta. Drönare kan relativt enkelt producera material med hög upplösning, men för att använda dem mer systematiskt krävs aktiva satsningar på teknisk utveckling och kvalitetsledning.

Uppgifterna i rapporten kan användas i det kommande arbetet med att uppdatera uppföljningsanvisningarna och förnya miljöförvaltningens geografiska informationssystem. Erfarenheterna av fjärranalys och litteraturöversikten stöder en ökad teknisk uppföljning av myrarna. Erfarenheterna kan tillämpas på uppföljningen av restaureringen av myrar även på andra ställen än i statens skyddsområden.

Nyckelord	myrar, restaurering, uppföljning, skötseluppföljning, hydrologisk uppföljning, utveckling av uppföljning, anvisningar, Hydrologi-LIFE, fjärranalys, drönare

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Contents

Abbreviations

CI	Confidence Interval
DOC	Dissolved Organic Carbon
DSM	Digital Surface Model
DTM	Digital Terrain Model
EU	European Union
FAO	Food and Agriculture Organization
GPS	Global Positioning System
GRVI	Green Red Vegetation Index
GSD	Ground Sampling Distance
IQR	Interquartile Range
MK	*Myrtillus* spruce mire (Fin. Mustikkakorpi)
MKmu	Drained *Myrtillus* spruce peatland forest (Fin. Mustikkakorpimuuttuma)
PPK	Post-Processing Kinematic
RTK	Real-Time Kinematic
RhK	Herb-grass spruce mire (Fin. Ruoho- ja heinäkorpi)
Rhtkg	Drained herb-grass spruce peatland forest (Fin. Ruoho- ja heinäturvekangas)
RRN	Relative Radiometric Normalization
SAKTI	Protected area habitat patch information system
SASSI	Information system for planning and monitoring protected areas
SN	Tall-sedge fen (Fin. Saraneva)
SNmu	Drained tall-sedge peatland forest (Fin. Saranevamuuttuma)
SR	Tall-sedge pine fen (Fin. Sararäme)
SRmu	Drained tall-sedge pine peatland forest (Fin. Sararämemuuttuma)
SWC	Soil Water Content
SWI	Saga Wetness Index
UAS	Uncrewed Aerial System
UAV	Uncrewed Aerial Vehicle
VLOS	Visual Line Of Sight

1 Introduction

The draining of peatlands has led to biodiversity loss worldwide and undermined the ecosystem services of peatlands, such as regulation of runoff, cleaning of waters and carbon sequestration (Leifeld & Menichetti 2018, Page & Baird 2016). Peatland restoration has been proven an effective means of recovering the above-mentioned and slowing down biodiversity loss (Haapalehto et al. 2017, Laine et al. 2016).

In the international context, restoration of peatlands to their natural state is guided by such documents as the United Nations Framework Convention on Climate Change and the European Union's Habitats Directive and Biodiversity Strategy 2030 (European Union, EU 2020, Food and Agriculture Organization, FAO 2020). As restoration projects gain momentum, there is a growing need to monitor the impacts of restoration in order to verify the effectiveness of the actions taken, carry out the necessary technical repairs, and develop restoration methods (González et al. 2013, Suding 2011).

The first peatland restoration experiments in Finland were carried out manually in the 1970s and 1980s immediately after drainage operations (Aapala et al. 2013). Since the 1990s, machines have mainly been relied on in restoration work. EU LIFE funding and financing under the national METSO programme increased the surface area of restoration projects significantly.

By 2020, more than 31,000 hectares of peatlands had already been restored in Finland (Kareksela et al. 2021). Whereas restoration is a routine part of Metsähallitus Parks & Wildlife Finland’s work in nature reserves in the 2020s, increased environmental awareness in society and understanding of the degradation of peatlands as well as emissions trading have also promoted restoration activities on private lands and in state-owned multiple-use forests.

The planned EU Nature Restoration Law is likely to boost restoration activities significantly, which will increase the pressure to not only develop traditional restoration and monitoring methods but also introduce new monitoring methods suitable for large areas.

Restoration refers to an active measure that promotes the recovery of a degraded, damaged or destroyed ecosystem towards one of its previous pre-degradation states (Tolvanen 2011). Peatlands are typically restored by filling in and damming man-made ditches. The ditch lines can be cleared to make way for an excavator, and trees are also removed from areas between the ditches if necessary, as this affects transpiration on the site.

A guide on restoration methods was published in 2002 (Heikkilä et al. 2002), followed by an updated and more thorough guide in 2013, which also discusses monitoring arrangements (Aapala et al. 2013). Guidelines for monitoring restored peatlands and forests had been put between two covers as early as 2007 (Päivinen & Aapala 2007). These guidelines were already supplemented and updated in 2009 (Figure 1, Hyvärinen & Aapala 2009). Monitoring has also been developed more recently, and the guidelines are waiting for an update. The monitoring guidelines were drawn up by expert groups on restoration and ecological management (ELO, Metsä-ELO and Suo-ELO).

In the Hydrology LIFE project (LIFE16NAT/FI/000583), peatlands, streams and bird lakes were restored on 103 sites in 2017–2023. The project also developed the monitoring of peatlands by improving existing methods and exploring new technical possibilities.

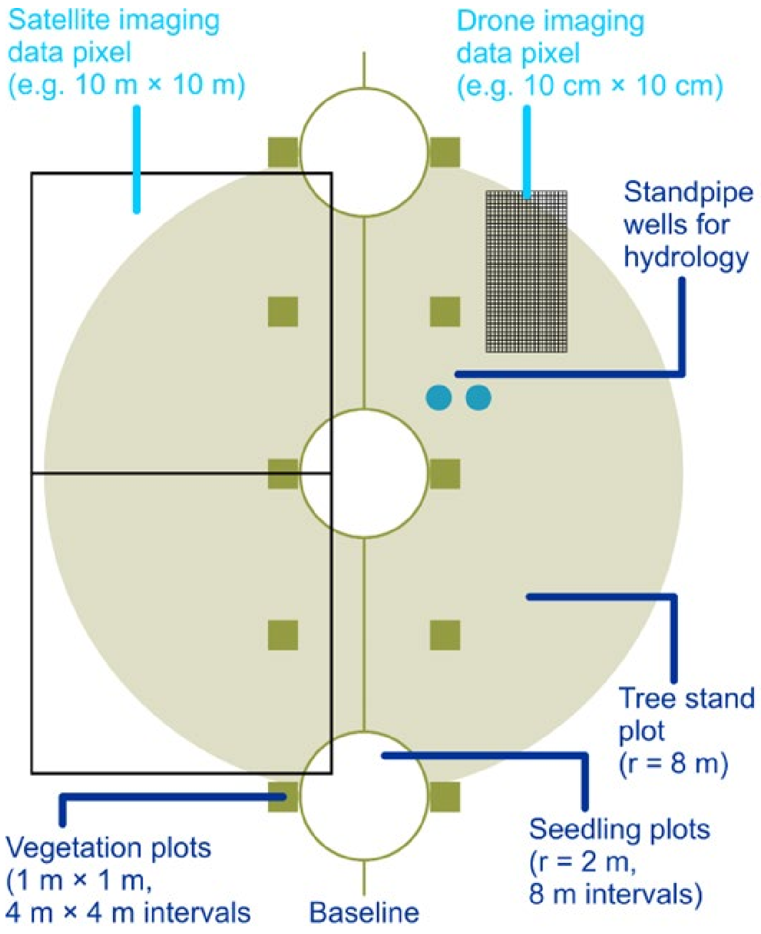

Figure 1. Traditional and developing peatland monitoring. The Figure shows typical resolutions of remote sensing data compared to traditional monitoring sites. Figure: Lauri Ikkala, Adapted from Hyvärinen & Aapala (2009).

A survey conducted in the final stage of the project asked respondents about their views of the goals of peatland monitoring. Most respondents identified assessing changes in peatland habitats caused by restoration as the key goal, which makes it possible to measure the impacts of restoration and develop restoration methods. The impacts are divided into primary impacts observed on the site and secondary ones in its surroundings (including in downstream water bod-ies).

The methods include practical monitoring based on examining the technical success of restoration visually ('general monitoring' or 'management monitoring') and long-term and systematic monitoring of peatland hydrology and the recovery of species ('impact monitoring'; Aapala et al. 2007).

In addition to areas showing good or excellent recovery, restored sites typically contain areas where the projected recovery has not got underway immediately. General monitoring makes it possible to address observed shortcomings where necessary. If there is no area clearly requiring corrective action, it may be appropriate to monitor the situation for a longer period of time before the need for repairs is reassessed. In any case, peatland restoration is a process that takes at minimum several decades.

Impact monitoring that relies on the peatland monitoring network makes it possible to draw scientific conclusions and to generalise data collected on individual sites in order to increase national understanding. The network includes some 160 peatland sites which, even by international comparison, is a significant setting for a systematic study of the impacts of restoration. The hydrological and vegetation data produced by the network have been collected since around 2013.

The first general monitoring exercise of the sites restored in the Hydrology LIFE project has been completed. Systematic monitoring of water quality and level was also conducted on some sites. The project additionally analysed ten-year time series of data from peatland monitoring network sites.

The benefits and potential of remote sensing in restoration monitoring were examined in the project through a literature review and by producing and analysing high-resolution drone data. Remote sensing has been used for monitoring peatlands for a long time, starting with historical aerial photographs. As measurement technology develops and satellite activity increases, tapping remote sensing data has become an increasingly important part of peatland monitoring (Minasny et al. 2019). Over the last decade, drones have increasingly filled the gap between manned flights and observations on the ground (Dronova et al. 2021, Jeziorska 2019).

This report describes experiences gained in Hydrology LIFE project with the aim of developing general monitoring and hydrological monitoring as well as setting up a framework for monitoring by remote sensing.

2 Methods

The data and observations on which this report is based were collected through restoration fieldwork and at workshops related to the Hydrology LIFE project, by processing the accumulated monitoring data, and by producing scientific publications.

The first general monitoring visit on peatland sites restored in the project and examined in this report usually took place one to two years after the measures.

During the project, hydrological monitoring and analyses were conducted on 46 long-term monitoring sites, of which 27 were restored peatlands and 19 were pristine control sites. A ten-year time series was completed on 43 sites in 2022. These data were analysed for a scientific publication (Päkkilä et al. 2023a). On eight sites, not only water quality and levels but also runoff are monitored. The connections between the pore water and runoff water were analyzed for a scientific publication (Päkkilä et al. 2023b). These sites mainly belong to Finland's national peatland restoration monitoring network.

In addition, peat samples were also collected on some sites restored in the project where exceptionally high and low nutrient and Dissolved Organic Carbon (DOC) concentrations had been observed in previous monitoring (6 sites, 23 study points). These samples were analysed to study the impacts of peat consistency on the quality of pore water and runoff water from the site, making it possible to identify typical peatland properties associated with an exacerbated water emission risk (Päkkilä et al. 2023c).

One of the objectives of the project was to test and develop new, cost-effective remote sensing methods with wide spatial coverage for monitoring peatland restoration to demonstrate local and regional changes caused by restoration in peatland hydrology and vegetation.

In practice, the prerequisites for setting up monitoring by remote sensing were studied by producing a literature review of remote sensing use in monitoring peatland restoration (Ikkala et al. 2023) and by describing and analysing high-resolution drone data.

A drone camera was used to capture so-called visible light data, or ordinary photographic materials, on 43 sites at 27 protected areas. The sites were mainly photographed once before and once after restoration. Most of the flights were completed to support general monitoring, and no control measurements on the ground were made. The purpose of control measurements is to calibrate the geometry of a model created based on imaging data or a parameter examined using spectral image data, such as soil surface moisture.

Control measurements were carried out for the purposes of impact evaluations, however. On the methodology development sites in Mujejärvi, Olvassuo and Salamajärvi areas (several sites photographed in each), control data were also collected, special drone equipment was operated, and various analysis methods were tested. The special equipment included multispectral and thermal cameras that capture wavelengths outside the visible spectrum and a laser scanner mounted on a drone. The digital surface model produced in the project was also used for topographical cumulative flow and wetness analysis (Ikkala et al. 2022).

Except for the literature review article, less attention was paid to data collected by satellites and manned aircraft. However, satellite datasets were presented and tested more extensively at the Peatland Monitoring Workshop organised in Jyväskylä in autumn

2022 to promote the development of existing monitoring efforts and the deployment of remote sensing. In addition, the use of these datasets has been studied more extensively in a project titled Developing monitoring methods for the status of restored peatlands conducted with special funding from the Ministry of the Environment (Räsänen et al. 2023).

In addition to the Peatland Monitoring Workshop, experiences gained in the Hydrology LIFE project were gathered at numerous workshops, the most significant ones of which were the international workshop "Remotely Sensed Indicators for Peatland Restoration Success" held in Oulu and Olvassuo in Autumn 2019 and the 'Visible Light Remote Workshop' in June 2020. The notes made at these workshops were used to produce this report.

In addition, a Peatland monitoring survey was addressed in winter 2023 at those who participated in monitoring work in the project. The 33 survey questions focused on respondents' experiences regarding the practices and development needs of monitoring (2 general questions, 8 questions about general monitoring, 11 about hydrological monitoring, and 12 about drone monitoring). In total, 18 people took part in the survey, of whom 15 responded to the questions about general monitoring, while 8 responded to the questions about hydrology and 10 to the ones about drones. The survey responses were used to formulate the proposals contained in this report.

3 Proposals for developing general monitoring

Maarit Similä, Sakari Rehell and Lauri Ikkala

3.1 General monitoring

General monitoring is carried out on all restored peatlands on Finnish state-owned land. When as concrete and detailed goals for the restoration have been defined in the planning phase as possible, the achievement of these goals can be determined by monitoring (Hyvärinen & Aapala 2009). General monitoring is intended as a light and flexible monitoring method. It is descriptive: rather than accurate measurements, it is based on visual observations. There are major differences between peatlands to be restored and those that have already been restored. This is why one of the challenges facing personnel monitoring their management is collecting sufficient data on each site to determine if the goals have been achieved.

General monitoring serves the completion of the restoration project. It makes it possible to assess the success of the restoration and helps the planner and the coordinator of the practical work understand which methods work in different peatlands and how restoration methods should be developed further. Based on general monitoring, neighbouring landowners and other stakeholders can also be informed of the observations.

The first general monitoring visit takes place once the water level has risen in a restored peatland and its flow patterns can be observed. As a rule, this visit is made less than one year, or no later than two years, after the restoration. At the time of the first general monitoring visit, the technical success of the measures is examined, and the main goal is to remedy any shortcomings as quickly as possible before they cause bigger problems. Minor repairs to dams or water flow paths can often be made on the spot if the person carrying out the general monitoring has brought a shovel or a hoe.

If it turns out that the impacts of the restoration are unpredicted or problematic in some way and they cannot be rectified during the monitoring visit, corrective actions to be taken in the near future can be planned. If the problems are not acute or a decision is made to follow up on their development, the general monitoring can be repeated in a few years.

If no problems are discovered on the first general monitoring visit, the second visit will be made about ten years after the restoration, at which time the direction of changes in the peatland is usually easy to see. On the ten-year monitoring visit, the long-term effects of restoration and the recovery of the natural processes of the peatland are examined visually. The aim is to conclude general monitoring and find that the restoration project has been ‘completed’. At this point at the latest, the status of Natura habitats is checked, and the representativeness of habitats is updated in the environmental administration's Geographic Information System (GIS).

If the ten-year general monitoring visit reveals that the site has not developed as projected, the need for any additional measures is assessed, and the necessity to do something differently on corresponding sites in the future is evaluated. Where necessary, a new site is created in the environmental administration's GIS regarding any repairs needed.

Some of the peatlands restored between 2007 and 2019 are also included in the monitoring network for restored peatlands, which follows up short-term and long-term changes in vegetation and hydrology after restoration.

In general monitoring, attention is paid to such as the following aspects (Hyvärinen & Aapala 2009):

- Sites with valuable species or habitats
- Leaking dams
- Water flows: are they diverted back to their original paths, or still tending to flow along the filled ditch
- Recovery of sites with groundwater effects
- Recovery or restoration of nutrient-rich peatlands: is water of the right type channelled to the right areas?
- Recovery of original channels and hidden streams
- Areas where the water level has risen unexpectedly high
- Areas where rewetting does not appear to be successful
- Points where there is a risk of wetting lands outside the protected area
- Other issues requiring repairs or follow-up
- Valuable species: several follow-up visits may be needed before the ten-year general monitoring visit
- Have trees developed as projected: the first general monitoring visit reveals if there is too much water in some areas and if the trees are at risk of dying, whereas unwanted seedling establishment is usually visible by the ten-year general monitoring visit
- Has the field and ground layer vegetation developed as projected (usually only visible on the ten-year general monitoring visit).

Other possibilities for using general monitoring data:

- Continuous development of planning and putting into practice restoration projects (tacit information) when the impacts of the measures are visible and the methods used have been recorded
- Communicating about the impacts of restoration on social media and conventional media
- Updates to Natura site status assessments: Impact of measures taken on Natura sites.

3.2 Current practices of general monitoring

The guideline for restoration monitoring (Hyvärinen & Aapala 2009) contains instructions and a follow-up form for general monitoring. It is the most recent written version of the guidelines, but the methodology has been developed further in different regions of Metsähallitus Parks & Wildlife Finland, and the practices of general monitoring vary. There are also variations in the practices of recording general monitoring data.

A survey conducted by the Hydrology LIFE project in early 2023 mapped the current general monitoring practices in different regions and the need for guidance and changes. Fifteen responses were received (Table 1).

In other words, different methods and accuracies are used on different sites for general monitoring. In the current situation, there are shortcomings in the recording of data. Observations made on some general monitoring visits may not be recorded anywhere.

Table 1. Work stages and current practices of general monitoring based on an online survey conducted in 2023. The columns list all options. Each person carrying out general monitoring usually only uses some of the options.

Advance preparations and visits	Fieldwork	Recording of observations and other office work
• A topographic map of the area and site maps of restoration work brought along to the visit • Was the restoration plan deviated from in the implementation phase (see site documentation) • Examination of aerial photographs • Was a field device with[1] or without an updatable habitat patch batch[2] brought along • Production and examination of an elevation model for ten-year general monitoring	Site walk • Challenging or otherwise central areas • Drone imaging • Photographs taken from the ground Notes • Coordinate points for field device • Observations marked on the map • General monitoring form filled in • Biotope data recorded using a field device	• On paper kept in a physical file • In SAKTI[2] • As a habitat patch for measures • As a site for general monitoring • Proposal for measure/site regarding repair needs • The next general monitoring visit as an SI site[3] in SASSI[4] or as a proposal for a measure in SAKTI

1 Field device used by Metsähallitus Parks & Wildlife Finland to record data.
2 The habitat data for each patch are updated in the Environmental Administration's Protected Area Habitat Patch Information System (SAKTI). For example, updated habitat patch batches saved to the field device can be used to update the data.
3 Planning and inventory need proposals saved in the GIS.
4 Information system for planning and monitoring protected areas used by the environmental administration.

3.3 Development of the general monitoring of peatlands based on a survey, workshop notes and other experiences

Respondents to the general monitoring survey would prefer a general monitoring method that is not overly restrictive. As there is a large number of restored peatlands with natural differences in various parts of the country and the impacts of drainage vary, a strictly uniform and formalistic approach was not even considered possible. Many respondents would like to see the methods used for general monitoring remain light and flexible also in the future. The benefits of general monitoring were found to be the greatest when the same person plans the restoration, coordinates the practical restoration work and carries out the monitoring.

Respondents would like to see **minimum data content and a consistent method for recording the data specified for general monitoring**. This was considered particularly important to facilitate the work of new employees who monitor peatland management.

Metsähallitus does not currently have access to field computers which could record general monitoring observations in formats other than coordinate points. Neither does the GIS have any other location for recording general monitoring observations except work sites created on general monitoring visits, in which verbal descriptions and point data can be saved as so-called auxiliary sites.

When the GIS is upgraded, harmonisation of the recording method could, for example, take the form of a mobile application developed for peatland monitoring, which would be compatible with the environmental

administration's GIS to be upgraded. General monitoring would also be well served by an application that could use open spatial datasets in the field, such as historical aerial photographs, elevation and flow models as well as drone imaging data from the site.

The date on which the next general monitoring visit needs to be made is decided on the first visit. An extra general monitoring visit is needed between the first and the ten-year visit if, for example

- A neighbouring landowner requires regular monitoring at shorter intervals.
- There is a risk that old trees will begin to die as a result of excessive rising of the water.
- The area is significant for recreational use.
- Some change that gives cause for concern is observed in new aerial photographs.
- A new method has been tried, and experience-based information on it is needed.

When operating on the boundary of a protected area, neighbouring landowners should be offered an opportunity to participate in the general monitoring visits.

The number of peatlands which need to be restored, and which will consequently require general monitoring, is large. In practice, there has only been time to make ten-year monitoring visits described in the guidelines (Hyvärinen & Aapala 2009) on rare sites. **Allocating resources to carrying out the ten-year monitoring visits would be important, however, as it is not yet possible to verify changes in vegetation or nutrient levels, or the long-term stability of water flow arrangements, on the first monitoring visit**.

Currently, tree data on individual species are not collected as part of habitat inventories, and it is unlikely that data concerning trees in restored peatlands have been updated in the GIS in recent years, apart from logging sites. An update of biotope data (at least the drainage situation and Natura habitat representativeness) is required after restoration, however.

A parameter describing hydrological recovery that could be estimated (or even measured) should also be added to the GIS, which would specifically serve general monitoring. In the best case scenario, monitoring this parameter would also serve the more general assessment of the success of restoration and general development of restoration work.

Finding sites with problems relating to their restoration in the GIS should be made easier. This should be taken into consideration when upgrading the GIS.

The usability of general monitoring in the overall evaluation of restoration success could be examined in a thesis or similar, comparing general monitoring observations with observations made based on hydrological, vegetation and remote sensing datasets.

In sites with springs and in nutrient-rich peatlands, field tests of water quality would facilitate the planning and monitoring of restoration. Portable instruments could be used to measure at least water temperature, pH and conductivity. Water that is colder than its surroundings in summer indicates groundwater discharge. Measurements of conductivity and pH can be used to assess if calcareous, alkaline or other less acidic waters are channelled as intended.

It is hoped that remote sensing methods (see Chapter 5) **will make it possible to carry out general monitoring from the office**. The status of a peatland can be assessed at least to some extent without a field visit especially based on the National Land Survey of Finland's (NLS) open data and satellite image data. However, the NLS's production schedule does not necessarily meet the monitoring needs. Similarly, the use of satellite image data is limited by the high share of cloudy days and the relatively low spatial resolution of the data, which typically ranges from several to dozens of metres.

Drones are a practical tool on wet and inaccessible sites. The planner can select the schedule of the imaging themselves, and drones often give a better overview of the area than what can be gained by looking at it from the ground level. Drones can also be used to find out which points should be visited in the field and examined more closely. Drone images can also often be used in communications. Drones were mainly used to take individual photographs and videos in the project in connection with general monitoring. More systematic drone surveys would also support general monitoring and be easy to carry out, but they would require more storage capacity and processing of the data.

3.4 Conclusions on the development of general monitoring

- Continued general monitoring will be necessary to check if restoration projects have been successful, to learn from experience and to improve restoration methods.
- The current guidelines for general monitoring contain a useful checklist of issues to be noted in general monitoring. As restoration activities develop, however, the guidelines should also be updated from time to time.
- The minimum data content of general monitoring should be specified, and the instructions for recording the data should be harmonised.
- Efforts should further be made to develop a regional spatial data parameter or similar for the environmental administration's GIS, which is to be upgraded. This parameter could be used for the systematic development of restoration work and its monitoring as well as for knowledge management.
- Good practices in using remote sensing methods should be shared between those who plan and monitor restoration projects.
- Drones should be available for anyone who wishes to use them for the general monitoring of peatlands. However, planners find that drone imaging should not be a mandatory part of general monitoring, as imaging is only possible in fairly calm weather conditions, and the schedule of the fieldwork season does not always make it possible to wait for suitable conditions.

4 Proposals for developing hydrological monitoring

Lassi Päkkilä, Lauri Ikkala, Hannu Marttila, Petra Korhonen and Maarit Similä

4.1 Hydrological monitoring

The primary objective of peatland restoration is to restore the natural hydrological conditions of the site (Hyvärinen & Aapala 2009). Hydrological changes are some of the key parameters to be monitored in peatland restoration projects as they create the preconditions for the recovery of the peatland ecology and ecosystem services. The goal-setting of restoration projects is based on a general hydrological analysis describing the original, current and targeted water flow patterns on the site (Hyvärinen & Aapala 2009).

The current hydrological monitoring methods have been collected in separate monitoring instructions (Hyvärinen & Aapala 2009). According to current monitoring practices, hydrological changes are monitored before and after restoration using (see also Figure 2):

- Automatic water level sensors for water table measurements.
- Field visits, on which peatland water samples are taken to test for concentrations, and the water level is measured manually four times a year as calibration for automatic measurements.
- Runoff monitoring on selected sites.
- Visual assessment in the general monitoring.

Long-term monitoring after restoration makes it possible to understand the longer-term impacts of restoration that manifest themselves over time.

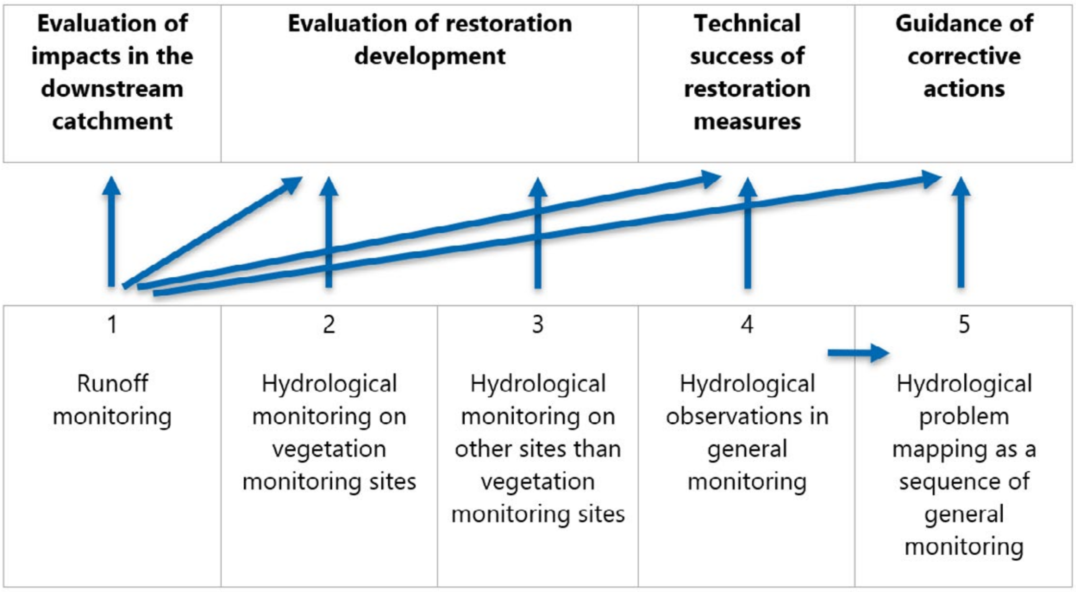

Figure 2. Elements of hydrological monitoring. In the Hydrology LIFE project, temporary hydrological observation points (3) were also placed in areas outside those selected for vegetation monitoring. Figure: Lauri Ikkala (Modified from Hyvärinen & Aapala 2009).

4.2 Current practices and development of hydrological monitoring based on survey responses, workshop notes and other experiences

Water table measurements

Water tables are measured continuously for the frost-free season using automatic sensors, or data loggers, and manually four times per field season, simultaneously with taking the water samples four times during a field season. Sensors measure the water level in a well every 30 minutes. Hydrological monitoring also covers pristine sites besides the restored sites. The sensors have been located in areas between ditches on restoration sites, which are at the greatest risk of remaining drier than their surroundings in restoration. In this project, pairs of sensor devices were also placed in the ditch running beside the area in question. This helps to interpret differences in the water table and hydrological gradients between ditch lines and the strips between them.

Standpipe wells were installed at a depth approximately between 0.5 m and 0.9 m by drilling a hole in the peatland, in which the well is immersed. While this method of attachment was found stable based on the survey responses, some movement was also observed. According to the monitoring guidelines (Hyvärinen & Aapala 2009), a wooden post is placed nearby as a marker, as this enables you to correct the height of a well that has moved during the winter. Utilising these markers has varied, and markers were not installed for all wells during the project. Based on experiences gained with ground control points for drones (see section 5.3), these posts should be securely attached to the mineral soil below the peat layer. In particular, soil frost may move a pipe or post vertically, resulting in a higher elevation in the spring. On the other hand, the growth of Sphagnum mosses and, over the long term, peat accumulation may cause a pipe to sink deeper in relation to the peatland surface.

If a well is covered with mosses, according to the instructions the original pipe should be ex-tended with another shorter length (Hyvärinen & Aapala 2009). To make it easier to find lost wells (and especially when the observations are used as control data in remote sensing), it is advisable to measure their coordinates with a Real-Time Kinematic (RTK) satellite positioning device. Based on the experiences gathered during the project, mosses that grow during the summer tend to shrink back in winter, making it easy to find the pipes again in the spring, even if they are hidden among the mosses in late summer. Elk, reindeer and foxes have additionally been known to move the pipes or chew them.

Water level sensor data are related to the peatland surface by manual measurements made on field visits. This is essential for the accuracy and success of monitoring. A blowpipe is normally used to measure the water level in the wells. The blowpipe is inserted in the well and lowered down while blowing into it. The scale on the pipe is used to read the water table depth in the well when the blowing generates a bubbling noise as the pipe end is immersed below the wa-ter. The blowpipe must be long enough to work even in dry periods. The survey findings indicate that respondents were happy with the blowpipe because this method is simple, but they also hoped to test a beeper (a device that emits a sound when it hits the water).

Relating water levels in the well to the peatland surface is not always straightforward, as the peatland surface round the well may be uneven, and the surface elevation fluctuates over the yearly cycles. In addition to the growth and shrinking back of Sphagnum mosses, the peatland surface level has been found to vary in accordance with the water content during the yearly cycle (Howie & Hebda 2018).

Due to the spatial and temporal variability of the surface, it is important to measure the vertical distance between the standpipe end and the surface level of the peatland round it each time the water table is measured manually. Based on the survey, the field personnel found that this distance was relatively clearly determined by the canopy of the Sphagnum mosses growing around the well. However, the top height must be averaged visually, which creates a subjective dimension in the measurement. The individual tops of mosses were not reported to affect the measurement. The averaging was carried out within a certain radius from the pipe (such as a palm width).

FAO (2020) has proposed the idea of a polyvinyl chloride (PVC) collar placed round the pipe to determine the level of the surrounding peatland surface. The collar should be light enough not to press down on the peatland surface but heavy enough not to float if the water rises above the ground surface. As the elevation of the peatland surface varies during the year, the collar should be placed round the pipe on each visit, rather than installed once and for all as a permanent reference height. Furthermore, if the peatland surface elevation varies in the surroundings of the pipe, the highest surface defines the settling of the collar.

Taking and sending off water samples

In addition to measuring the water table, water samples are collected on field visits for laboratory analysis. Field visits have an important role in the long-term monitoring of restoration sites: regular water quality samples taken at predetermined intervals help to understand and document the impacts of long-term changes and seasonal variations.

Water samples are usually pumped from a separate sampling well using a simple siphon pump. There is a filter sock round the pipe to prevent solid particles from entering the pipe. During a dry period, it has sometimes been necessary to take part of the sample from a sensor well. One respondent reported that, when the pump was malfunctioning, they had obtained the sample by sucking water into a hose (but not into their mouth) and then letting water into the sample bottle from the bottom of the hose. Water for the samples is pumped from the bottom of the measuring well.

Based on survey responses, water samples are collected as follows (a combination of different responses):

1) The water table is measured.
2) The sample bottles are rinsed with a small quantity of water.
3) The well is emptied by pumping the water into an additional bottle, or, if water is definitely available, out to the land (sample 1).
4) The well is given time to fill up (for 10 minutes or longer if possible).
5) The sample bottle is pumped full of water (sample 2).
6) The number of the delivered water sample and anything unclear is recorded.

If sample 2 cannot be obtained due to drought, sample 1 is delivered to the laboratory. Otherwise, sample 1 is poured away. If there was no certainty of sufficient water, one respondent said they checked the matter with a blowpipe (by blowing air down close to the water's surface). If there was not enough water to fill the bottle, the partly filled bottle was sent to the laboratory after first squeezing out excess air. When the bottle is filled partly, only some of the ordered analyses can be made.

The water sample is placed in a cooler. In warm weather, cooling cartridges are also carried around in the field in a cooler or backpack. The sample is sent to the laboratory on the same day in a cooler sealed with tape. Before the package is sent off, the cooler cartridges are replaced with fresh ones, and the package is wrapped in newspaper. Matkahuolto was mainly used for transporting the samples, but also the national postal service. Some of the respondents did not know when the parcel would be delivered, whilest others selected delivery by the next morning.

The existing sampling instructions are unclear regarding dry periods. The comparability of samples 1 and 2 may be questionable. Dry periods are also challenging for monitoring the water table, as they result in gaps in the time series.

Effect of the person collecting the sample

The results of measurements and samples are also influenced by the person taking them. Based on survey responses, the measurements were always taken by the same person on some sites, but occasionally, the person could change: for example, in the holiday period or due to fixed-term employment relationships or changes in tasks or areas in which a person works. Instead of the restoration planners, hydrological fieldwork was a task given to the rangers in one area. The person's impact on the results can be reduced by means of clear, written instructions and regular training. More objective monitoring could also be achieved by taking a photograph of the hydrological monitoring point and documenting the land surface in the pipe surroundings with photographs, for example.

Water quality measurements in the field

The survey also contained questions about hydrological parameters which the planners would like to determine while in the field. Laboratory analyses account for a significant part of the costs. Field tests could make it easier to arrange field workdays. Because samples have to be sent off without delay, sampling could not be combined with other field tasks. Optimally, on-site measurements could also be taken for a larger number of spots, rather than just collecting samples. On the other hand, replacing laboratory work with field measurements would significantly increase the amount of field work would, in particular, require investments in field measurement devices.

Not all parameters (such as nutrient and solid matter contents) that are now determined in the laboratory can be tested for in the field. Measurements of pH, electrical conductivity, temperature and ultraviolet absorption can be performed with high-quality field instruments. Measuring pH in the field would also be a good idea because this value may change during storage and it also depends on temperature. In addition, a field testing method for observing water movements was called for, e.g., to determine the speed of water movement in the surface peat layer.

4.3 Observations on hydrological data

Hydrological changes caused by restoration

Filling in the ditches and constructing dams increase the water table in the peatland and usually already reduce its fluctuations during the first months and years after restoration (Menberu et al. 2016). In the years following restoration, striving to understand the changes in water flows in the peatland is important. Do natural connections with the upstream catchment area and groundwater recover? The filling in and damming of ditches and removal of trees also cause a disturbance in the water chemistry of the surface layers of the peatland, which will moderate in the years following restoration (Menberu et al. 2017). However, the duration of this disturbance depends at least on the intensity and extent of the activities as well as the nutrient content and vegetation type of the peatland.

Water flowing from the catchment area of the peatland carries nutrients and trace elements, and water flowing through the peat leaches humic acid from it. Groundwater discharging from deep layers into the peatland may also enable certain types of plants (e.g. calciphilous species) to thrive. Plant species specialising under various conditions reflect the prevailing hydrology and water quality of the peatland. Indications of hydrological changes can be obtained by monitoring the vegetation.

In order to understand the success of restoration, observing the changes must be long-term, and the observed changes must be compared to changes on a similar pristine peatland site. This way, the variations caused by weather conditions in an individual monitoring year can be excluded. This is why it is important to ensure that a pristine control site is available when monitoring a restored site, and that the two sites are always monitored in tandem.

In hydrological monitoring of restoration, the same pristine peatlands have been used as control sites for some nearby and similar sites that have, however, been restored at different times. In these cases, the pristine control site has often only been monitored in step with the monitoring schedule of one restored site, which has meant that the other one has been left without a control site for particular years. In particular, this has been the case as the monitoring intervals grow longer five years after restoration.

On many sites, the hydrology will slowly return to its natural state, and the success of monitoring should be ensured when planning the fieldwork of future monitoring periods. In the future, the monitoring of a pristine control site should be scheduled for all years when a corresponding restoration site will be monitored.

Earlier observations on monitoring network data

Menberu et al. (2017) analysed the impacts of restoration on peatland water quality 1–5 years after restoration which was compared to the drained state before restoration (year 0). The concentrations of total phosphorus (Ptot), total nitrogen (Ntot) and dissolved organic carbon (DOC) in the pore water of drained sites were many times higher than on pristine sites. As a result of restoration, nutrient concentrations in pore water increased in the first year after restoration but were found to decrease, mainly to a level lower than in the drained situation, in the next four years.

The results are in line with the findings of previous studies (Haapalehto et al. 2014, Koskinen et al. 2017). The findings indicate, however, that undesirable changes in water quality diminished faster than reported in some previous runoff studies (Sallantaus et al. 2014). This suggests that qualitative changes in runoff water after restoration have a high likelihood due to processes in areas disturbed by the restoration work, including filled ditch lines. Consequently, it is important to examine such areas at spots on the site after restoration and, additionally, the areas that have been disturbed more should be better taken into account when planning future peatland restoration measures.

The highest pore water nutrient concentrations were observed on intermediate nutrient-rich and nutrient-poor sites where pore water is more acidic than on nutrient-rich sites. Here, the terms nutrient-poor, intermediate nutrient-rich and nutrient-rich refer to the nutrient level of the peatland, rather than directly to the peatland type. Due to the higher pH, nutrients are more bioavailable for plants on nutrient-rich sites and consequently used more efficiently. On the other hand, a greater flow of water through peat may result in the leaching of nutrients on nutrient-rich sites.

The data also indicate that in areas flooding more strongly than expected, the nutrient and DOC concentrations were significantly higher than in places where the water level was below the peatland surface. If the restored peatland type does not require high water levels, it is advisable to avoid unnecessary flooding on the site. Comparing the qualities of the pore water and runoff water, they were found to correlate with each other, and high nutrient concentrations in the pore water might also cause a higher runoff load. The results show that it is important to account for the hydrological processes typical of each peatland type in restoration measures.

However, the results suggest that restoration causes loading in water bodies, especially in the years following restoration. This is why an effort should be made to direct runoff water to areas within the restoration site or to undrained peatland areas outside the restoration site, where the nutrients and DOC carried in runoff waters can be reretained by vegetation, thereby reducing the volume of matter carried to water bodies.

When planning restoration methods, an attempt should be made to consider the primary hydrological mechanisms of the peatland. Surface flow paths in the peatland and the surrounding catchment area before and after restoration can be assessed using digital elevation models (see Chapter 5.7). This can help to determine the technical solutions that will ensure an even distribution of water. The analysis can show the intervals at which dams should be built, and how tall and long dams and surface embankments should be built. Especially if the construction of dams is a priority in restoration and ditches are not filled in, the correct size and spacing of dams are extremely important.

The filling in and damming of ditches can also be supported by planting moss (on ditch banks) or by moving peat and peatland plants to the restoration area (The Finnish Association for Nature Conservation 2023), for example. If there are steep slopes in the peatland to be restored, directing water to the entire peatland area may be challenging, and water movements from the surrounding catchment area to the restoration site should be planned carefully.

Observations on monitoring network data after 10 years

The peatland restoration monitoring network engages in hydrological monitoring on 46 sites, 27 of which were previously drained and later restored, while 19 are pristine control sites. In 2022, 43 sites in total had been monitored for at least ten years after restoration, and on eight sites, the volume and quality of runoff water had also been followed. Runoff water monitoring has been carried out on two nutrient-poor spruce mire sites as well as on three nutrient-rich and three intermediate nutrient-rich fens.

The following text includes the following abbreviations for the peatland types of the sites:

- MK, *Myrtillus* spruce mire (Fin. Mustikkakorpi)
- Mkmu, Drained *Myrtillus* spruce peatland forest (Fin. Mustikkakorpimuuttuma)
- RhK, Herb-grass spruce mire (Fin. Ruoho- ja heinäkorpi)
- Rhtkg, Drained herb-grass spruce peatland forest (Fin. Ruoho- ja heinäturvekangas)
- SN, Tall-sedge fen (Fin. Saraneva)
- Snmu, Drained tall-sedge peatland forest (Fin. Saranevamuuttuma)
- SR, Tall-sedge pine fen (Fin. Sararäme)
- Srmu, Drained tall-sedge pine peatland forest (Fin. Sararämemuuttuma)

Observations on water table datasets

The restoration measures mainly increased the water table rapidly, after which it remained close to the peatland surface, at a level similar to a natural state (Päkkilä et al.

2023a). The drier years (for example, in 2018, 2019 and 2021) were reflected in the water table data (Figures 3, 4 & 5). On an intermediate nutrient-rich restored pine mire, for instance (Suo-63, SRmu, Figure 3), the water table rose to the peatland surface level as a result of restoration, but in the seventh (2018) and 10th (2021) year after restoration, in midsummer the water table was very low, or close to its prerestoration level, and at that time significantly lower than on the controlling pristine pine mire site. On the other hand, the hydrologically dry years (2018 and 2021) are visible in the water table depth data of both restored nutrient-poor spruce mire site Suo-7 (MKmu) and its pristine reference site (Figure 4).

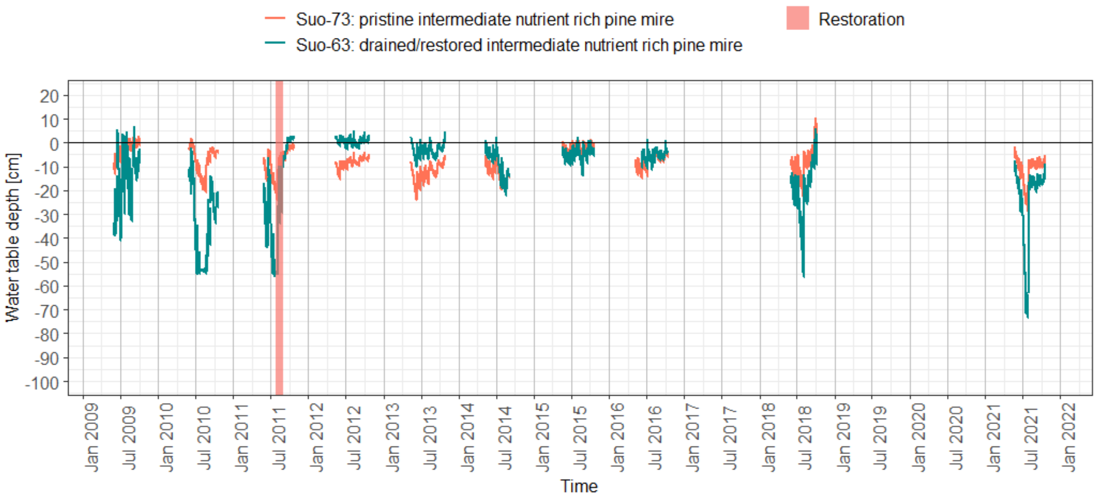

Figure 3. Water table depth on a drained and restored intermediate nutrient-rich pine mire site Suo-63 (SRmu) and its pristine reference site Suo-73 (SR) (both in Kesonsuo, Ilomantsi). 0 cm represents the level of the peatland surface, and negative water table depth values represent a water table below the peatland surface. Figure: Lassi Päkkilä.

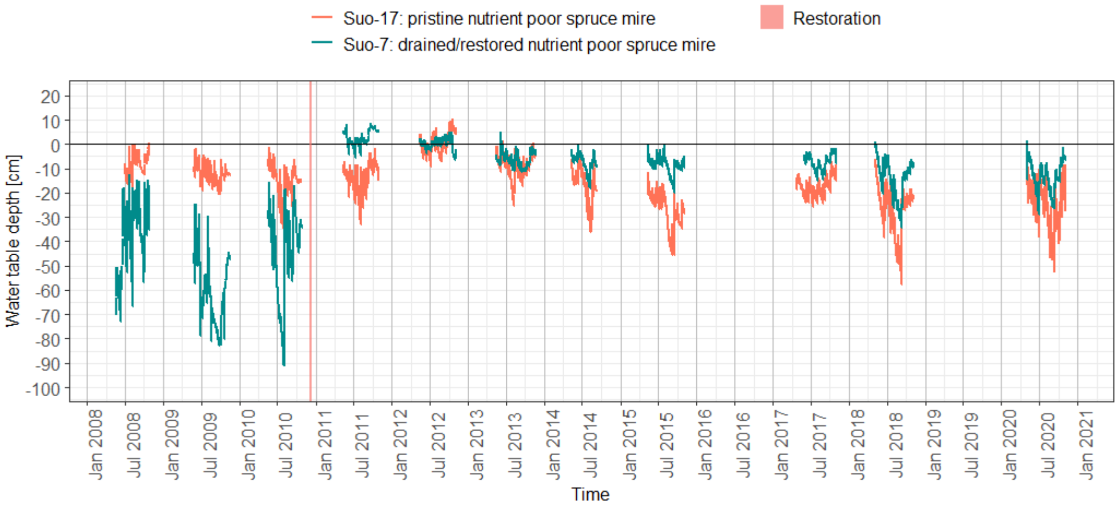

Figure 4. Water table depth on a nutrient-poor and restored spruce peatland site Suo-7 (MKmu) (Helvetinjärvi, Ruovesi) and its pristine reference site Suo-17 (MK) (Susimäki, Juupajoki). 0 cm represents the level of the peatland surface, and negative water table depth values represent a water table below the peatland surface. Figure: Lassi Päkkilä.

Figure 5 shows the water table depth data on intermediate nutrient-rich spruce mire site Suo-24 (Rhtkg) and its reference site Suo-35 (RhK). In the year following restoration, the water table was high on the restored site, but already during the second year, it had dropped lower than at the pristine reference site. In the seventh year of the restored site, the water table remained deep in the peatland, but during the 10th year, it was reasonably high, compared to previous measurement years.

The impacts of restoration can consequently also be captured with point data monitoring of water table depths, and in this case, the potential technical failure of restoration can be noted.

No monitoring was carried out on a pristine control site during the seventh and 10th years of the restored site in Figure 5. The site data emphasise the importance of systematic monitoring: if no measurements have been performed on a pristine control site, the resulting success of restoration cannot be captured.

The technical success of monitoring should also be ensured, as it is likely that the water table depth on the site has dropped below the sensor's measurement range at several measurement periods. The water quality data for site Suo-24 given as an example are also deficient in later years after restoration, as no samples could be collected due to drought.

For the corresponding water table descriptors for all monitored sites, see Appendix 1.

Observations on water quality data

The concentrations of nutrients (Ntot and Ptot) as well as dissolved organic carbon (DOC) in the peatland water fluctuated more and were mainly at a higher level than the runoff water concentrations from the same peatland (Päkkilä et al. 2023a, Figure 6). An exception to this in the datasets is the year immediately following restoration, in which particularly phosphorus concentrations in the runoff water were higher than in the peatland water.

On the runoff monitoring sites, the disturbance in phosphorus concentrations continued for 1 to 5 years after restoration, and elevated concentrations were also seen in pore water. In datasets concerning the seventh and 10th years following the restoration, however, the disturbance had already moder-

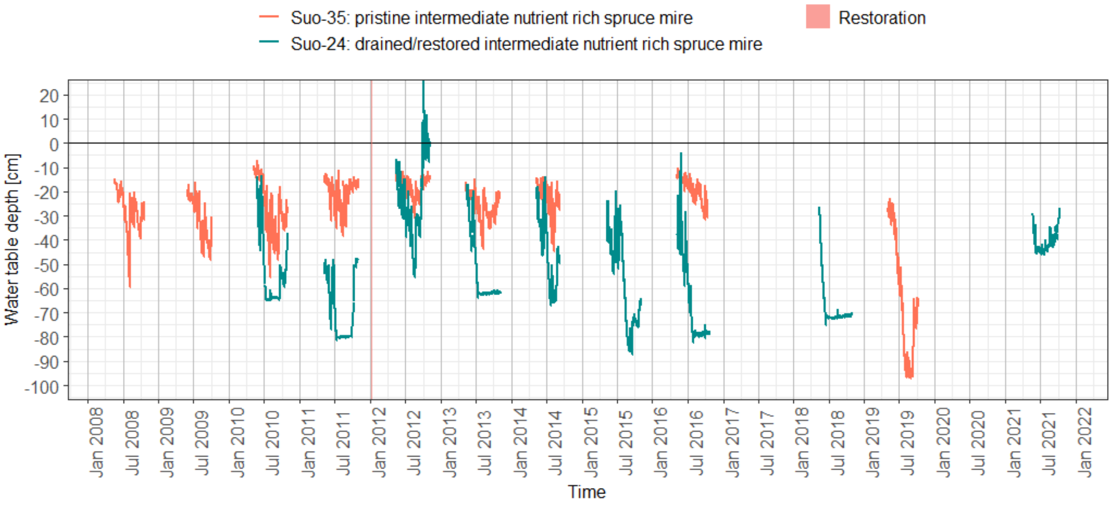

Figure 5. Water table depth on an intermediate nutrient-rich and restored spruce peatland site Suo-24 (Rhtkg) (Raasi, Yläne) and its pristine control site Suo-35 (RhK) (Taipaleensuo, Kalvola). 0 cm represents the level of the peatland surface, and negative water table depth values represent a water table below the peatland surface. Figure: Lassi Päkkilä.

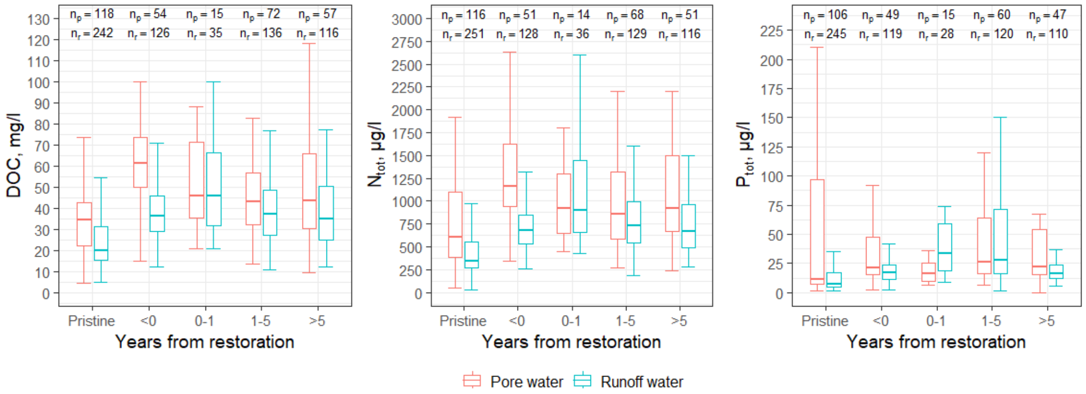

Figure 6. Concentrations of dissolved organic carbon (DOC), total dissolved nitrogen (N_{tot}) and total phosphorus (P_{tot}) in pristine peatlands as well as on drained and restored runoff water monitoring sites in pore and runoff water. Period <0 describes the drained situation, whilest periods 0–1, 1–5 and >5 describe the restored situation up to 10 years after restoration. Potential outliers have been removed from the graph (value > |1.5*IQR| (interquantile range)). Figure: Lassi Päkkilä.

ated considerably. In particular, phosphorus concentrations in runoff water were nearly equivalent to a pristine state, and the variation in concentrations was smaller than in peatland water.

It should also be noted that on pristine sites, there were major variations in the phosphorus concentrations of pore water, and in a drained state, pore and drainage water concentrations of all nutrients were higher than in pristine conditions.

The year following the restoration also stood out regarding the quality of runoff water (and its variations) for total nitrogen and DOC. However, runoff water concentrations already reverted to a lower level than pore water concentrations within one to five years after restoration, and they also continued to decrease in the seventh and 10th years. In the 10th year, the Ntot and Ptot concentrations in pore water were equivalent to a pristine state (Figures 8 and 9). Nevertheless, there were considerable variations in DOC concentrations, for example, especially in pore water in the period >5 years after restoration.

This behaviour of water quality may be explained by the dry and hot summers in 2018 and 2019, for example, on site Suo-7, where runoff monitoring was also carried out. There, the DOC and total nitrogen concentrations in peatland water were relatively high in dry summers, even though the linear regression model showed a decreasing trend in the concentrations (Figures 7 and 8). Menberu et al. (2017) found in their study that high air temperature of the month preceding the sampling was one of the most important factors explaining the high DOC concentrations in pore water on drained sites. According to their study, high soil temperature on the sampling day and the week preceding the sampling was one of the main factors explaining the high DOC concentration on restored sites.

The impact of dry years was also observed on intermediate nutrient-rich fen site Suo-105, where the total nitrogen and DOC concentrations in pore water still differed slightly from the pristine state in the 10th measurement year, even if they had already nearly reached the pristine level in the fourth and fifth years (Figures 10 & 11). On this site, the seventh and 10th years were in summers 2018 and 2021.

On the other hand, little or no disturbance was observed in phosphorus concentrations even in the year following the restoration, excluding the deviations in the third and fourth years (Figure 12). In general, the nutrient concentrations were lower in the two intermediate nutrient-rich fens than in the two nutrient-poor spruce mires.

When examining the links between pore water and run-off water quality, it was found that they do correlate but in slightly different ways, depending on the land-use type and the parameter under consideration. In particular, the DOC concentrations in runoff and pore water correlate on all sites, including the drained and restored situations.

This correlation of total nitrogen concentrations in drained peatlands is slightly less strong than on natural and restored sites, whereas the correlation of total phosphorus concentrations is weaker in poorly restored peatlands, and especially four to 10 years

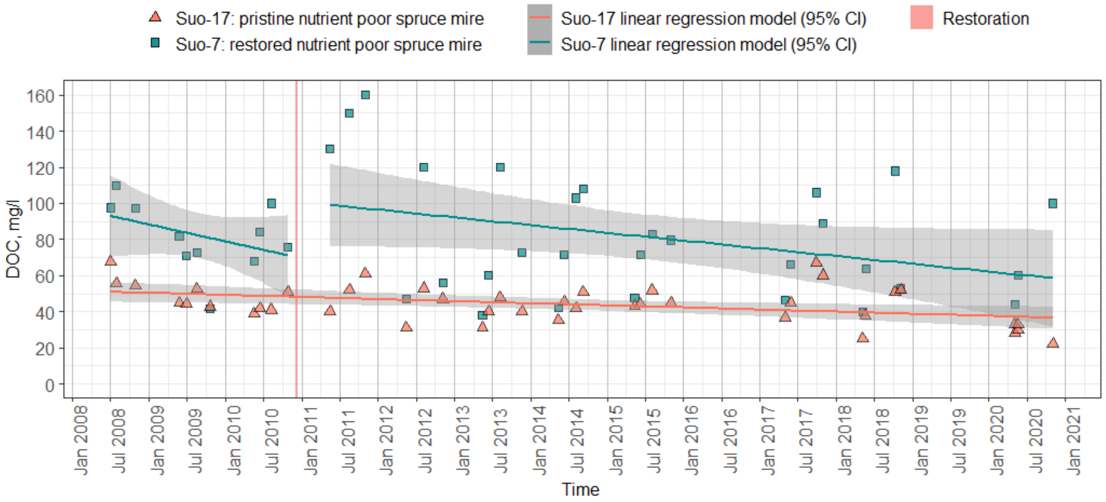

Figure 7. Concentrations of dissolved organic carbon (DOC) in pore water and linear regression models with a 95% confidence interval (CI) on a nutrient-poor drained and restored spruce mire site Suo-7 (MKmu) (Helvetinjärvi, Ruovesi) and its pristine control site Suo-17 (MK) (Susimäki, Juupajoki). Figure: Lassi Päkkilä.

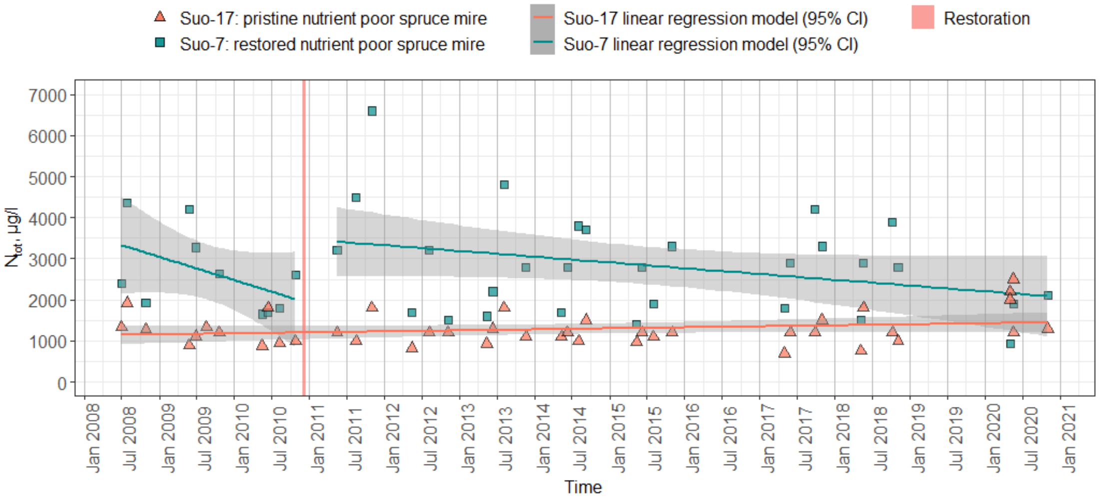

Figure 8. Concentrations of dissolved total nitrogen (N_{tot}) in pore water and linear regression models with 95% confidence interval (CI) on a nutrient-poor drained and restored spruce mire site Suo-7 (MKmu) (Helventijärvi, Ruovesi) and its pristine control site Suo-17 (MK) (Susimäki, Juupajoki). Figure: Lassi Päkkilä.

after restoration, at which time the correlation was statistically insignificant.

The loading in water bodies caused by restoration can be assessed with some level of certainty by monitoring the pore water quality alone, but an estimate of the runoff volume is also needed for this.

For the corresponding water table descriptors for all monitored sites, see Appendix 2.

Figure 9. Concentrations of dissolved total phosphorus (P_{tot}) in pore water and linear regression models with a 95% confidence interval (CI) on a nutrient-poor drained and restored spruce mire site Suo-7 (MKmu) (Helvetinjärvi, Ruovesi) and its pristine reference site Suo-17 (MK) (Susimäki, Juupajoki). Figure: Lassi Päkkilä.

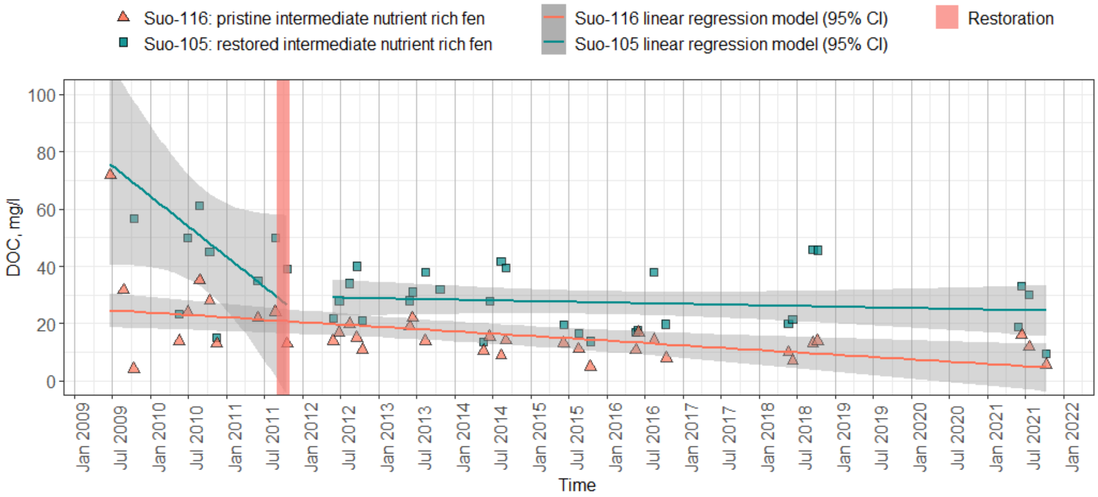

Figure 10. Concentrations of dissolved organic carbon (DOC) in pore water and linear regression models with 95% confidence interval (CI) on an intermediate nutrient-rich drained and restored fen site Suo-105 (SNmu) and its pristine control site Suo-116 (SN) (Both in Syöte, Taivalkoski). Figure: Lassi Päkkilä.

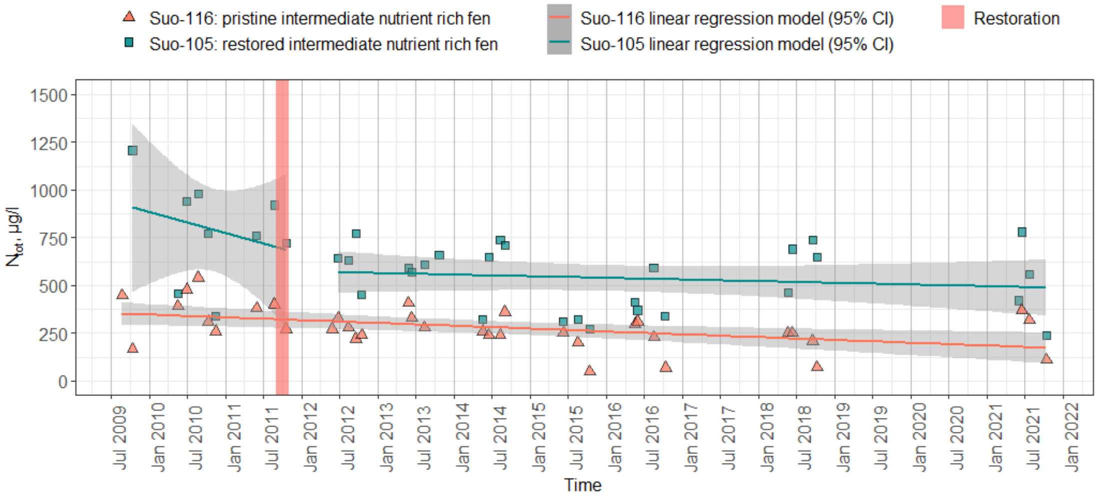

Figure 11. Concentrations of dissolved total nitrogen (N_{tot}) in pore water and linear regression models with 95% confidence interval (CI) on an intermediate nutrient-rich drained and restored fen site Suo-105 (SNmu) and its pristine control site Suo-116 (SN) (both in Syöte, Taivalkoski). Figure: Lassi Päkkilä.

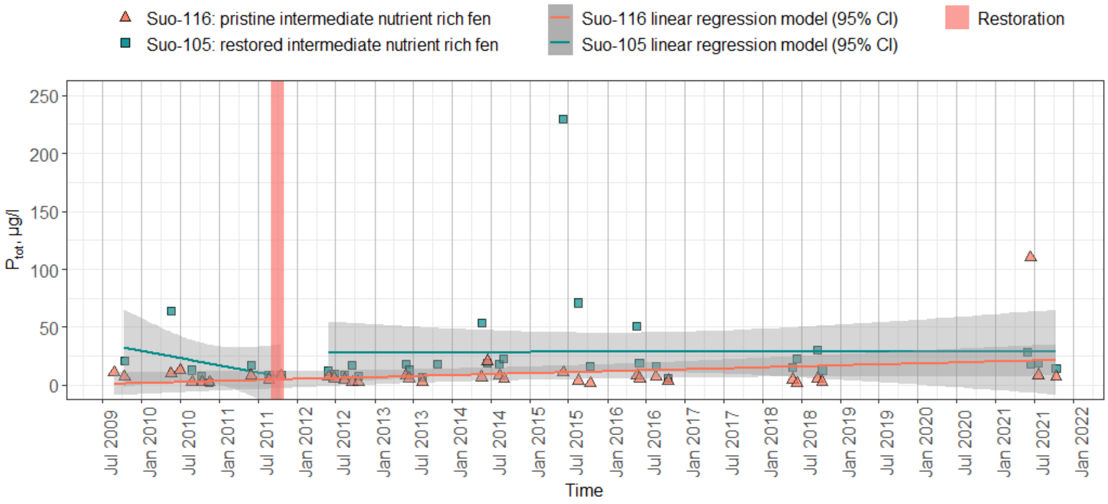

Figure 12. Concentrations of total dissolved phosphorus (P_{tot}) in pore water and linear regression models with 95% confidence interval (CI) on intermediate nutrient-rich drained and restored fen site Suo-105 (SNmu) and its pristine control site Suo-116 (SN) (both in Syöte, Taivalkoski). Figure: Lassi Päkkilä.

Observations on peat, pore water and runoff water quality connections

In the Hydrology LIFE project, also surface peat samples were collected and analysed (Päkkilä et al. 2023c). In the preliminary analysis, the average concentrations of pore water and the peat concentrations were compared, and it was found that the phosphorus concentrations of pore water and dry peat, and the nitrogen concentrations of pore water and wet peat were positively correlated.

The aluminium and iron content of peat dry matter strongly correlated with the phosphorus content of peat dry matter and the pH of pore water. The phosphorus content of the pore water also correlated with the aluminium content of the peat, but not with the iron content.

The pH of the pore water correlated with the phosphorus content of the peat.

When looking at only the restored sites or correlations between runoff water and peat quality, fewer statistically significant correlations were found. Connections were found between the quality of pore water and runoff water, and it seems that the quality of surface peat can also affect the quality of pore water, and thus the risk of nutrient leaching.

Correlation coefficients for peat, and pore and runoff water qualities can be found in Appendix 3.

4.4 Conclusions on the development of hydrolog-ical monitoring

- Whilest the instructions for hydrological monitoring provide a good basis for the work, they need to be clarified in places, especially with regard to the operating practices for dry periods.
- A larger number of water level sensors distributed spatially or at least both on ditch lines and between them, would help to understand the hydrological change better.
- The 10-year time series provides a unique tool for monitoring the long-term impacts of restoration, even by international comparison. Continued monitoring can help to investigate changes and long-term trends, also in pristine peatlands.
- Restoration actions restore peatland hydrology into a natural-like state in many respects, when water level rises, its fluctuation decreases, and the water quality disturbance caused by the activities subsides. Still, different peatlands react to restoration in different ways and hydrological recovery takes time.
- The water levels in the restored peatlands may be more sensitive to variations caused by dry periods than in pristine peatlands.
- Restoration work causes a disturbance in peatland pore water and runoff quality.
- Pore water disturbance levels out in five to 10 years depending on the nutrient under study and peatland type.
- Runoff phosphorus concentrations were in pristine-like levels in the tenth year after restoration, but DOC and nitrogen levels remained elevated.

5 Proposals for setting up monitoring by remote sensing

Lauri Ikkala, Petra Korhonen and Maarit Similä

5.1 Remote sensing in the monitoring of peatland restoration

This section is based on the manuscript for a scientific review article produced during the Hydrology LIFE project (Ikkala et al. 2023) and experiences gained during the project.

Deployment of remote sensing

Any visual observations made for the purposes of general monitoring reach no further than the walking route of the person carrying out the fieldwork. Traditional systematic monitoring methods, including hydrological measurements and vegetation quadrats, also only provide information on individual points in the terrain, and scaling them for large areas is labour-intensive and expensive. The soil, hydrological conditions, vegetation and greenhouse gas balance of a mire vary considerably in its different parts, however (Holden et al. 2011, Korrensalo et al. 2020, Page & Baird 2016, Zhang et al. 2020). Such factors as the water level, the chemical composition of the water and the development of vegetation depend on the distance to the filled ditch line after restoration (Haapalehto et al. 2017).

Remote sensing makes it possible to understand spatial variability in peatlands (Minasny et al. 2019). Remote sensing refers to making observations on Earth's surface by measuring electromagnetic radiation reflected from or emitted by it (Schmugge et al. 2002). In remote sensing, the measuring instrument, such as a camera or other sensor, is attached to a platform that flies above the site.

Remote sensing platforms include satellites, manned aeroplanes and helicopters, and unmanned drones. Aircraft have been used for examining peatlands for a century, and satellite images also go back for several decades. Over the past ten years, drones have bridged the gap between manned aerial photography and ground-level measurements.

Remote sensing data can be captured using four mutually complementary features: spectral, radiometric, spatial and temporal resolution (Adam et al. 2010, Kalacska et al. 2018, Klemas 2013, Reif & Theel 2016). The determination of these resolutions depends on the platform, flight altitude, flight path, sensor, optics and measurement frequency.

The platform, sensor and method to be selected depend on the type of features to be examined (status of disturbance and restoration), intensity (magnitude of changes) and scale (size and patterns of the restoration site) as well as the rate at which the changes are happening. Spatial resolution is determined by the objectives of the monitoring and spatial variability of the parameter to be examined (Figure 13).

Potential of sensors

Compared to staying on the ground level, the perspective can be widened merely by lifting a camera higher up. Spectral data refer to images captured using certain bands of visible light or wavelengths outside the visible spectrum.

The few broadbands of visible and near-infrared wavelengths imaged with multispectral cameras are sensitive to changes in vegetation, for example (Harris et al. 2015). In the regions of short-wave infrared and ther-

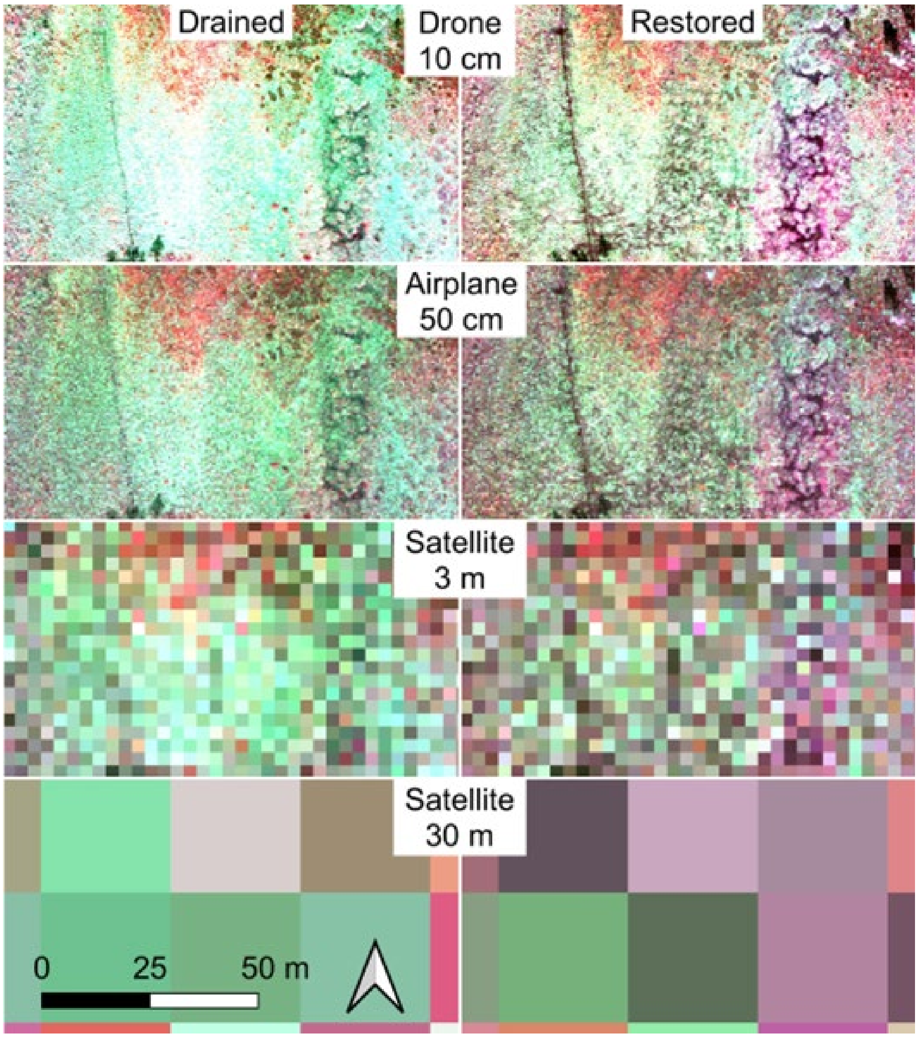

Figure 13. The effect of spatial resolution on the imaging of typical changes caused by restoration. Multispectral data on the surface of an open peatland captured by drone scanning has been presented as a false colour image. The colour tones indicate changes in the moisture and temperature of the peatland surface. The data have later been thinned to the resolutions typical of different platforms. The lower the resolution, the more of the spatial variability in the peatland surface remains hidden. Figure: Lauri Ikkala, Image data: Pasi Korpelainen.

mal infrared, surface soil moisture can also be examined (Burdun et al. 2020a, Meingast et al. 2014).

More advanced hyperspectral cameras that capture hundreds of narrowband wavelengths can compile accurate spectral resolution datasets that help identify such aspects as the composition of exposed peat (McMorrow et al. 2004) and the physiological and chemical characteristics of vegetation (Harris et al. 2015).

A three-dimensional model of the peatland and, consequently, ground surface elevations and the structure of any trees can be determined using a laser scanner or drone surveys (Korpela et al. 2020, Lovitt et al. 2017, Niemi et al. 2015). Compared to a drone camera, laser scanning usually produces more accurate digital surface models on sites where dense vegetation blocks visibility of the ground surface, as laser beams penetrate inside the vegetation through even small gaps (White et al. 2016).

A microwave radar sensor can also be used to study the properties and moisture of the peatland surface (Räsänen et al. 2022). Radars and laser scanners are referred to as active sensors because they measure the echoes of an outgoing pulse. Cameras, on the other hand, are passive sensors that use a separate radiation source.

Typically, multi-sensor methods (such as a combination of multispectral and laser scanning data) produce a higher predictive accuracy than single-sensor data (Räsänen & Virtanen 2019). In drone surveys, for example, several spectral datasets and a three-dimensional model of the site can be produced on a single flight (Beyer et al. 2019).

Remote sensing methods for monitoring restoration

In peatland restoration, remote sensing can be used to examine hydrology, vegetation, topography, peat properties and greenhouse gas emissions (Table 2).

As the earth absorbs electromagnetic radiation, determining the water table depth directly by means of remote sensing is usually not possible (Schmugge et al. 2002). Due to the capillary phenomenon, however, the water table depth can be estimated based on the surface soil moisture (Kalacska et al. 2018) and, in stable conditions, also from ground and field layer vegetation (Burdun et al. 2023). When remote sensing measurements are compared to in-situ observations, it should be remembered that remote sensing is used to observe moisture of undisturbed soil, whereas in groundwater pipes the capillary rise has been cut off.

The most common methods for determining surface soil moisture are microwave radar sensors, spectral indices and trapezoid models (Räsänen et al. 2022). Peatland hydrology can also be examined based on the number and locations of open water areas. While groundwater discharge points can also be observed based on conventional photographs, especially infrared data captured at a low altitude effectively distinguish discharge points, which can be seen on a warm day as areas that are colder than their surroundings (Isokangas et al. 2019).

For vegetation, remote sensing can be used to survey land cover categories, vegetation types, plant communities, individual plant species, functional groups of plants, or functional features of plants (Cole et al. 2014, Kalacska et al. 2015, Räsänen & Virtanen 2019, Räsänen et al. 2020). Such parameters as vegetation water content or primary production can also be determined with remote sensing methods (Lees et al. 2020).

Determination of greenhouse gas dynamics by remote sensing is usually based on either generalisation of ground surface measurements using a terrain surface classification or on assessing gas flows based on models describing primary production and ecosystem respiration (Lees et al. 2018).

Many spectral properties of peatlands and peatland vegetation have only been measured in laboratory conditions or using field spectroscopy applied to individual points, and imaging from actual airborne platforms has not yet been studied a great deal. Ball et al. (2023) were among the first to compare the spectral properties of restored and pristine peatlands using aerial photography and satellite data.

Various indices have been developed for topographic data, which can be used to study geomorphological changes (Hasan et al. 2012, Richardson et al. 2010). For example, Ikkala et al. (2022) used the topographic Saga Wetness Index (SWI) to assess the hydrological effects of blocking a ditch network (see Chapter 5.6).

Timing of remote sensing

The best method for demonstrating the impact of restoration is a before-and-after time series. The imaging should always take place at the same time of the year, however, as the season affects the comparability of the

Taulukko 2. Indicators for the success of restoration and their targeted states by category as well as traditional systematic methods for monitoring them and potential parameters based on remote sensing.

Category	Targeted indicator status	Conventional systematic monitoring methods	Potential parameters based on remote sensing
Hydrology	Increased water level, typical water level relative to the peatland surface, and recovered water level range	Groundwater wells: manual observations and water level data loggers	Open water coverage, soil moisture, vegetation that indicates wetness conditions
Hydrology	Recovered surface and groundwater flow paths and ponds	Groundwater wells: manual observations and data loggers, topographical measurements	(Micro)topography, open water coverage, soil moisture
Hydrology	Recovered groundwater discharge	Stable isotopes and other tracers in water, water temperature measurements, fibreoptic measurements, thermal cameras	Temperature differences
Vegetation	Plant communities similar to those in pristine peatlands	Vegetation compartments and transects	Vegetation cover, species and communities of species, functional groups of vegetation, vegetation structure
Vegetation	Recovered tree structure	Diameter at breast height, trunk density	Emergence of seedlings, tree growth, tree size distribution, tree dieback and death
Peat	Increased peat formation	Drillings, ground-penetrating radar, *Sphagnum* moss growth rate measurements	Depth and structure of peat
Peat	Soil subsidence stops	Marker posts, topographic measurements	(Micro)topography, peat depth
Peat	Peat degradation stops, microtopography recovers	Drillings, marker posts, topographic measurements	(Micro)topography, peat quality
Peat	Recovered greenhouse gas dynamics	Eddy covariance and chamber measurements	Indirect parameters indicating greenhouse gas dynamics, drone sampling

images due to variations in vegetation (Cole et al. 2014) and water levels (Halabisky et al. 2018).

Limited datasets (including those collected once a year) only describe individual meteorological, hydrological and phenological conditions. To account for the effects of wetter and dryer periods and the development of vegetation, a more frequent scanning interval would be required. In order to understand natural variations between years, the first step should be a calibration period several years before restoration.

There is considerable spectral and structural variation in peatland vegetation throughout the yearly cycle. A study found that peatland vegetation can be classified most successfully in spring or early summer (Cole et al. 2014). Vegetation anisotropy (reflection of light differently in different directions) has also been shown to be at its lowest in spring (Kalacska et al. 2018).

The driest period of the summer at the end of July or beginning of August in Finland provides more stable conditions than spring, a season during which the environment is undergoing rapid changes, and the time of snow melt varies from year to year. On the other hand, spring is the best time to examine the spread of water and leaks in dams. In autumn, a large volume of dead plant material may be found on the peatland surface. Imaging should be coordinated with the schedules of vegetation and hydrological monitoring, which would improve the possibilities of using field observations as reference data.

As the time series of monitoring does not go back to the situation before the peatland was drained, also conducting a simultaneous survey on a pristine control site is advisable. This makes it possible to distinguish the impacts of restoration from natural variations and technical survey errors as well as to assess if the indicator values of the restored site are approaching a natural state (Ikkala et al. 2022).

It is advisable to use the same sites for pristine control sites as for hydrological and vegetation monitoring. From the perspective of remote sensing, the restoration and control site should additionally have similar tree cover at the time of the imaging.

Quality of remote sensing datasets

The quality of datasets plays a key role when using remote sensing data. As the advantage of open data provided by the National Land Survey and satellite datasets can be regarded their professional production, whereas the responsibility for quality usually rests with the peatland researchers themselves when a drone is used to collect the data.

To make it possible to detect changes in time series, georeferencing, or relating the datasets to the correct location on the map, must be so accurate that the pixels to be compared are saved for the same locations each time the measurement is made (Räsänen & Virtanen 2019).

In addition to georeferencing, the most important quality assurance method of optical datasets is radiometric calibration (Kalacska et al. 2015). As the light source for the imaging is the sun, the nature of the light varies depending on the location of the sun and cloudiness. Satellite data often comes with ready-made corrections, whereas when producing drone data, attention must be paid to calibration.

As remote sensing is an indirect measurement method, it is important to calibrate and validate the methods and results using ground truth data collected on the peatland surface. This is particularly important for scientific purposes, but verification should also be part of practical monitoring work.

When producing datasets, it is also important to create metadata that describes the data with sufficient accuracy. In terms of interpretation and comparability, the exact date of imaging is essential.

5.2 Open datasets

The National Land Survey produces remote sensing data collected by aircraft in its aerial photography programme every three years and in its laser scanning programme every six years, covering almost all of Finland. In addition to aerial photographs, near-infrared frequencies are used to produce false colour images in which soil moisture can be distinguished better than in photographs. The laser scanning datasets are published as three-dimensional point cloud models, but ready-made derivative data calculated by the National Land Survey are easier to use: digital elevation models with shaded relief images.

The datasets are available in the National Land Survey's download service (NLS 2023a), but they can additionally be viewed in Paikkatietoikkuna interface (Figure 14, National Land Survey 2023b). They are also directly available via open interfaces as wallpapers for spatial data software (Kapsi 2023). Data can additionally be found directly in the SAKTI system, in which many planners have already used them to support the planning, implementation and monitoring of restoration projects.

A project workshop found that the shaded relief elevation model found in Maankamara service (Geology Survey of Finland 2023)

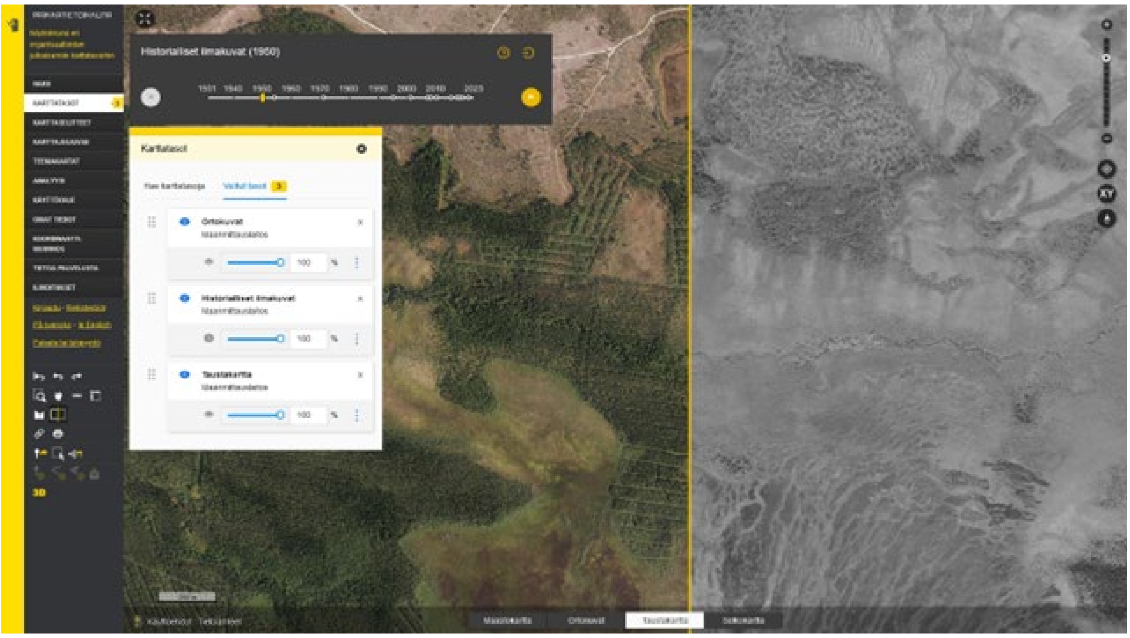

Figure 14. Screenshot from Paikkatietoikkuna (National Land Survey of Finland 2023b). The web-based user interface provides a quick way of viewing time series of historical aerial photographs.

offered a clearer presentation than the one produced by the National Land Survey.

In addition to the current raster format topographic map and vector format Topographic Database, the National Land Survey has published historical printed maps which have been georeferenced and can be viewed in the MapTiler user interface (Kutilainen 2023). Georeferenced old aerial photographs can be found in Paikkatietoikkuna, and they can be downloaded from the National Land Survey's (2023a) service.

Aerial photograph and map time series are often the easiest or only way to find out about the situation of a peatland before it was drained. Additionally, they help to understand the impacts of drainage, for example by looking at tree growth. There are also significant gaps in the time series, however, and not all old aerial photographs are available in the service.

In Paikkatietoikkuna, you can measure elevation profiles using digital land surface models. Once the second round of laser scanning in Finland has been completed, user-friendly time series tools will hopefully also be available for examining laser scanning data. In general, ready-made and tailored data sets and tools could facilitate the use of the great potential of open data for monitoring.

Satellite images enable the monitoring of long-term and seasonal variations. The longest-standing high-quality datasets go back as far as the 1980s (Landsat), and in some cases, data has even been captured on a daily basis (e.g. MODIS and PlanetScope).

Open satellite datasets often have a relatively low spatial resolution (such as Landsat 30-100 m, MODIS 250-500 m or Sentinel 10-1000 m), and they are unable to account for variability in peatland surfaces particularly well. However, many commercial satellites produce images with a resolution of less than 1 m.

One of the greatest challenges of optical satellite datasets is cloud cover, which prevents the making of observations on the ground surface. In Finland, cloud cover is present on a large share of days during the fieldwork season. While radar datasets also penetrate through cloud cover, they are more difficult to process and interpret than optical data. However, satellites offer high potential for making out the larger regional or national picture (such as for the monitoring needs of the EU Biodiversity Strategy and the Nature Restoration Law).

Experiments with satellite imaging data were limited during the project. For more extensive use of satellite images, more refined methods and ready-made products would be required, which would mainly only leave the interpretation of the data up to the planners. To interpret the images, knowledge of changes in the field is required, however, which is why centralised interpretation of the data is not the best option, either.

To enable more in-depth familiarisation, planners would have liked hands-on guidance instead of experimentation on their own. The use of satellite image datasets was studied more extensively in a project titled Developing the status monitoring of restored peatlands (Räsänen et al. 2023).

When downloading open data, it is important to remember to save the metadata that come with them to ensure traceability in the results.

5.3 Drone imaging

A drone refers to an unmanned aircraft on which various measuring instruments and sensors can be installed to collect remote sensing data (Jeziorska 2019). While the word drone is often used in English, the terms Uncrewed (formerly Unmanned) Aerial Vehicle (UAV) and Uncrewed Aerial System (UAS) are also widely used in literature. The term UAS underlines the importance of the entire control system, whereas the other names refer to the aircraft only.

In the Hydrology LIFE project, drones were initially operated in compliance with the national aviation regulations, whereas towards the end of the project period, the EU Drone Regulation (EU 2019) entered into force gradually during the transition period of 2021–2024. Under this Regulation, drone operators have an obligation to register (the register is kept by Traficom in Finland), and they must also complete a theory exam online.

Under the Open Category rules of the Regulation, the maximum flight height is 120 m above the closest point of the surface, and the operator must have constant visual contact with the drone (VLOS, Visual Line of Sight). If there is a need to deviate from the Open Category rules, the activity falls within the Specific Category, for which a separate operating licence is required.

Drones can be used to capture photographs (an individual object of interest on a restoration site, e.g. an important dam) and videos (individual ditch lines to be filled in), or to operate more extensive and systematic survey flights. For survey purposes, the operator specifies the boundaries and imaging settings for the area to be mapped, most importantly the altitude and overlap, after which the survey software calculates the required flight path and image acquisition locations, and the drone performs the survey flight under automatic control. Imaging settings can typically be saved, making it possible to repeat a corresponding scan without changes later, which improves the comparability of the monitoring data.

With large image overlap and using separate software, a three-dimensional model can be produced from the survey data. The desired final products can be then produced in raster format, including orthomosaic images and a digital surface model. In an orthomosaic image, individual aerial photographs, usually hundreds of them, are combined into a large picture in which each pixel is viewed directly from above. A digital surface model refers to an elevation model of the surfaces visible to the drone. The digital surface model can be filtered to produce a ground surface model when a sufficiently large area of the ground surface has been imaged.

Drone surveys are particularly well suited for monitoring open and semi-open peatlands. In peatlands with drainage for forestry, tree growth has usually increased at least partly, and in many regions, the share of open peatlands is also naturally small. In areas with dense tree crowns, only changes in trees can be monitored from the air.

Survey data concerning the ground surface in partially wooded areas are also less accurate than on an open site, as the ground surface points are visible in a smaller number of images (Lovitt et al. 2017). If the trees are mostly deciduous, operating in the leaf-free season may facilitate more comprehensive surveys of the ground surface. If trees are cleared along ditch lines before the ditches are filled, it may be possible to survey the ground surface along the ditches between clearing and excavator work. In this case, the changes caused by excavation work can be documented with spatial precision. Tree trunks left on the ditch lines may prevent the peatland surface from being visible in the images, however.

The ground sampling distance (GSD) and consequently also spatial resolution of the datasets depend on flight altitude and camera properties, cell resolution and lens focal length. Deliry & Avdan (2021) suggest that, in addition to these factors, the accuracy of drone survey data also depends on image overlap, number of ground control points, ground topography, weather, and the aircraft, sensor and software used. When they compared fifty drone studies, the precision was typically around 5 cm horizontally and vertically.

The positional accuracy of the data depends above all on the accuracy of georeferencing. Drone surveys with conventional Global Positioning System (GPS) devices are possible without ground control points, but their accuracy will remain in the range of metres, even if the final products have a resolution level of centimetres. Such datasets are sensitive to the doming effect (James et al. 2017). To achieve an accuracy of centimetres, the drone model must also be manufactured for surveying purposes.

With the help of ground control points (usually 15 or less is enough, Deliry & Avdan 2021), the dataset accuracy can be increased to correspond to its resolution. The control points are objects on the ground that are clearly visible from the sky (such as a white cross, plastic bucket lid, etc.) and placed at even distances in open areas around the site (not linearly) and at different elevations.

It is important that the ground control points stay in place between the time they are measured and the drone survey is carried out. Their coordinates are measured with high accuracy, usually with a Real-Time Kinematic (RTK) satellite tracking device. Ikkala et al. (2022) found that the vertical accuracy of a surface model decreases further away from the control points, especially in wooded areas.

Some of the ground control points should be excluded from the georeferencing and used as geometric checkpoints. Especially where the altitude data is used for the analyses, it is advisable to compare the data with altitudes measured in other ways. In areas with dense undergrowth, the photogrammetrically produced ground surface may also differ significantly from how it would be interpreted in the field.

On the methodology development sites of the Hydrology-LIFE project, permanent ground control points were established by pounding wooden posts through the peat layer into the mineral soil and screwing a cross of white battens onto their tops. The fixed control points made repeatable surveys possible without carrying out laborious control point measurements for each flight (Figure 15).

Thick peat layers proved to be a challenge, as the posts were either left floating on the peat surface, or they were replaced with fresh tree stumps. On the Iso Leväniemi research site, a control point rise of 72 mm on average was observed on the thick peat layer after restoration (Ikkala et al. 2022).

Figure 15. Permanent ground control points before and after restoration (different points in all images). A sharpened post (A) is pounded through the peat and secured in the mineral soil. A cross of battens or some other object easily visible in aerial photography is attached to its top. It should be fastened with two screws to prevent it from rotating. Control points on tree stumps (B) are anchored to the surface layer of the peatland, which is why they are susceptible to moving as the peatland surface changes. On the Olvassuo site in Iso Leväniemi, the swelling of the peatland and *Sphagnum* moss growth had partly covered the control points only four years after they were set up and the peatland was restored (C-D). For this reason, it is advisable to set up the permanent control points slightly above the peatland surface from the start. Photos: Lauri Ikkala.

As the peat volume and consequently the elevation of the peatland surface also changes according to the water content (Howie & Hebda 2018), the coordinates of the control points relative to the peatland surface must always be measured in connection with a survey flight. Stumps are also uncertain platforms in this respect, as tree roots do not usually reach below the groundwater level, which is why the points are only anchored to the peatland surface.

In more advanced drones, an RTK positioning device is integrated into the aircraft itself, which means that high-accuracy positioning by the drone reduces the need for ground control points. In this case, orthomosaic images can be captured with a high accuracy even without control points (Stott et al. 2020). If the data are used to create an elevation model, however, at least one ground control point (Forlani et al. 2018) or oblique photography (Nesbit et al. 2019) should be used in addition to the RTK survey.

In order to obtain an RTK correction signal, a licence for a service providing this function is required, as well as a continuous mobile data connection, which is not always available on remote peatland sites. If there is no mobile connection for the correction signal, using your own base station or Post-processing Kinematic (PPK) correction is possible.

The high accuracy of the data enables detailed technical monitoring. On the other hand, high resolution also creates obtrusive detail, such as shades of shrubs and trees as well as wind-induced swinging of objects, which do not affect traditional remote sensing with lower resolutions.

The radiometric calibration of multispectral scans can be performed using reflectance panels (Figure 16) imaged with the target. The reflectivity of the panels with different wavelengths has been determined in the laboratory, and their material produces the most diffuse (Lambertian) reflection possible. If the lighting conditions during the imaging process are variable, it is advisable to scan the panels before and after the flight and each time the battery is changed. If the lighting is highly variable, an irradiance sensor may also help to normalise the data (Beyer et al. 2019).

Figure 16. Radiometric calibration panel set. In the project, four MosaicMill 50 cm × 50 cm panels (reflectivity 2%, 9%, 23% and 46%) were mainly used to calibrate multispectral scans. The reflectivity of the panels should be in the same range as that of the site being surveyed. A single panel is usually sufficient for calibration, but with several panels, the calibration can be verified. When capturing images, the lighting of the panels should be similar to the lighting on site. In this image, plants and their shadows partly cover the panels, but even in this case, most of the panel surface area can be used for calibration. Photo: Maarit Similä.

5.4 Drones in the monitoring of peatland restoration

What can be imaged?

The usability of drones depends particularly on the objectives of the monitoring. When water levels are high, surface water movements, dam retention and possible leaks can be monitored. In addition to treeless areas, the filling of ditches can be documented. The imaging optimally supports monitoring after restoration in areas that have become extremely wet and that are difficult or impossible to access on foot. Drone images also help determine the area impacted by restoration. Based on the level of open water areas, it may be possible to indirectly assess the water depth in the peatland (Rahman et al. 2017).

The time series of one to two years achieved in the project were relatively short for the purposes of comprehensively describing the restoration of the peatland, but the initial development comes up in them quite well. The duration of the project made it possible to document the building of restoration structures, tracks of machines in the peatland surface and hydrological changes that resulted from restoration.

With longer time series, changes in vegetation could also be monitored. Drones do not enable comprehensive monitoring at the level of species, as identifying Sphagnum moss species typical of peatlands, for example, often requires microscopic examinations. Specimens of some vascular plant species can be identified and counted in the images at a certain time of the year if their characteristics are sufficiently obvious, such as bog cotton tufts (*Eriophorum vaginatum*) while the plant is flowering (see also Kalacska et al. 2013).

On the other hand, the coverage of Sphagnum mosses growing as a carpet is easier to determine in 2D orthomosaic images than the coverage of vascular plants with vertical stems. A surface model can also be used to determine the heights of shrub layers.

Drones can also be used to monitor the dieback of individual trees as the water level rises. Additionally, if the objective is to restore the natural open characteristics of the peatland, seedling establishment is an interesting feature that can typically be assessed based on the images.

Area delineations

If reference data are collected on the ground surface (incl. water level or vegetation observations for the peatland monitoring network), these locations should be included in the areas to be surveyed. On the other hand, the ten vegetation quadrants per site or individual groundwater level measurement points, which are included in the current guidelines, are as such insufficient support material for remote sensing, and preferably, for example, at least 30 of them should be found across the entire area to be mapped.

Monitoring should be targeted at areas where significant changes are expected to occur. The selection of the area also depends on the objectives of the monitoring. In the Hydrology-LIFE project, areas of approximately 15 to 20 ha were surveyed with drones; in other words, these areas covered a very small portion of the entire area restored. The survey area should be selected to represent a central part of a site with few or no trees, the peatland type to be restored, or a specific characteristic of the peatland. On the other hand, the geometry of the ditch network to be blocked and any trees on the site affect the delineation.

If the research site is small, it is advisable to expand the area to be surveyed outside it. A suitable pristine peatland that can be used as a control site may be found in the vicinity of the restoration site, or the survey may be expanded towards the catchment area upstream of the site to understand the origin of the water flowing into the peatland, or downstream to document the impacts of restoration on the water system. As image overlap affects the accuracy of the data, a safety margin of at least one line of images must always be excluded from the actual delineation of the research area.

The size of the area to be surveyed is also affected by operational constraints: flight altitude (targeted data resolution), available battery capacity (flight time) and VLOS requirement. Power consumption and battery technology as well as computing capacity are advancing rapidly, which means that the area which can be meaningfully surveyed by drones is constantly expanding. Only multirotor drones were used in the Hydrology LIFE project, whereas larger areas can be covered with fixed-wing aircraft (Dronova et al. 2021).

Aircraft

Outside the methodology development sites, small DJI Mavic Pro and Mavic 2 Pro drones were mainly used for so-called mass imaging. These devices are carried in a backpack or shoulder bag. This is handy when there are no roads leading close to the peatland. Such basic devices were found useful, as they are affordable and can be easily replaced if necessary.

More advanced devices (in this project, DJI Mavic Enterprise, Phantom and Matrice series) are needed for more challenging imaging needs when data that are more suitable for systematic analysis are required. They are typically larger and thus heavier to carry around in the field. Operating them additionally requires more in-depth familiarisation. The requirements of drone models suitable for accurate 3D surveys include an optically low-error camera, time synchronisation of positioning and exposure, and a global shutter.

In the project, special devices were only used at certain sites and always operated by the same persons. In addition, centralising guidance in the use and maintenance of basic devices to responsible users designated in each office is advisable.

Many specialist flight operations were outsourced to external service providers. Such a small number of specialised operators was regarded as the more effective option, but the final survey indicated that many operators would have been interested in using shared specialist devices if working hours were reserved for familiarisation with them.

To use the more advanced devices and methods, however, supporting data collected on the ground with an RTK positioning device is usually required in connection with the flights. These tasks were considered more labour-intensive than just operating a drone, and they require more working hours. The more advanced methods typically also require active methodology development and numerous testing visits in the field.

Imaging guidelines

Instructions for drone operation were issued in imaging guidelines produced during the project. Based on tests, operators were instructed to select 80 m as the flight altitude. While more detail could have been captured by flying at a lower altitude (Figure 17), the area covered would have been smaller. Flying above large sites up to the altitude of 120 metres permitted by the EU Regulation would have been possible without separate permits. Indeed, the flip side of achieving a sufficient resolution always is the limited extent of the area that can be surveyed. In visible light data, a resolution of approximately 3 to 5 cm was achieved with the settings used, while the resolution in multispectral data was around 5 to 10 cm and in thermal data around 10 to 20 cm.

When flying close to the maximum altitude, however, it should be kept in mind that basic drones indicate the altitude relative to the point of departure, whereas the requirement under the EU Regulation concerns the distance of drones to the ground immediately below them. In more advanced drones,

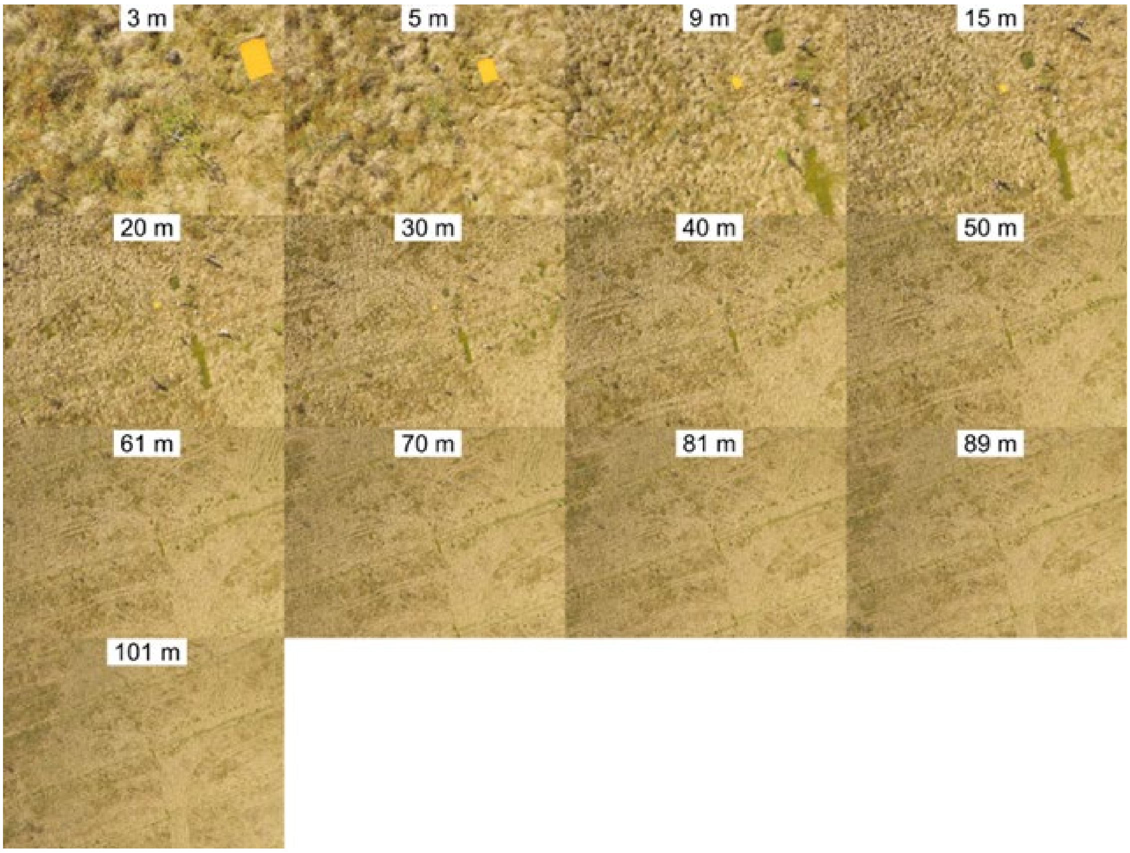

Figure 17. Impact of flight altitude on the detail shown in a single image and the area covered by the image. The size of the orange-yellow panel shown in the images is 50 x 70 cm. The area covered by an image taken at the height of three metres is approx. 3 m x 4 m, and an image taken at 101 m covers an area of approx. 130 m x 180 m. In the Hydrology LIFE project, the mapping height was mainly 80 m. Image data: Jari Ilmonen.

the flight altitude can be tied to the ground surface below the aircraft using an altitude model. This is mostly relevant in hilly environments.

Images captured close to the ground surface may replace traditional photographs taken at ground level, especially in challenging terrain and on extensive sites. Individual close-ups of certain points of the peatland surface that can be retrieved automatically could increase understanding of the changes without a survey flight, which is a slower method that requires processing.

While the positioning accuracy of a few metres achieved with basic drones limits the safe approach to the ground surface on tree-covered sites, it also restricts the height at which the images are captured when flown low, ensuring that the location from which the peatland surface is imaged is sufficiently consistent each time. This problem is solved by the accurate positioning offered by RTK drones. The most common commercial drones also contain collision prevention sensors.

The overlap between neighbouring images is set before the flight. The larger the overlap, the higher the number of images that show a certain point in the terrain, and the more accurate the data obtained. The overlap is divided into frontal overlap parallel with the flight path, and side overlap between these paths.

The overlaps (frontal 90% and side 75%) were kept large to ensure a high data quality despite shading caused by vegetation. In practice, the frontal overlap is only limited by the time it takes before the camera is ready for the next exposure. The side overlap, on the other hand, affects the spacing of the flight paths, in other words, the total number of paths and consequently the length of the flight, time use and battery consumption.

Automatic imaging settings were typically used in the project. While adjusting white balance, light sensitivity and exposure compensation would have produced images with more consistent quality, this would have required more thorough familiarisation of the operators. The visible light images were captured in JPG format. A raw image format would have allowed for more adjustment in the images while also significantly increasing the file size. Spectral images were saved in TIF of R-JPEG formats.

After each flight, the operators filled in the following data in a flight log kept in table format: site name, protection area, site description, date, times, operator, aircraft and devices used, type of operation (testing, survey, free flight), weather conditions, accumulated image count, overlaps and flight altitude used, and freely worded notes. The files were transferred to the processor over the network. Several different cloud services were tested during the project. The Sharepoint workspace used in the early stages of the project, in particular, did not work with larger datasets, and files were often lost in transit. Transferring large datasets by post on a memory card finally proved the most successful solution.

Processing of datasets

Several competing software packages and online services are available for processing survey data. The software used and the parameter settings made in it affect the results. Online services are usually intended for a wider range of users, which means that orthomosaic images and elevation models can be easily produced but the adjustable parameter settings are limited. The processing of the data in the project was mainly carried out centrally using Agisoft Metashape software on a fixed workstation at the University of Oulu.

During the processing, a three-dimensional point cloud model was generated with the remote sensing data, which was further used to produce an orthomosaic image, an elevation model and a vegetation index. The Green Red Vegetation Index (GRVI) was used to describe plant biomass and phenology (Zhang et al. 2019):

$$GRVI = \frac{G - R}{G + R}$$

in which

G = reflectance value of the green channel
R = reflectance value of the red channel

The index images were mainly found useful but difficult to interpret without familiarisation. Automatic colour calibration and white balance adjustment were performed on the orthomosaic images, however with limited impact on the end products. More efficient tone calibration would be called for to make comparisons between images taken at different times less dependent on the lighting conditions of the day.

The end products were saved as georeferenced TIF and JPG files. In orthomosaic images, uncompressed TIF images were of better quality than JPG images, but also significantly larger. The presentation format of JPG elevation models (Metashape colour scale and shaded relief) was determined by the software used for the processing, whereas TIF models were left in numerical float format to give users free hands for their analyses and visualisations.

The processing of data takes time. The fastest way to use the data immediately in the field is to check the situation at points of interest in the terrain in individual images or merely the live view of the camera. Planners find that in the planning phase, the results should be available at the latest in the autumn when the importation of the plans into the GIS begins. Some planners felt that the results should be obtained as quickly as possible, for example in two weeks.

Regarding technical monitoring, having access to the datasets before the next year's activities are planned would be ideal (August of the previous year) in case the restoration work needs to be repaired. In the context of long-term impact monitoring, there was less urgency in obtaining the results.

In the future, operators might be able to upload the survey images to the network from the field, data connections permitting, which would mean that the data would have been processed in the cloud service by the time the planner returns to the office. A precondition for this is having a licence and the requisite user rights to an appropriate cloud service.

Experiences of deployment

Project actors expected the drone data to provide images and elevation models for planning, understanding and observing the site, and especially compartment-level data on changes for monitoring restoration. Experience has shown that while drone imaging is no substitute for field observations, it offers a new perspective on examining peatlands.

Operators mainly found the new technology useful and easy to learn, whereas there were also some challenges. Some were put off by the thought of learning to use the new technology, while others said they were too busy or found the threshold for in-depth familiarisation too high. However, it was reported that bold experimentation got operators off to a good start.

Experience in using both freely captured images and videos and systematic survey data was gained in the project. Survey flights were found to be the easiest technique, as once the area is delimited and configurations made, the drone flies the required path independently.

In addition to monitoring, drone images were also used for planning and carrying out restoration work. Drones were found useful for getting a grasp of even relatively large areas quickly and being able to examine the site in the office with no time pressure. In the planning phase, an overview of the drainage situation in the area can be obtained, and challenging areas for restoration can be identified. Drones were also regarded as a good tool for communication purposes.

The challenges associated with drone operation and technology (Table 3) were felt to increase the uncertainty associated with the work. Even if the equipment were tested at the office in advance, technical problems may still prevent the collection of data in the field.

The highest number of technical problems was experienced when controlling the drone with a separate phone or tablet. The drone manufacturer's remote control device with an integrated display was more reliable than a separate device. However, the technical usability of the devices was considered good when operators managed to make them work.

Drone imaging was often the last task on a field trip. At best, the images could be taken while doing other field work without major additional difficulty, but technical problems and poor weather delayed the work or required an additional trip to the site, which was liable to upset the general work arrangements.

Uncontrollable weather and lighting conditions pose a significant challenge to drone imaging. When the schedule is tight, the day of the field trip cannot be selected based on the weather. The most typical obstacle to drone operation is rain. The drones used in the project were not waterproof, and even if they had been, rain would have significantly deteriorated the image quality.

The lighting conditions were usually determined at random based on when drone operation was permitted by other work. Optimal lighting conditions would be bright weather, however, diffused by clouds (no shadows of vegetation) with stable conditions (no change during imaging).

Table 3. Drone operators' and restoration planners' observations of operational challenges, technical challenges and drone monitoring data.

Operational challenges	Technical challenges	Observations on drone data
• Variable or otherwise challenging lighting conditions (sensitive to overexposure or motion blur) • Shared user IDs of devices (Apple, Google) and applications (DJI) are difficult to use or not permitted • Caring for equipment in shared use • Maintaining the correct battery level during winter • Time must be reserved for testing the equipment before fieldwork • Datasets are cumbersome to save, transfer and process • Data management is challenging in Metsähallitus organisation • Requirement of filing a flight plan, which is experienced as tricky, in the ADIZ zone on the eastern border or elsewhere with airspace reservations	• Short battery life of drones and remote controls, which can be shortened further by a need to investigate technical problems in the field • Communication problems between the drone and remote control • Jamming of apps and mobile devices used as remote controls • Device updates in the field • GPS positioning problems • Excessive calibration need of the compass • Losing manoeuvrability during flight • Interruptions in drone control, drone going out of control or falling	• You can get a better grasp of the site than by field observations • Images captured before restoration are useful for quantifying the soil available for filling ditches and assessing ditch depths • The blocking of ditch lines is easily visible in images taken after restoration, and the wetting of flark surfaces can be seen in some images • The images revealed previously unknown objects, including ditches and springs • There were also differences between the drone data and field observations, for instance in the need to clear ditch lines • Machine operator's ditch-filling technique can be documented for training purposes • With changing seasons, different things can be seen more clearly (such as deciduous trees in images taken in the autumn) • In addition to surveys, capturing drone images freely is also informative

In low light conditions, the shutter speeds become longer, and the images can easily be blurred by drone movements (flying or swinging). This risk is also increased by high winds, which may undermine the controllability of the drone.

In fresh winds, the drones flew downwind a bit too fast, whereas flying against the wind was slow, and sometimes the system even urged for the flight to be interrupted. High wind speeds of more than 10 to 15 m/s prevent drone operation altogether, even if the wind resistance of drones has improved greatly in recent years. The newer and larger drones are more stable in windy conditions.

Use of results

Orthomosaic images and elevation models were mainly used for visual comparisons. The positioning data contained in orthorectified end products enable quick comparisons between a certain point in the terrain on different dates. However, planners encountered some challenges in exporting data to the spatial data software or visualising them in it without support.

Various systematic analyses (incl. terrain surface classifications) can also be carried out on the final products, but this task was seen as too demanding for the operators. It was felt that instead, one person with expertise in this task should perform the analyses centrally.

Many key issues for restoration were observed in the images and surface models, including the blocking of ditch lines and spreading of water to the peatland (Table 3). It was also felt that wetness could be assessed more objectively in the images than based on field observations. On the other hand, changes in wetness (or vegetation indicating it) were not always found easy to detect, or at least the images first require 'visual calibration' in the field.

The general usefulness of drone data was also questioned, however, as the National Land Survey produces high-quality remote sensing datasets in its aerial photography and laser scanning programmes. These open datasets should consequently be used more systematically in the monitoring of peatlands.

Above all, the advantages of drone operation compared to open data use include flexibility, which makes it possible to schedule the monitoring to suit the specific needs of the project, and a higher resolution when the half-a-metre or so of the open datasets (or two metres or so in older laser scanning data) is not sufficient. Ditches that were not visible in the National Land Survey's laser scanning data were also found on sites. On wooded sites, however, laser scanning is a more accurate way of producing a digital surface model than a drone survey.

The overwhelming advantage of open data is their coverage. The limited battery capacity of drones, the size of the data (high resolution) and the maximum flight altitude limit the surface area that can be covered. Battery technology is developing rapidly, however. Whereas in the initial phase of the project, one battery gave around 20 minutes of flight time, the flight time promised for the new generation of drones of the same size towards the end of the project was 45 minutes.

Planners would like to see drone data combined with other datasets, such as hydrological data, in order to compare similar hydrological situations based on the images or to obtain support for hydrological changes in the corresponding period.

5.5 Results: Visible light imaging

In visible light imaging, the sites were surveyed before and after restoration using photographic cameras integrated into drones.

In total, visible light data were captured on 43 sites in 27 protected areas (Appendix 4). The sites to be imaged were usually surveyed one year before and one to two years after the restoration. Orthomosaic images and digital surface models (DSMs) produced by imaging were used in these examinations.

The clearest changes visible in the images are those relating to the filling and damming of ditches: where did the material used for filling ditches come from, where had ditches not been filled, and where dams, surface embankments or feeder ditches had been placed (Figure 18). This way, even a person with no previous familiarity with the site can get an idea of the restoration measures carried out in the peatland and the placement of structures.

Trees, if they have not already been cleared, make it difficult to detect ditches in the images captured before restoration. After restoration, the ditch lines are usually open. In orthomosaic images and surface models, such aspects as the blocking of ditches can be assessed. In particular, a digital surface model can be useful for assessing ditch depths (Figure 19). In the before-and-after time series, such details as the locations of the deepest ditches and the success in blocking them can be examined. As photomapping only captures the visible surface, there may be water flows under the vegetation that do not come up in the images.

In terms of the objectives of restoration, it is essential to see if water has returned to areas where it naturally belongs. In orthomosaic images, it may be possible to see if water has spread outside the filled ditch lines, or between the ditches, as a result of ditch blocking. The images also make it possible to interpret if the restoration project has succeeded in preventing water flows in ditches that have not been filled in for such reasons as excessively soft ground.

In the best case scenario, the data create an overall picture: how the level of wetting varies in different parts of the peatland, and if restoration has also had an impact on the wetting of the undrained section. Looking at the big picture may help locate individual ditches or areas in the peatland that may need to be checked in the field.

In addition to wetting, natural water flow patterns can be located in the orthomosaic image, and changes to them caused by restoration can be evaluated (Figure 20. If the flow pattern is already visible before restoration, the reverting of waters to it as a result of restoration can be examined. The natural flow patterns are not always visible, however, especially before restoration. In this case, it may be useful to compare the situation after restoration to historical aerial photographs or restoration plans.

From the viewpoint of hydrological recovery, changes in flark surfaces may also be interesting. In time series, such aspects as the wetting of flark surfaces that have dried out as a result of drainage or the extent of open water surfaces can be observed.

Problem areas may also be located, and the need for any further measures may be assessed. Based on the datasets, collapses in dams and dam retention can be examined (Figure 21). Images taken at the highest water levels are the best way to observe the spread of water. This is when the pressure on dams is also at its greatest.

The trunks of felled trees were clearly visible in the images, as was the yellowing of conifer needles after the wetting of the peatland. The images also document the digger operator’s excavation technique, and they can later be used to instruct new operators in excavation techniques for restoration.

The greatest benefit from visible light time series can be obtained when they are examined together with the restoration plan, which makes it possible to pay special attention to the risk areas identified at the planning stage.

The weather and lighting conditions have a significant impact on the radiometric quality of survey data. While there are no established methods for the radiometric calibration of visible light images, the application of the Relative Radiometric Normalization (RRN) method, for example, has been successful in improving the visual quality of visible light data (Pastucha et al. 2022).

All observations based on the datasets (flooding over the dam, rising water levels) could not be fully ascertained by looking at the images, however, and a field visit was needed to verify them. Old ditches, in particular, could appear to be overgrown in the images, even if there still were significant water flows among the Sphagnum mosses or under dense shrubs. On the other hand, examinations of drone data highlighted problem areas that were missed on a field visit. The combination of shaded relief images and aerial photographs brought up very old channels and collapsed flark surfaces.

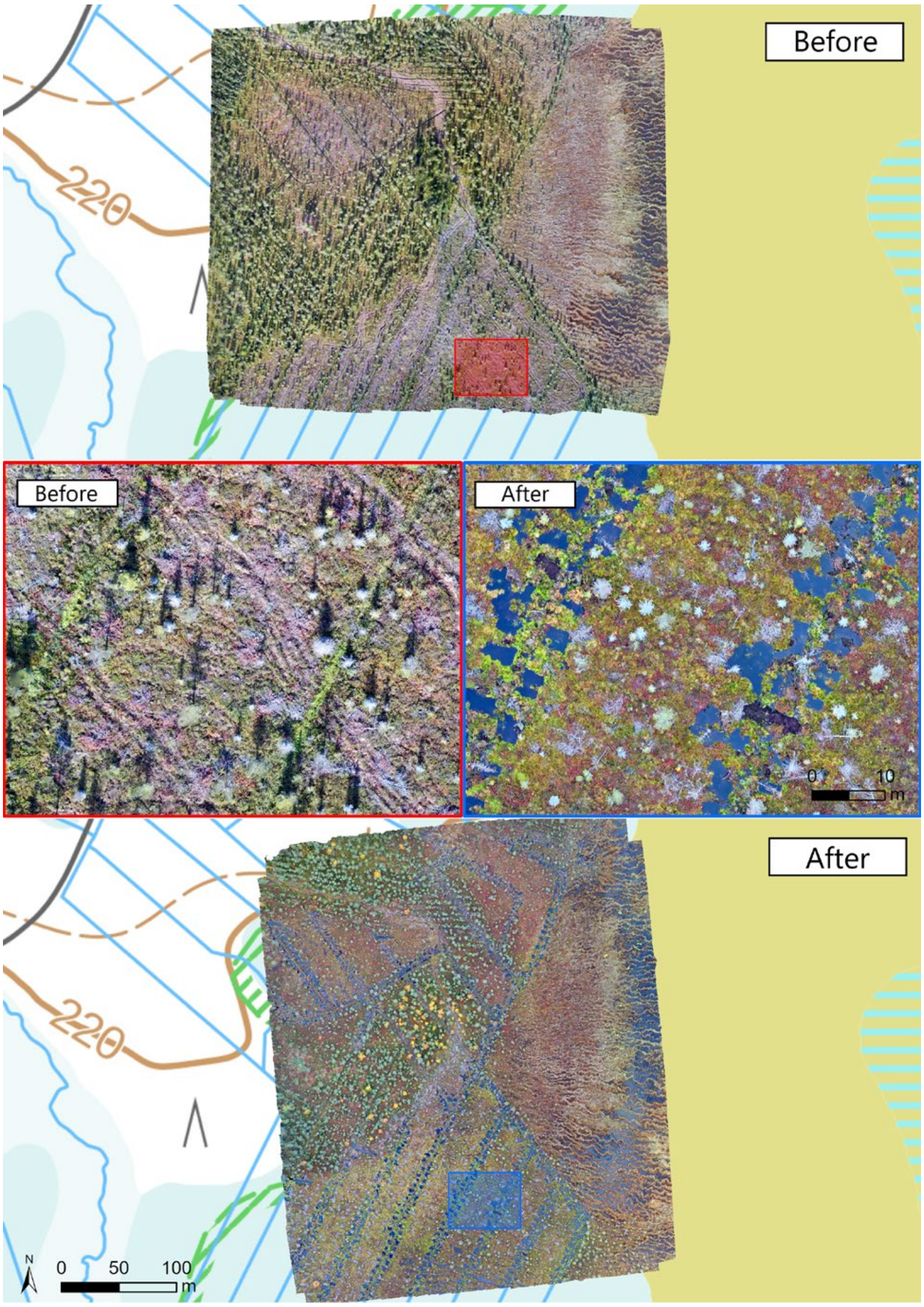

Figure 18. Haikara-aapa (Haikara-aapa-Vitsikkoaapa peatland reserve). After restoration, peat dams can be clearly seen in drone images. The effect of lighting conditions is also visible in this pair of images. Automatic colour tone balancing has not succeeded in producing images with the same brightness. Figure: Petra Korhonen, Image data: Mika Puustinen, Background map: National Land Survey of Finland.

Figure 19. Mykränsuo (Kesonsuo nature reserve). Deep ditch in the northern part of the site before and after restoration. Figure: Petra Korhonen, Image data: Maarit Similä, Background map: National Land Survey of Finland.

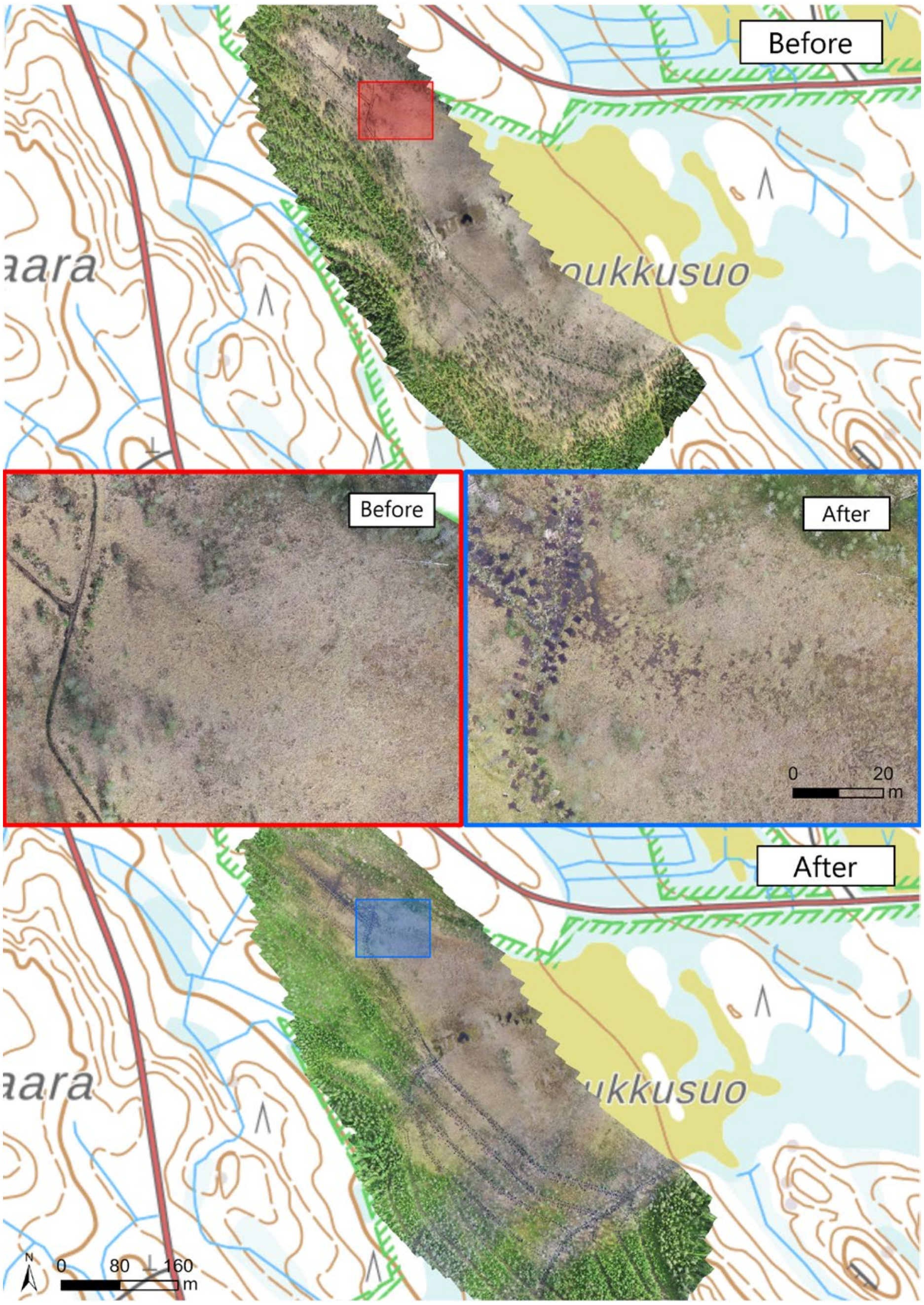

Figure 20. Loukkusuo (Jonkerinsalo nature reserve). One of the main water flow paths could be traced vaguely in the orthomosaic image before restoration. As a result of restoration, a large volume of water returned to its original path, and the flow path can also be seen more clearly in the orthomosaic image. Figure: Petra Korhonen, Image data: Maarit Similä, Background map: National Land Survey of Finland.

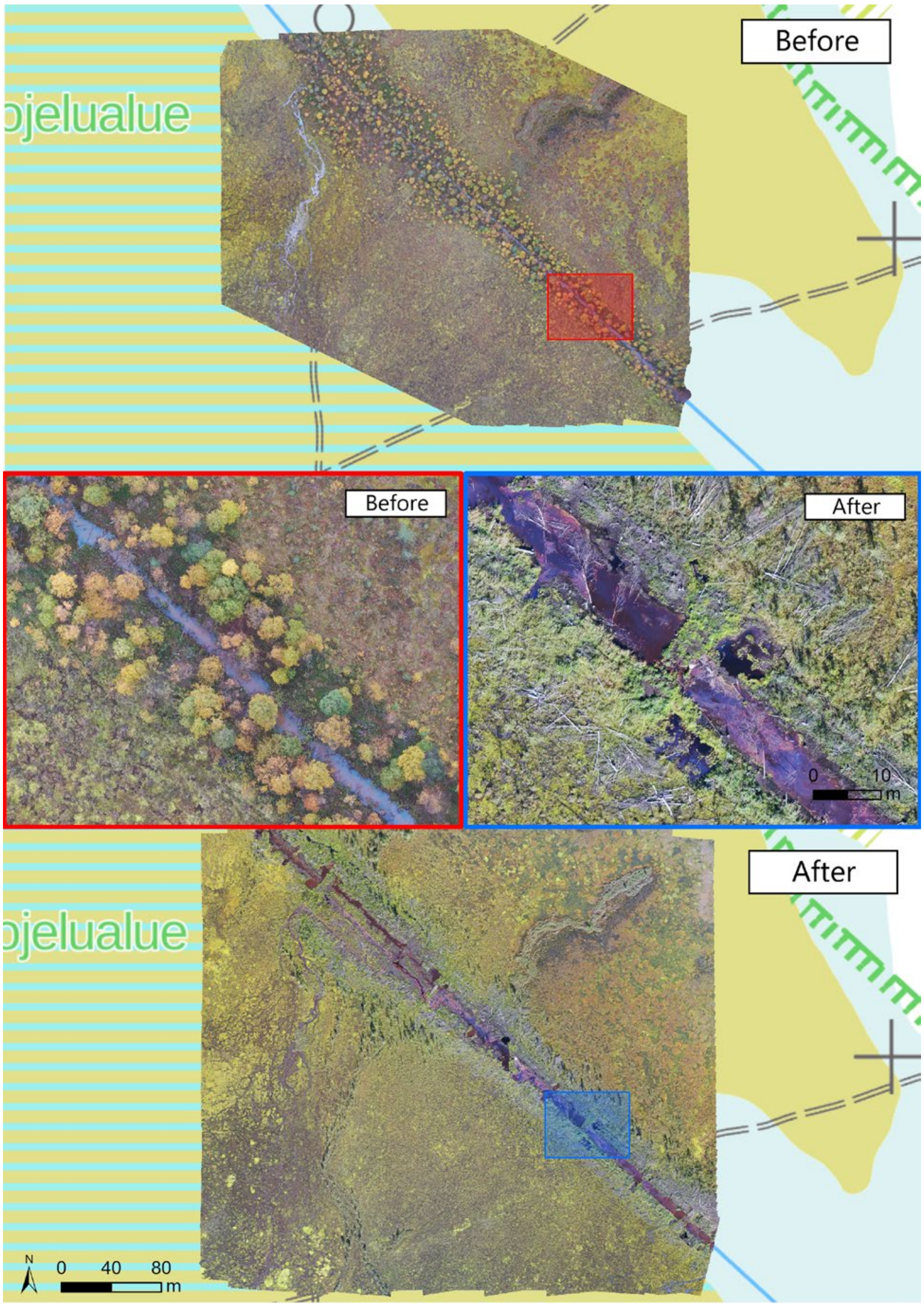

Figure 21. Kemihaaransuo peatlands (Kilpiaava peatland reserve). The peatland was restored by damming a large canal. Some dams allow water to flow over them. However, the water is level with the surrounding peatland surface, and overflows were not found to hinder the recovery of the peatland. The places where the water flows over the dam will be an object of close monitoring in the years to come. Figure: Petra Korhonen, Image data: Mika Puustinen, Background map: National Land Survey of Finland.

5.6 Results: Multispectral and thermal imaging

Multispectral and thermal imaging was performed on many sites in the project, focusing on the methodology development sites (Appendix 4). Reflectance panels for radiometric calibration were acquired during the project, but they were not available for some of the initial imaging visits of the project. No irradiance sensor was used, which is why changes in lighting conditions during the survey could not be taken into account.

A radiometric camera was used for thermal imaging to provide temperature data for each pixel in the original images. However, these data did not survive the processing of the survey datasets. While no systematic analyses of the data were carried out during the project, visual comparisons showed their potential for peatland monitoring.

Before-and-after time series were produced on Iso Leväniemi in Olvassuo and Loukkusuo in Mujejärvi (Jonkerinsalo nature reserve). Only minor changes were seen in images of Loukkusuo peatland, possibly because they were taken only a few weeks after restoration, and also because the impact of groundwater is less significant in Loukkusuo peatland. Whereas in Olvassuo, changes caused by restoration came up in the data (Figure 22).

Groundwater has a strong impact on Iso Leväniemi, which originally was an open rich fen on the sloping edge of Leväsuo aapa mire complex. The selected research site was near an undrained area that had stayed fairly open and that had dried especially along ditches along the edges. The terminal moraines of Kälväsvaara are found to the north of the site, and groundwater stored in it discharges into ditches and seepage areas. The images were taken on warm August days with an interval of almost exactly one year, around two months before and ten months after restoration.

The false colour images mainly show the same things as those seen in the photographs, except that the colour tones highlight changes in moisture. Seepage areas were already visible in the middle of the open area while the peatland still had ditches (Figure 22D). However, the blocking of the drain along the northern edge of the site clearly increased the volume of groundwater discharged through these seepage areas, which can be seen as darker tones in the photograph and reddish tones in the false colour image.

The change in seepage areas was the most obvious in the thermal images, however (Figure 22D). The seepage areas could not be seen at all in the thermal image taken before restoration; this indicates very slow discharge and flow of groundwater along the surface. Based on the thermal image taken after restoration, blocking the catchwater drain clearly increased the volume of cold groundwater on the peatland surface. It appears that groundwater discharges and flows along natural-looking seepage area patterns rather than as a continuous trickle. Similar seepage area patterns appeared throughout the open area of the research site (outside the thermal images in Figure 22).

Based on all the images (Figure 22D), it additionally appears that to the west of the seepage area network that was also visible before the drains were blocked, new similar seepage areas that could not be seen in the images captured before restoration are emerging.

The thermal images taken before restoration (Figure 22A–C) also show groundwater that is colder than its surroundings flowing along ditch lines as a dark tone. The thermal image helps to detect the exact locations of overgrown ditch bottoms more accurately than the photograph (Figure XB).

The photograph taken of the same location after restoration (Figure 22B) shows that the filling of ditches has created open water surfaces perpendicular to their direction. The

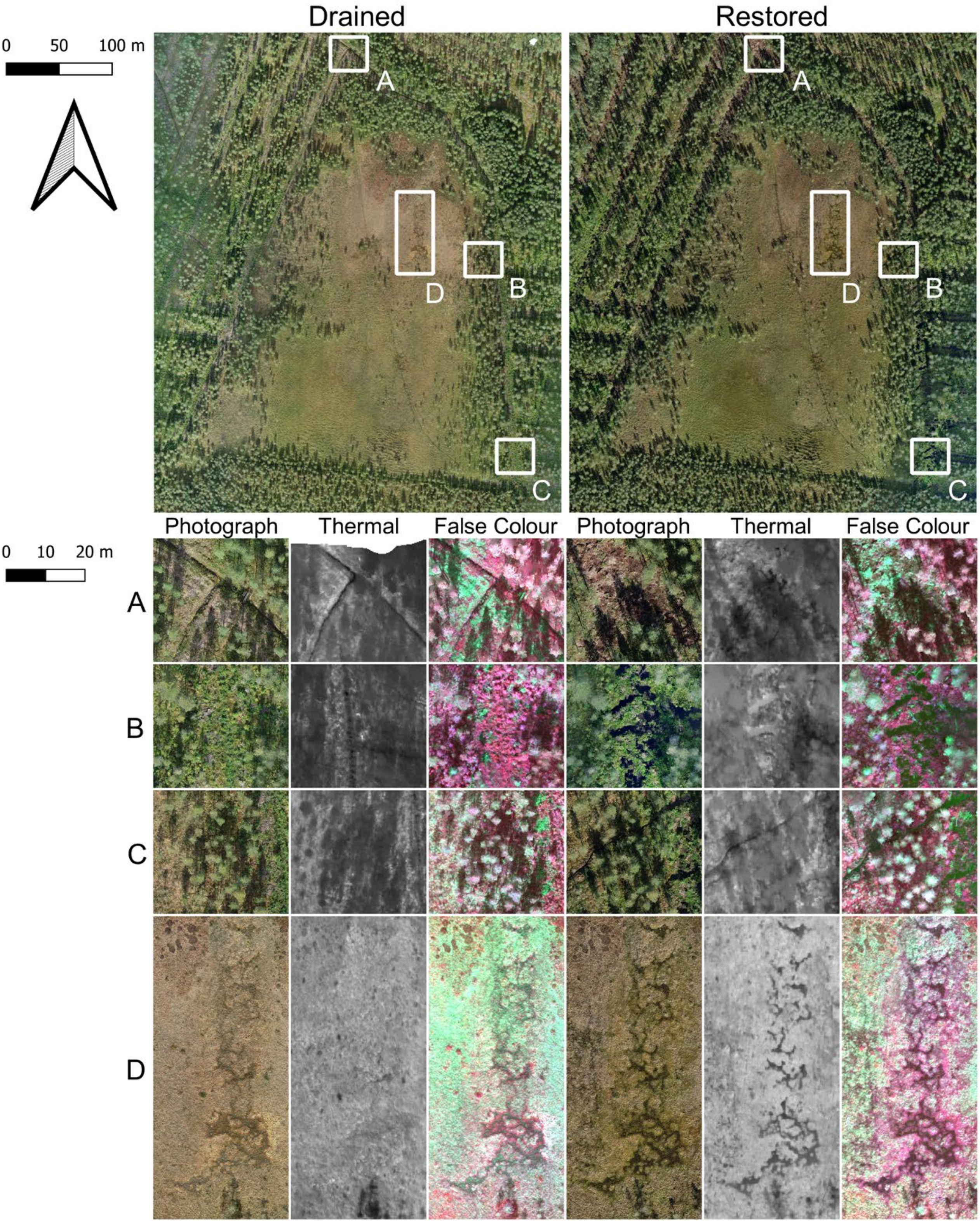

Figure 22. Comparison of orthomosaic images based on photographs, thermal images and false colour images from Iso Leväniemi in Olvassuo. In the thermal image, light tones correspond to warm areas and dark tones with cold ones. Visible light and near-infrared bands captured with the MicaSense Rededge M multispectral camera are shown as a false colour image. In false colour images, wetter surfaces look reddish and dryer ones greenish. Figure: Lauri Ikkala, Image data: Pasi Korpelainen.

thermal image taken after restoration shows that these pools are lighter in tone, indicating that they are warmer than their surroundings. From this, we can conclude that the dams are holding and that there is no significant flow of cold groundwater through these pools along the old ditch line. On the eastern side of the pools, however, it appears that groundwater is seeping to the surface.

The images in Figure 22C show a small feeder ditch dug by hand after restoration, the purpose of which is to lead water from the ditch line to the open peatland. The drain was dug as a corrective measure after a flow was observed to remain in the edge ditch on the general monitoring visit of the first spring.

5.7 Results: Topohydrological analysis

Ikkala et al. (2022) examined topographic changes in the peatland surface and their impacts on peatland hydrology on sites restored in the Hydrology LIFE project. The restoration sites in Loukkusuo (Jonkerinsalo) in Mujejärvi and Iso Leväniemi (Olvassuo) as well as their pristine control sites in Tammalampi and Kirkaslampi, respectively, were surveyed with drones 2 to 11 months before and 1 to 10 months after the restoration. The data were used to observe primary changes, or ground elevation changes caused by the excavator, and slower and smaller secondary changes, which mainly consisted of the swelling of peat caused by rewetting during the study period. Changes in the wetness of the sites were also studied with topohydrological analysis using the flow accumulation algorithm and SWI for the digital terrain models (DTMs).

See Figure 23 for changes in peatland surface elevations. A ground elevation increase of 0.6 to 1.0 m was observed in the spots where ditches were filled and dams were built (Figures 23A1, A3 and B1). See Figure 23A2 for the area where soil wetness prevented ditch blocking, however. The ditch was already more or less blocked at the beginning of the restoration project, and it directed water to the open peatland in the middle of the ditch line.

Smaller secondary changes were also observed on the sites which, however, could be confused with data inaccuracies in places. In the open area of Iso Leväniemi, where the data appeared accurate, surface elevation was observed especially on the lowest surfaces of the peatland (Figures 23B2, B3). The vegetation on the lowest surfaces has been shown to be the most sensitive to elevation changes (Howie & Hebda 2018), possibly due to their loose structure and lack of vascular plant roots.

Loukkusuo peatland was photographed only a few weeks after restoration in the middle of the driest period of the summer, which could explain the fact that no systematic swelling was observed there. Subsidence observed in image 23A3 may have been associated with inaccuracies, but the observation was also supported by the reduction in water volume observed in the topohydrological analysis in the same area. In orthomosaic images (Figures 23A1–3, B1), the 'handwriting' of machine operators can also be observed, in other words, locations of pits made while filling in the ditches and interconnections that may be harmful from the perspective of restoration.

Based on the topohydrological analysis, the flow patterns shifted from ditch bottoms more evenly across the peatland surface after restoration (Figure 24). In Loukkusuo peatland (Figure 24A), the ditches had been excavated more or less parallel with contours, which is why the drain network discharged into a downstream undrained peatland along three main paths even before restoration. After the ditches were blocked, however, the same volume of water from higher up on the slope was divided between more than ten flow paths, which made the peatland 2.9% wetter, and the wetness range decreased by

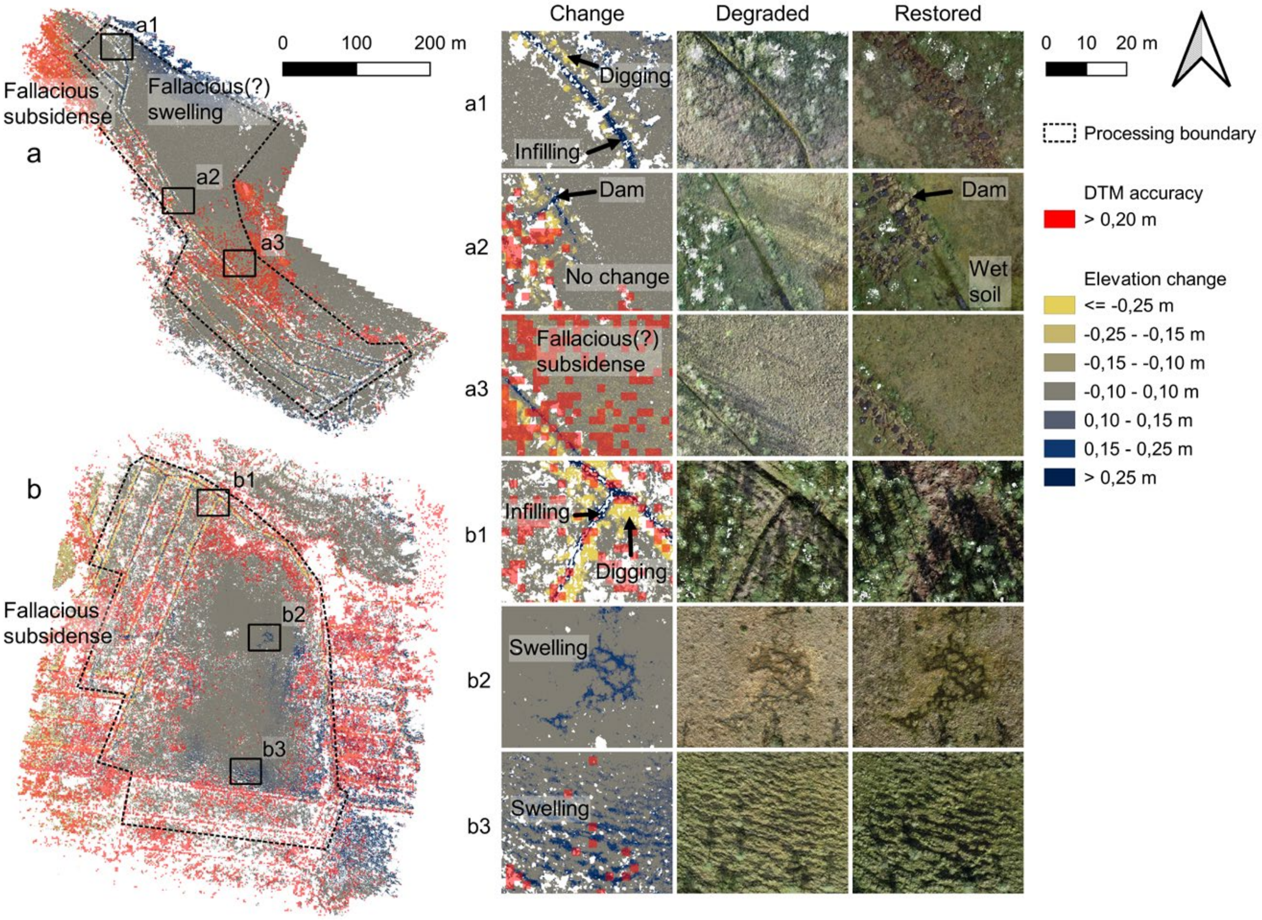

Figure 23. Topographic and visual changes on the restoration sites of Loukkusuo (A) and Iso Leväniemi (B). A positive elevation change indicates a rising surface. Close-ups A1-B3 show changed areas in orthomosaic images. The areas with poor elevation accuracy (elevation differences between the digital surface model obtained with drone data and the laser scanning data of the National Land Survey > 0.20 m) are shown in red. Figure: Lauri Ikkala, Image data: Pasi Korpelainen, Maarit Similä. Republished under licence CC BY 4.0 © Ikkala et al. 2022.

15%. This means that the wetting of the peatland was divided more evenly.

Due to the orientation of the ditches, the dams built as part of restoration work in Loukkusuo were more or less parallel to the incline of the slope, which is why they have almost no significance in the topohydrological analysis. However, the analysis did not take into account soil properties. In reality, dams are needed if the filled ditch lines have a stronger impact on transporting water than the surrounding peatland. The role of the dams is additionally stressed during a flood when there is more surface water around. Dams built higher than their surroundings also anticipate the subsidence of structures in organic infill soils in the years to come.

On the Iso Leväniemi site (Figure 24B) with its steeper slope, where the ditches ran along the slope, the flow patterns of filled ditch lines also persisted after restoration. There was more convolution in the flow, however, which promoted rewetting and probably also slowed down the flow rate and prevented erosion. The mean wetness of the site increased by 7% and the wetness range decreased by 13%.

However, the lateral lines between the ditches also remained dryer after restoration. This could have been prevented by building

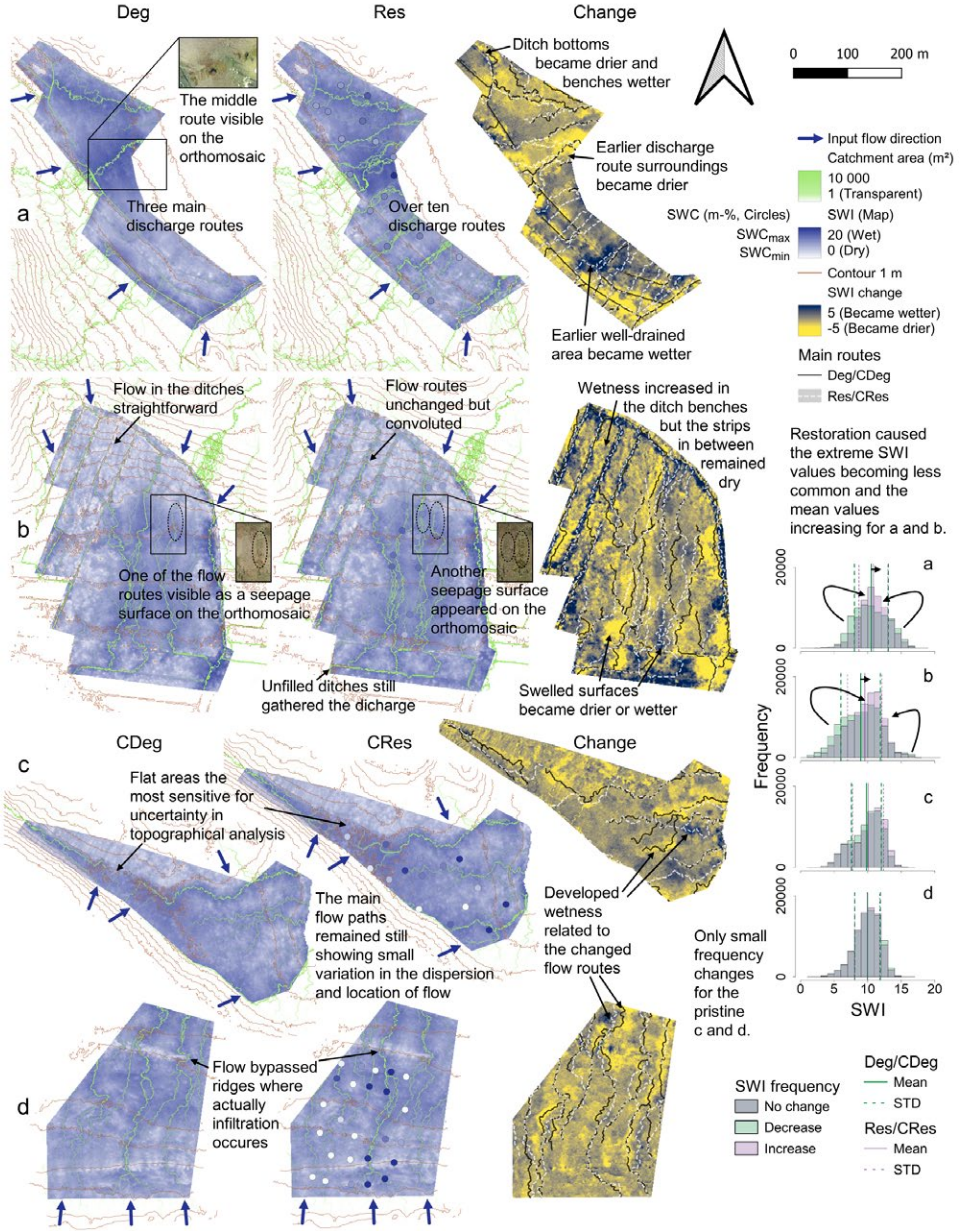

Figure 24. Changes in wetness and flow routes resulting from the restoration of Loukkusuo (A) and Iso Leväniemi (B), and corresponding simultaneous changes on the pristine control sites of Tammalampi (C) and Kirkaslampi (D). The SWI index (blue background image in the before and after images) and the flow accumulation (green paths) indicate changes in the distribution of the same water volume flowing down from higher up on the slope. Figure: Lauri Ikkala, Image data: Pasi Korpelainen, Maarit Similä. Republished under licence CC BY 4.0 © Ikkala et al. 2022.

higher and longer dams and surface embankments at shorter intervals to compensate for the steep gradient of the ditches and to spread water to areas between the lateral ditches.

The ditches on the site were deep, however, which made it difficult to find enough soil to fill them in without making a depression in the ground surface near the ditch. Drainage causes organic soils to subside, and the surroundings of ditches typically dry the most efficiently, which is why there has been more subsidence in them than in the areas between them. Consequently, they are susceptible to work as flow routes also after restoration (Haapalehto et al. 2011).

Changes observed on pristine control sites due to measurement errors and natural variations of surface elevations were significantly smaller than the changes observed on restoration sites. However, they were particularly significant on the flattest sites where even small elevation changes (measurement errors) are liable to shift flow patterns in the analyses.

Drone surveys and topohydrolocial analysis were found to be an effective new way of examining changes caused by restoration in peatland hydrology qualitatively and, for the first time, also quantitatively. The analysis indicated that the restoration of Iso Leväniemi and Loukkusuo sites could be considered successful due to the dispersion and convolution of flow patterns, increased mean wetness and reduced wetness range.

The wetness of the sites increased because the sloping ditch banks were replaced with flat fill-in surfaces that slow down the movement of water. Spreading the flow pattern is the most challenging where the ditches are deep and run parallel to the slope. Unlike what the extreme examples given in this study indicate, ditches are typically dug at an angle to the slope.

Peatland surface wetness patterns predicted by the SWI index were compared to surface moss samples collected after restoration in the field, which were dried and weighed in the laboratory (Figure 24, Soil Water Content, SWC). A statistically significant correlation between predicted water concentrations and those found in the samples was observed on restoration sites but not on pristine sites. The correlations were rather weak (R2 = 0.26-0.42), however, indicating that in addition to topography, many other factors also affect the wetness of the peatland.

Drainage may change peat properties, making them better suited for topohydrological analysis. On the other hand, the SWI is partly based on the upstream catchment area, which happened to be limited to the pristine control sites. Except in the areas covered by drone surveys, the National Land Survey's laser scanning data were used to determine the upstream catchment area.

The analysis results based on topography can be regarded as hydrological predictions for longer-term and stable conditions. The main source of error is likely to be overlooking soil properties. While topography is the most important factor that determines water movements, peat thickness and the water infiltration properties of the peat and the mineral soil below it also affect them (Kemppinen et al. 2017). The studied sites were located on the edges of aapa mires. It remains for further studies to establish how well topohydrological analysis is suited for raised bogs, for instance.

The only secondary change within the timeline of the study was the swelling of peat. Over longer time intervals, other secondary changes would include erosion, dam subsidence, vegetation growth and peat accumulation. A period of flooding also fell in the observation period in Iso Leväniemi, but no significant erosion was observed on the site. Instead, water from a filled edge drain was directed to the undrained central part as a corrective action. This small feeder ditch was too narrow to be taken into account in the analysis carried out with a resolution of 1 m, however. A higher resolution in the analysis would also account for dam erosion better, whereas microtopography that affects water flows less could influence the analysis.

The developed analysis method could also be used to demonstrate the impact of restoration on indirect rewetting sites, where the area covered by the measures is often small and whose larger areas of impact are difficult to determine. Drainage waters from upstream commercial forestry land have often been channelled past the peatland along an edge drain between the forest and peatland areas. By digging a relatively short guiding ditch, large volumes of water can be directed from the upstream catchment to a peatland that has dried out indirectly (without ditching on the peatland site). Our studies indicate, however, that wetness and the impact area of restoration on rewetting sites can be modelled better also taking the temporal variation into account using multispectral and thermal imaging data captured with drones than with topohydrological flow network modelling (Isoaho et al. 2023).

5.8 Conclusions on setting up monitoring by remote sensing

- Remote sensing can provide spatially continuous data concerning changes in wetness, vegetation, elevation, peat properties and greenhouse gas emissions for peatland monitoring.
- Potential sensors include photographic, multispectral, hyperspectral and thermal cameras, laser scanners and radar sensors.
- Remote sensing is suited for monitoring the peatland surface and its wetness, especially in open peatlands or those with few trees.
- The impact of restoration is demonstrated by producing a time series before and after restoration, preferably covering several seasons and multiple years before and after the restoration.
- A pristine control site is usually needed to verify the impacts.
- Remote sensing data must be verified using reference data collected on field visits.
- Better use should be made of the open datasets produced by the National Land Survey and satellite operators in the monitoring of peatlands.
- Inexpensive drones and simple methods have great potential to support the general monitoring of peatlands.
- While more advanced devices and methods are not equally suitable for everyone’s use, they can produce valuable data for the impact monitoring of peatlands.

6 Summary and recommendations

The systematic peatland monitoring network enables the evaluation of the impacts of peatland restoration and general monitoring helps to develop planning and carrying out restoration. Hydrological monitoring indicates whether or not the physical objectives of restoration have been achieved. Monitoring by remote sensing, on the other hand, contributes new data concerning changes in different parts of the peatland to the evaluation of the impacts of restoration. To define success, however, clear, site-specific criteria need to be defined and suitable indicators must be selected to enable appropriate assessment of whether or not the criteria are met.

6.1 General observations for developing peatland monitoring

Qualified implementation of long-term impact monitoring requires a careful orientation for the practitioners. The vegetation cover survey is performed visually. If several practitioners are performing the task or if the practitioner is replaced each year, a “calibration of the assessing eye” is needed at the beginning of the field season which ensures that the observed changes between the monitoring rounds or between different sites are real and not due to the different ways of performing the vegetation survey.

Survey accuracy is relevant also for hydrological monitoring in terms of reliability. The water level measured by a data logger sensor is referenced to the surrounding peatland surface manually with measurements by those collecting the water samples. Thus, the instruction for the measurement must be unambiguous, and a sufficient orientation must be given to the practitioner.

General monitoring would benefit if the person planning, coordinating the implementation of, and monitoring a restoration project is the same. If different practitioners are responsible for each stage, it is vital to properly document the site-specific objectives of restoration and the methods used. Only this makes it possible to assess if the restoration has met its goals, and if not, what should be done differently in the future.

- **Recommendation 1:** Continuity should be favoured when organising tasks related to monitoring. Unambiguous instructions should be provided for making inventories and taking measurements and samples, and the personnel should receive regular training in following the instructions. Furthermore, discussions between the field personnel and analysts should be increased.

6.2 General monitoring

General monitoring is carried out to evaluate the technical success of restoration. It identifies local needs for corrective or supplementary measures, but by noting successes and failures, restoration methods can also be developed. The appropriate schedule for general monitoring is 0.5-2 years (first time) and approx. 10 years (second time) after restoration. If shortcomings or problems associated with the restoration occur, an additional general monitoring visit before the 10-year visit may be necessary, as well as planning and carrying out corrective measures.

Flexibility in general monitoring should be ensured due to the large diversity of sites and the variety of methods suitable for each site. Minimum data content can, however, be determined, and it should be presented more clearly than today. An update of the monitoring guidelines for Finnish state-owned peatlands will be launched in 2024, and in this process, the minimum data content should be specified and communicated to the monitoring personnel. At least the change in the drainage situation after restoration should be recorded in the habitat patch data as well as the possible changes in the representativeness of the Natura habitat type, the latter during the general monitoring at the latest.

The collection of observations would be facilitated by a mobile application or field device that could be used to collect data during the general monitoring visit. The possibility of accessing open remote sensing and spatial data sets and drone data produced on the site in this application would also make general monitoring in the field more efficient.

A rapid field test for a hydrological parameter which could be saved as part of the site's spatial data set is also called for in general monitoring. When GISs are upgraded, their users should be involved in the development work.

- **Recommendation 2:** The minimum data content and a uniform data storage method for general monitoring should be specified. A possibility is explored to develop a user interface (mobile application) for general monitoring work, in which the observations are saved to the environmental administration's GIS database. The usability of general monitoring data sets for impact monitoring is advanced.

6.3 Peatland restoration monitoring network

The peatland restoration monitoring network uses systematically collected data to produce information about the impacts of peatland restoration on hydrology and plant communities. Even by global comparison, the network is significantly large and comprehensive as it includes not only restoration sites but also pristine reference sites and drained control sites. The 10-year time series produced by the network was analysed in the Hydrology LIFE project.

The data produced by the network attracted interest in the academic world beyond the scientists with whom the original agreement on processing the data was made. Opening the material for general scientific use will also enhance the impact of the monitoring network. Before opening, the collected data must be checked and the necessary corrections made. Sufficient metadata describing the datasets must also be attached to them. The open publication of the monitoring network’s observations over a ten-year period will likely be published soon after this report together with scientific publications analysing the data.

- **Recommendation 3:** Observations collected by the monitoring network should be published regularly (e.g. every five years) as open data for the use of all interested parties.

In addition to scientific publications, it is also important to convert the results into a popularised format and ensure their more general distribution. Any deviations found in the data should be checked in the field, which requires smooth communication between scientists and field personnel.

- **Recommendation 4:** The datasets produced by the monitoring network should be analysed and the results published regularly (e.g. every five years). A workshop should be organised in connection with each publication, where those analysing the data and planners responsible for monitoring the sites can discuss the results.

Monitoring is invaluable for understanding the impact of restoration. There are spruce mire, pine mire and fen sites in the monitoring network. It is questionable if the results of the network can be applied to other types of peatlands (different peatland types, or different levels of degradation) besides those monitored as part of the network. The experiences of the project indicate a need for systematic data collection on rich fens and flark fens. In addition, sites with groundwater effects and other special sites should be monitored more intensively than conventional sites.

As methods and sites diversify, on the other hand, other measures comparable with restoration should also be monitored and studied besides traditional restoration sites, including rewetting of indirectly drained sites, sites allowed to recover passively, and continuous cover silviculture sites. In addition to state-owned protected areas, systematic monitoring is also called for in state-owned commercial forestry areas and private lands where restoration activities are gathering momentum rapidly.

However, Metsähallitus' peatland restoration monitoring network has reached the upper limit of its size in terms of manageability, which includes ensuring that instructions can be easily passed on to practical operators and, on the other hand, field observations to scientists. Rather than expanding the current network, setting up new, separate monitoring networks for different sites is likely to be a more effective option. Harmonising the guidelines for different networks is important, however, to ensure comparability.

- **Recommendation 5:** The work of the peatland restoration monitoring network should be continued on current sites. Separate monitoring networks should be established for new types of monitoring needs. The guidelines and practices for the current monitoring network should be used as a basis for the new networks, and the harmonisation of the networks should be ensured.

6.4 Hydrological monitoring

The purpose of hydrological monitoring is to examine the key hydrological parameters of peatland restoration, patterns of water flows, and water distribution and quality. Without hydrological recovery, natural plant communities, other peatland communities and peat accumulation cannot be recovered.

Hydrological impacts of restoration in state-owned protected areas have been studied with a setup of 46 sites (27 restored and 19 pristine peatlands). Automatic water level sensors, manual water table observations that support them, and laboratory analyses of water samples have been used for monitoring. On selected sites, runoff water monitoring has additionally been arranged for downstream from the peatland.

Water level sensors have usually been placed in areas between ditches. The most significant changes in runoff water quality are likely due to ecohydrological processes in areas disturbed most by restoration, such as filled ditch lines. Consequently, for understanding the peatland’s hydrology as a whole and for developing the restoration methods, it would be beneficial to gather information about the changes also for the ditch lines. More detailed information on water movements between the filled ditch and the area between ditches would be obtained by placing pairs of sensors: one in the filled ditch, and one between the ditches. On the other hand, to gather reference data sets for remote sensing data on selected sites, the sensors should be distributed spatially all over the mapped area.

- **Recommendation 6:** Water table measurement wells with water level sensors and sampling points should be placed in pairs in ditch lines and the areas between ditches or spatially all over the site.

Water level observation data from a well are converted into water table depth observations by measuring the vertical distance of the pipe end from the peatland surface. However, the peatland surface elevation round the well varies, and such factors as the growth and compacting of vegetation, as well as the water content in the peatland also cause fluctuation.

- **Recommendation 7:** The vertical distance of the well end from the surrounding peatland surface should be determined by using a collar that is placed round the well separately each time the measurement is made.

It is additionally advisable to photograph the surroundings of the wells on every visit and to measure their locations with a high level of accuracy.

When taking manual water table measurements, water samples should be pumped from the wells using a siphon pump. During dry seasons, there might be water for only one sample bottle. Detail should be added to the sampling instructions, as it is unclear if sample 1, or the only one that can be obtained during a dry spell, is comparable to sample 2 obtained in wet periods.

- **Recommendation 8:** The differences between samples 1 and 2 are studied. More detailed instructions on collecting water samples 1 and 2 should be issued if needed.

Replacing accurate laboratory analyses of water quality with field tests is challenging. Some variables could be monitored using high-quality field instruments. Information on the speed of water movement in the surface layers of the peatland was also called for.

- **Recommendation 9:** Field tests of water quality should be trialled in monitoring regarding parameters for which high-quality field instruments are available (pH, conductivity, temperature and ultraviolet absorbance).
- **Recommendation 10:** A method based on timing should be developed for pumping the well empty that indicates water conductivity in the surface peat layer.

The impacts of restoration can be distinguished from natural variability by simultaneously monitoring pristine control sites. While using a common control site for several sites restored at different times will bring synergy benefits, it may also upset the scheduling of measurements. Based on the observations made by the monitoring network, the restoration of peatlands already increases the water table and reduces its range in the first months and years. However, the water table may be more sensitive to the effect of dry spells on restored sites than on pristine sites.

- **Recommendation 11:** For each restoration site, a dedicated pristine control site should be organised or, alternatively, it should be ensured that the control site is observed according to the schedules of both restoration sites

In addition, moving peat using an excavator causes a temporary increase in the nutrient and DOC concentrations of pore water in the peatland for some years. The highest pore water concentrations have been observed on intermediate nutrient-rich and nutrient-poor sites as well as in unusually dry years. Restored sites where the water has risen excessively also present a particularly high risk. However, increased concentrations in pore water do not appear to be transferred in equal amounts to runoff water.

6.5 General points about remote sensing

The conditions in a peatland vary both naturally and as a result of drainage and restoration in different parts of the peatland. With traditional monitoring methods, observations are limited to individual points in the peatland or along the walking route of the general monitoring. Remote sensing makes it possible to extensively assess variability in different parts of the peatland.

The instrument used for remote sensing may be a conventional photographic camera or a multispectral, hyperspectral or thermal camera that captures wavelengths outside the visible light range. A three-dimensional model of the site and a digital surface model based on it can be produced with photogrammetric surveys in open peatlands, whereas laser scanning works better in tree-covered areas. In addition, satellites use microwave radar.

Remote sensing makes it possible to study peatland hydrology, for example, based on surface moisture or the cover and spatial distribution of open water. Surface moisture can be evaluated using microwave radars or spectral datasets. In stable conditions, vegetation also gives indications of the hydrological conditions of the peatland. High-resolution thermal images may reveal groundwater discharge points, which are colder than their surroundings in the summer.

Remote sensing can also be used to monitor vegetation, for example, to detect plant communities and functional groups of plants, or to determine primary production. Greenhouse gas balances can also be estimated based on vegetation and wetness. In addition, remote sensing can be used to examine the depth and properties of peat.

The impact of restoration is demonstrated with a before-and-after time series. The monitoring intervals must be sufficiently short and their timing in the yearly cycle must be carefully considered to account for the impacts of year-to-year fluctuations, climate change and changes in vegetation during the growing season. The intervals should also be adjusted to the indicator to be monitored.

- **Recommendation 12:** Monitoring by remote sensing should be used both before and after restoration to demonstrate the impact of restoration. Optimally, both the before and after situations should be monitored for several years.

For technical (general) monitoring, information on leaking dams produced by remote sensing is needed before the field season following the restoration at the latest. In impact monitoring, hydrological impacts can already be seen during the first years, whereas changes in plant communities and peat accumulation are only visible over the decades.

- **Recommendation 13:** Remote sensing should primarily be scheduled to take place in the driest summer period (in late July and early August in Finland) and, secondarily, at the time of spring floods. Optimally, data should be collected throughout the field season and over several years.

Remote sensing is an indirect measurement technique, which is why field work is needed to collect control datasets if the plan is to use the images for systematic analysis rather than for visual interpretation only. Some of the control data are used to calibrate the produced model, while others are used to verify the functionality of the model.

- **Recommendation 14:** In connection with data production, supporting datasets should be collected in the field that are either geometric (ground control points) or give indications of the parameter to be measured (e.g. water level, soil surface moisture or plant species).

By also covering pristine sites by remote sensing, the sensitivity of the methods to natural variations and the sources of error in the method can be determined. Key factors interfering with remote sensing of peatland surfaces are dense tree crowns. This is why pristine sites should primarily be similar to restoration sites in terms of their openness. Drained control sites usually have too many trees for imaging methods to work.

- **Recommendation 15:** Pristine control sites should be used for remote sensing monitoring.

The National Land Survey produces aerial photographs of Finland every three years and laser scanning data every six years. In addition, the archive of historical aerial photographs provides invaluable information on the status of peatlands before drainage. Various open satellite datasets are also available. These datasets produced by professionals are of a high quality.

As they are produced regularly but at longer intervals, the National Land Survey's datasets serve long-term impact monitoring, in particular. Satellites can even provide monitoring data with high frequency if clouds do not prevent visibility. Better use should be made of these open remote sensing datasets in the monitoring of peatland restoration. More systematic use of these datasets should be promoted in future research projects.

- **Recommendation 16:** The use of open National Land Survey datasets and satellite data to support general monitoring should be promoted by training planners in their use. The use of open data should additionally be supported by developing a user interface (mobile application) for planners' needs, in which the data can be easily viewed in the field.

6.6 Drone monitoring

Drone monitoring, which was trialled in the project, should be made a permanent part of the peatland restoration toolbox. Rather than replacing traditional general or impact monitoring, however, it complements them with new types of high-resolution spatial data focusing on different parts of the peatland. Low-cost devices and simple methods are adequate for general monitoring, whereas, for impact monitoring, more systematic methods and quality assurance of the datasets produced are needed.

Drone activities are governed by EU legislation. The minimum requirements include an entry in a register (maintained by Traficom in Finland) and an online theory exam taken by pilots. Once these requirements are met, drones may be operated in continuous visual contact, far from people, buildings, airports and other restricted zones, and at a maximum height of 120 m above the ground.

- **Recommendation 17:** Drone activities should be coordinated in the organisation by a responsible person who liaises with Traficom, registers pilots for the online theory exam, and arranges the recording of flights in a log. The responsible person should also maintain their competence in legislative issues and regarding the necessary permits and licences.

Drones can be used to take individual photographs and videos or to carry out systematic survey flights for obtaining end products which reach an accuracy of approx. 5-10 cm on the site, including orthomosaic images and surface models.

The accuracy of the survey depends, above all, on the accuracy of georeferencing. To achieve an accuracy of one centimetre, an RTK precision positioning device must either be found in the drone itself, or this device must be used to measure the coordinates of the ground control points. RTK technology requires a continuous mobile data connection, whereas PPK measurements can be used on remote peatland sites, the correction of which can be carried out as post-processing.

If an RTK drone is not used, 10 to 15 control points should be placed evenly round the area to be surveyed, which makes the method more labour-intensive. The need for measurements can be reduced by building permanent control points fixed to mineral soil, the locations of which need not be checked as frequently.

- **Recommendation 18:** If the data are to be used for more systematic analyses than mere visual comparisons, they should be acquired using an RTK or PPK drone. Datasets can also be produced with other drones designed for surveying, but in this case, a sufficient number of ground control points must be provided.

The drone model used for the survey must also be designed for this purpose. The cheapest models are useful for supporting general monitoring, whereas the more expensive ones can produce more accurate and versatile datasets that are better suited for systematic examinations.

The planners are interested in learning to use more advanced equipment that could be rotated from one site to another, but the collection of control data needed for these methods was considered too labour intensive. For the purposes of general monitoring, the survey data can be processed with highly automated tools, for example in a cloud service, but in-depth familiarisation with the processing is needed for more systematic monitoring. Additionally, the storage and sharing of large datasets and issues related to software licences have not yet been resolved in Metsähallitus' organisation.

- **Recommendation 19:** Basic-level drones should be purchased and made available to all planners interested in them for capturing individual images and videos and carrying out visible light surveys intended for visual examinations. For processing these survey datasets, a licence for a commercial cloud service should be acquired, and a protocol for this should be developed.
- **Recommendation 20:** More advanced equipment and methods should be reserved for special experts familiar with their use, whose working hours mainly consist of operating this equipment and processing the data they produce.
- **Recommendation 21:** Training and workshops on drone imaging and the processing and interpretation of the data should be organised to lower the threshold for learning about new technology and exchanging experiences with others.

When drone data are used for systematic analyses, the producer must be familiar with the quality criteria for the methods and data. All survey datasets are subject to the requirement of geometric accuracy. In the case of spectral data, radiometric calibration must also be ensured.

The use of drones poses many types of technical challenges. This means that the most suitable operators are persons who basically enjoy working with and solving problems associated with technical equipment.

Setting aside the time needed for these activities should be reserved. Because changing weather conditions may prevent carrying out the plans, the schedules should be flexible. This is particularly essential for data collected for systematic monitoring, for which not only sufficiently calm and dry weather but also optimisation of lighting conditions are needed.

In addition to the hours spent in the field, time should be reserved for testing the devices in advance, data transfers, processing of data and examining the results. Even if somebody else operates the drone on the site, the planner responsible for the site should be familiarised with interpreting the resulting images.

The shared use of devices creates its own challenges for their maintenance. It is advisable for each office to appoint a person responsible for the proper storage of the equipment, troubleshooting technical problems and organising maintenance and spare parts. When equipment is picked up or returned, the responsible person should exchange information with the operator on how the device works, ensuring that problem situations do not come as a surprise to the next user.

- **Recommendation 22:** A person responsible for the devices should be designated in each office.

Drone imaging is best suited for monitoring open and wet peatlands. On sites with more trees, the ground surface along ditches can often be imaged after the trees have been removed. The imaging should focus either on individual objects of interest (dams, ditch lines) or, when producing a survey, on an area where the restoration is expected to bring about major changes.

- **Recommendation 23:** The focus of drone activities should be on monitoring open and semi-open peatlands in areas where major changes are expected to take place.

Compared to conventional general monitoring, the advantages of drone imaging include the possibility of getting an idea of relatively large areas rapidly and examining the site in the office with no time pressure. In the situation before restoration, the drone data shows the depths of ditches and the amount of soil available for filling them.

Drone imaging can document the success of measures: filling of ditches, movements and spreading of water along the peatland surface, and the degree to which the dams hold. The pits from which soil for filling in the ditches is excavated and the tracks of machines are documented in the images. Things may be discovered in photographs that could not be seen on a field visit. On the other hand, a field visit may be needed to learn to read correctly the changes that have occurred.

Visible light images as well as multispectral and thermal imaging data were shown to indicate changes in peatland wetness. However, there was no time to examine the methods suitable for these data in depth during the project. Methodological testing with the data collected in the project and on new sites should be continued in future projects.

- **Recommendation 24:** The trialling of drones and remote sensing methods produced on other platforms should be continued in future projects. The methods should be developed to enable their more systematic deployment in supporting general and impact monitoring.

Topohydrological analysis was for the first time successful in demonstrating the magnitude of the change in peatland wetness achieved by blocking ditches in different parts of the peatland.

The analyses of drone data indicate the spatial distribution of wetness in a way that earlier methods have not been able to achieve. The results identified the areas where dams and surface embankments built on the site were not sufficient for spreading out the water.

The topographical method developed in the project could already be used at the planning stage of restoration to simulate sufficient lengths and heights of dams which, accounting for the elevation fluctuation of the peatland surface, can also spread water in areas between ditches.

- **Recommendation 25:** The topohydrological method should be developed further for the needs of planning restoration projects and determining their impact areas.

In the Hydrology LIFE project, the longest drone data time series only continued a few years after restoration. While it was possible to demonstrate hydrological recovery even during this period, the development will continue and later also affect the recovery of vegetation. Changes in vegetation may continue for decades.

- **Recommendation 26:** The drone data time series started in the project should be continued systematically, for example, every five years. The results should be saved and used to develop restoration methods and the monitoring of restoration.

The drones were proven useful for peatland monitoring in the project. In addition to monitoring, drones can also be used for planning and carrying out restoration projects and for communication purposes.

- **Recommendation 27:** Drone use should be incorporated in general monitoring. Concerning impact monitoring, drone use should be promoted by planning a natural role for them as part of the peatland monitoring network or separately as project-based research activities.

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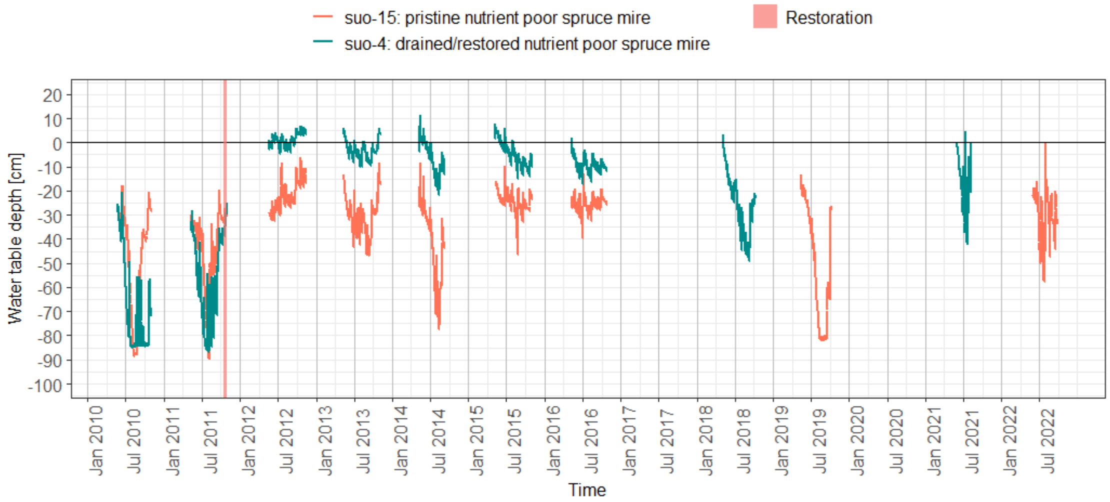
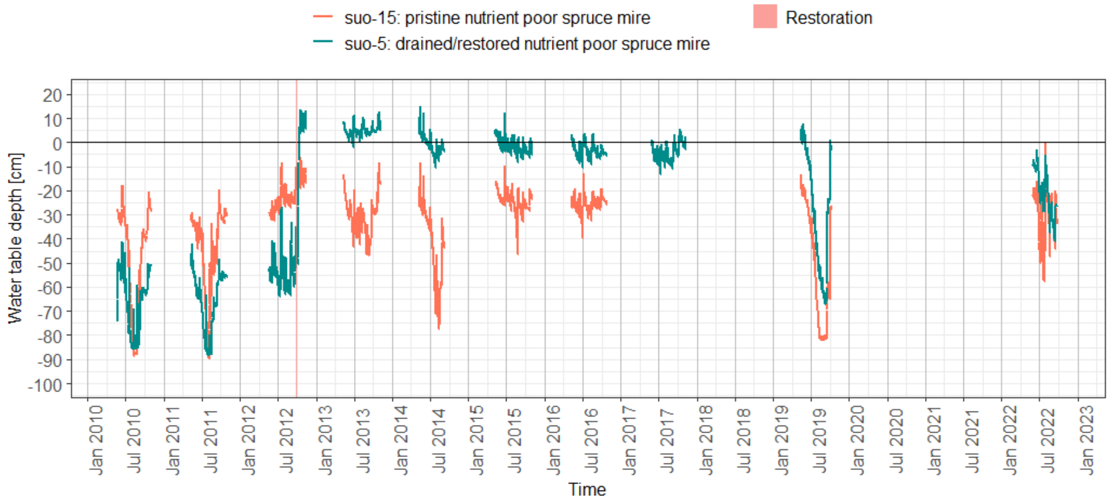
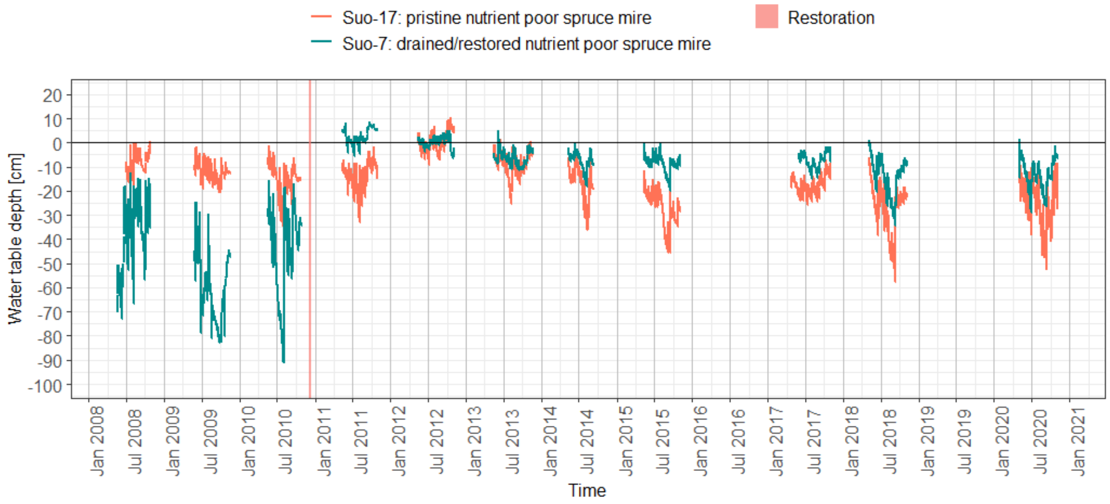
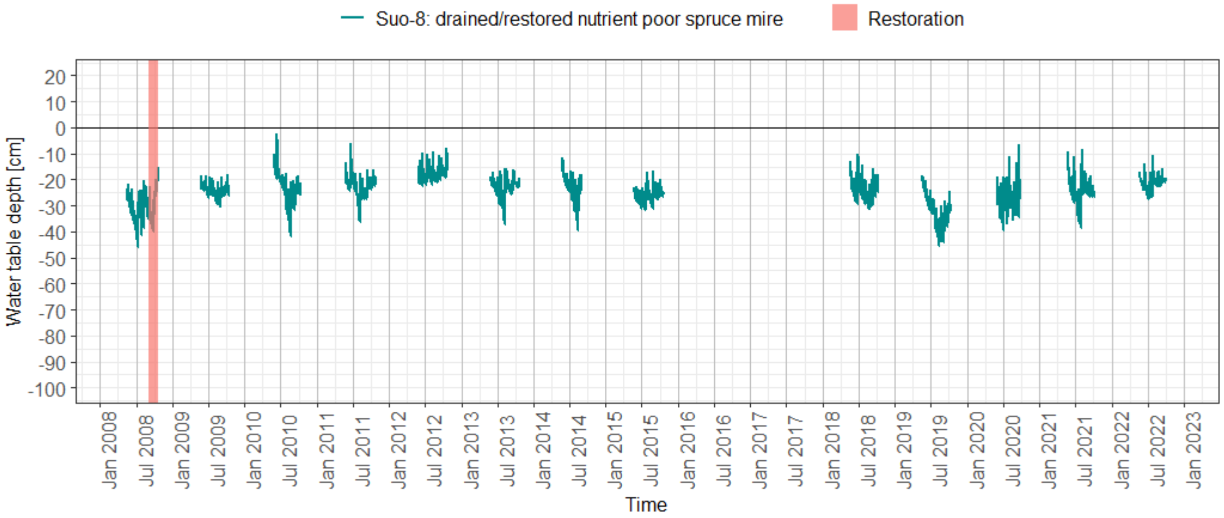
Appendices

Appendix 1. 10-year water table observations for the sites in the peatland monitoring network









Suo-8: drained/restored nutrient poor spruce mire
Restoration
Water table depth [cm]
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
Jul 2013
Jan 2014
Jul 2014
Jan 2015
Jul 2015
Jan 2016
Jul 2016
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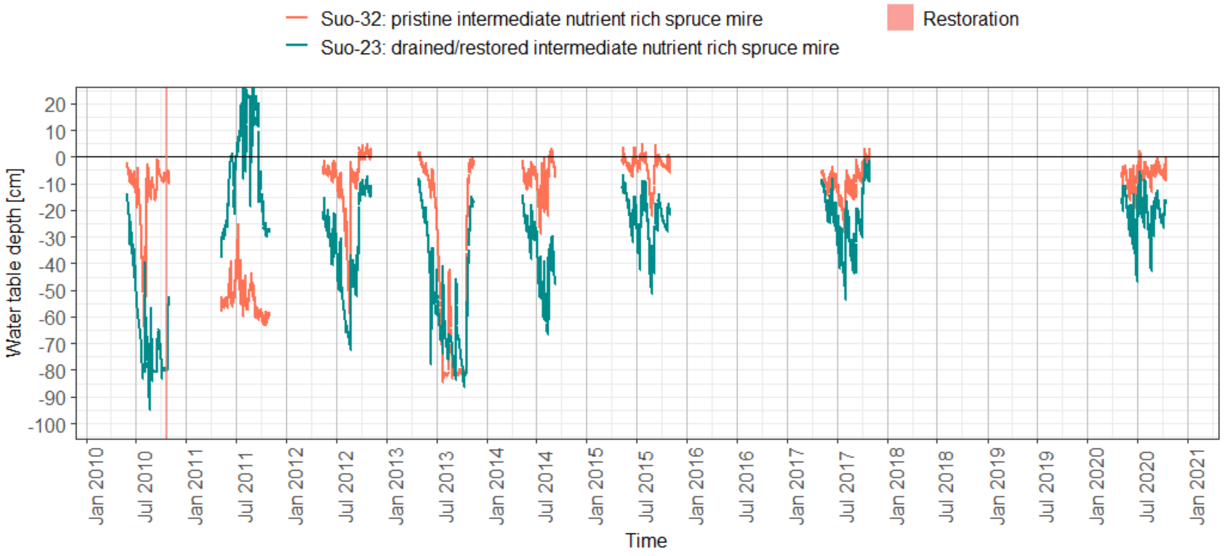
Jul 2018
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time



Suo-32: pristine intermediate nutrient rich spruce mire
Suo-23: drained/restored intermediate nutrient rich spruce mire
Restoration
Water table depth [cm]
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
Jul 2013
Jan 2014
Jul 2014
Jan 2015
Jul 2015
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Time

Suo-35: pristine intermediate nutrient rich spruce mire
Suo-24: drained/restored intermediate nutrient rich spruce mire
Restoration
Water table depth [cm]
20
10
0
-10
-20
-30
-40
-50
-60
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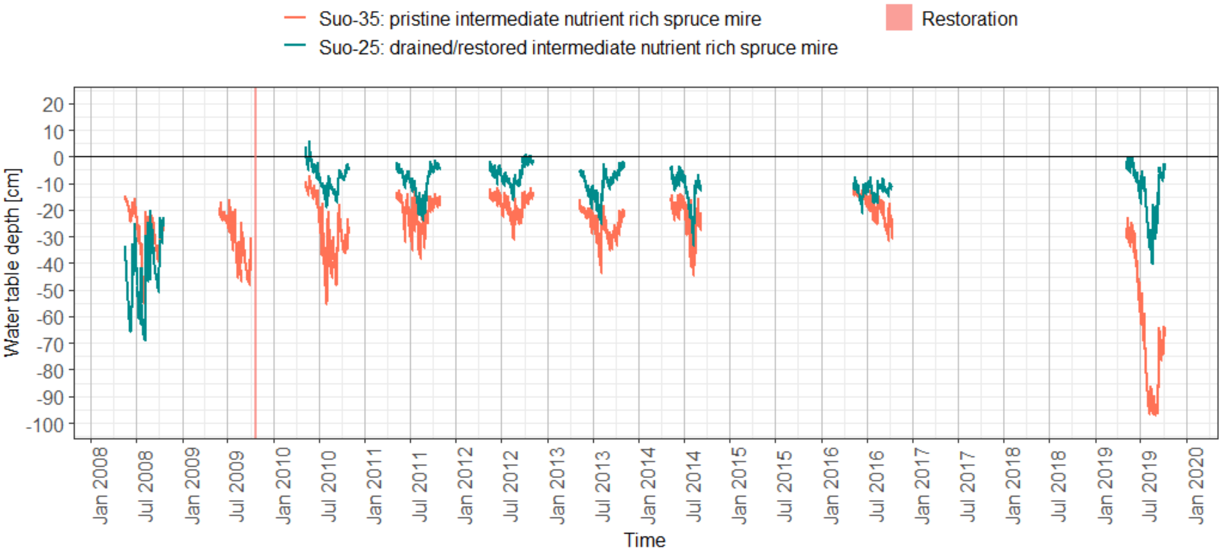
Suo-35: pristine intermediate nutrient rich spruce mire
Suo-25: drained/restored intermediate nutrient rich spruce mire
Restoration
Water table depth [cm]
20
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-10
-20
-30
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-80
-90
-100
Jan 2008
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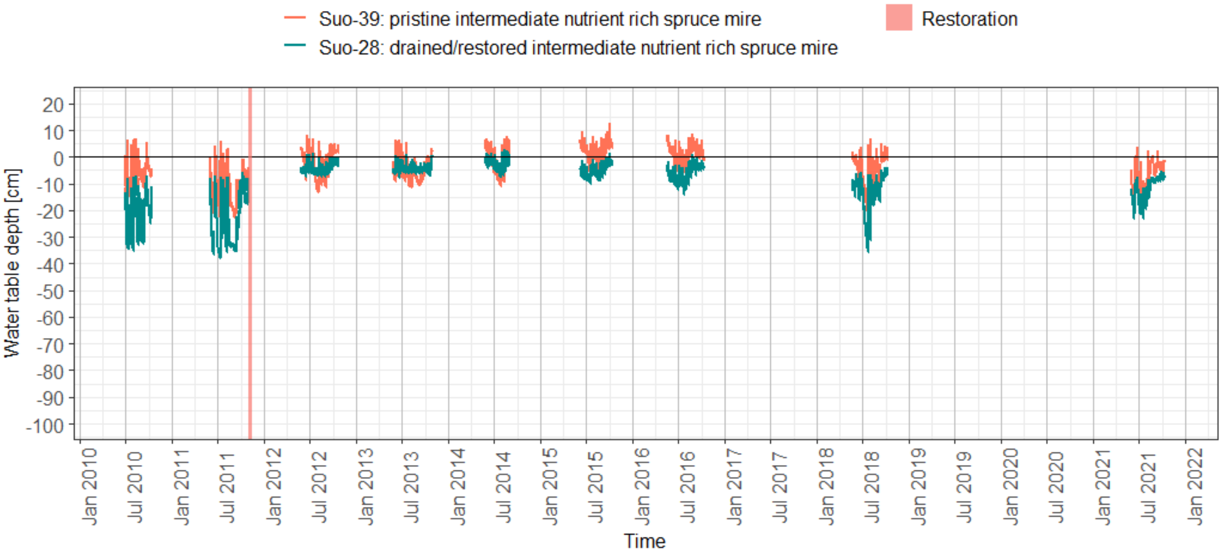
Suo-39: pristine intermediate nutrient rich spruce mire
Suo-28: drained/restored intermediate nutrient rich spruce mire
Restoration
Water table depth [cm]
20
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-20
-30
-40
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Jan 2010
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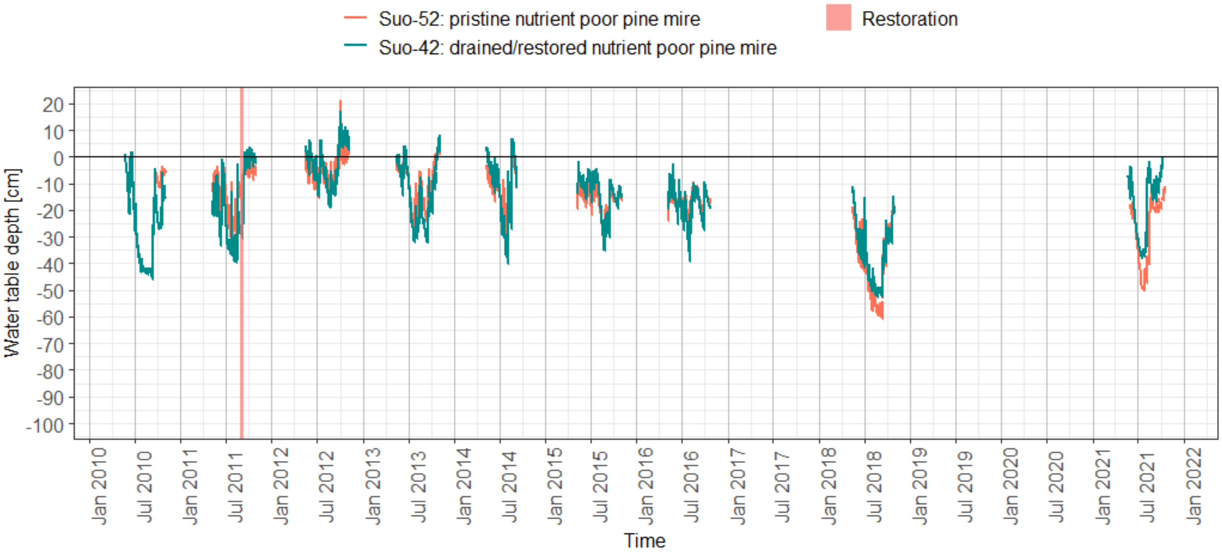
Suo-52: pristine nutrient poor pine mire
Suo-42: drained/restored nutrient poor pine mire
Restoration
Water table depth [cm]
20
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0
-10
-20
-30
-40
-50
-60
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Jan 2010
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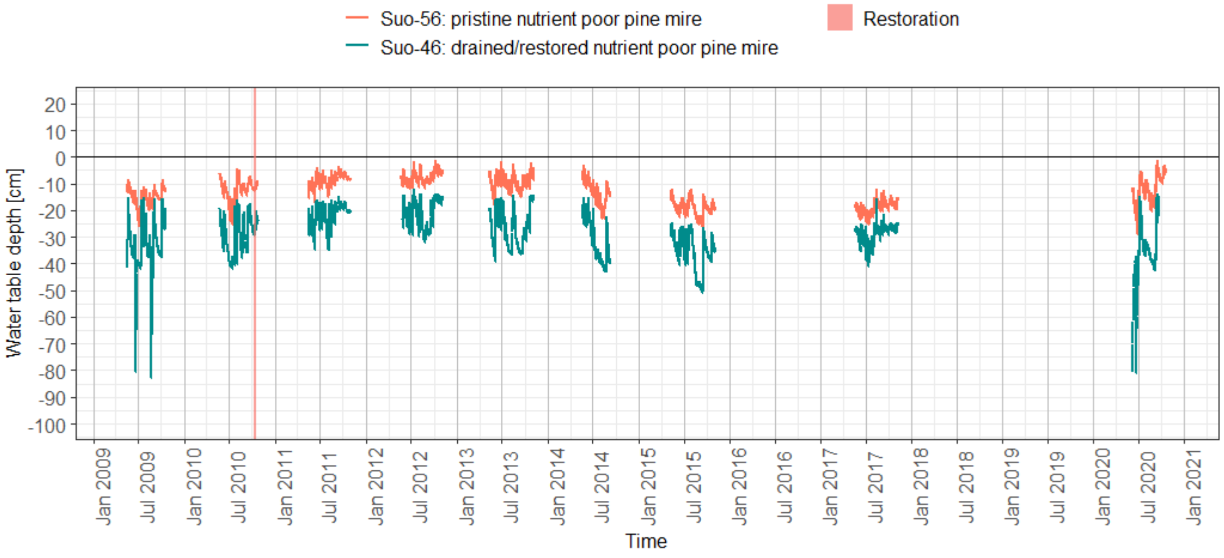
Suo-56: pristine nutrient poor pine mire
Suo-46: drained/restored nutrient poor pine mire
Restoration
Water table depth [cm]
20
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-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
Jan 2009
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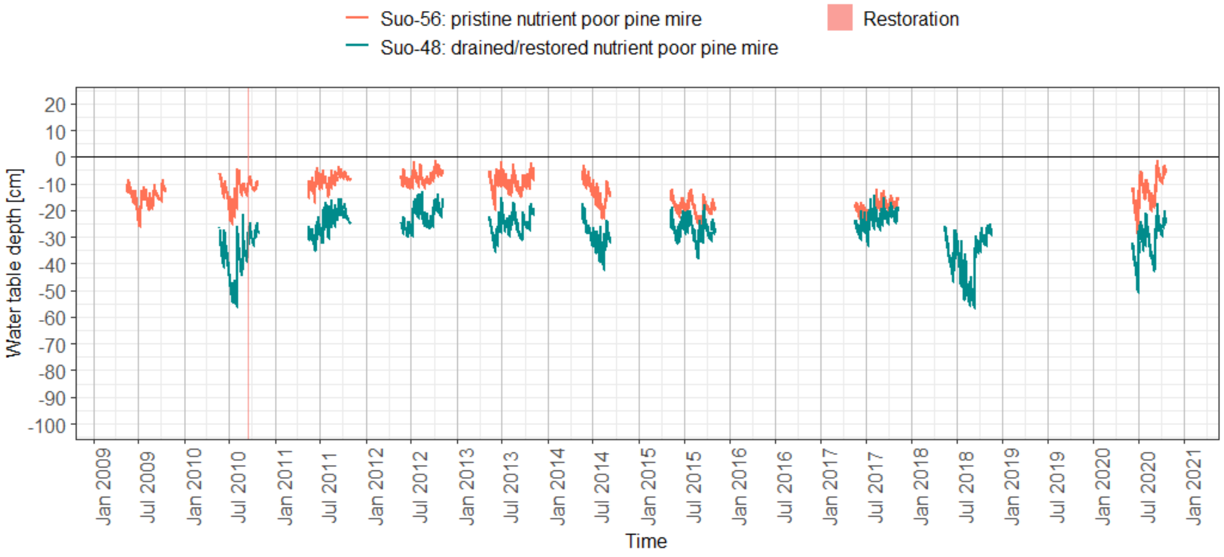
Suo-56: pristine nutrient poor pine mire
Suo-48: drained/restored nutrient poor pine mire
Restoration
Water table depth [cm]
20
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-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
Jan 2009
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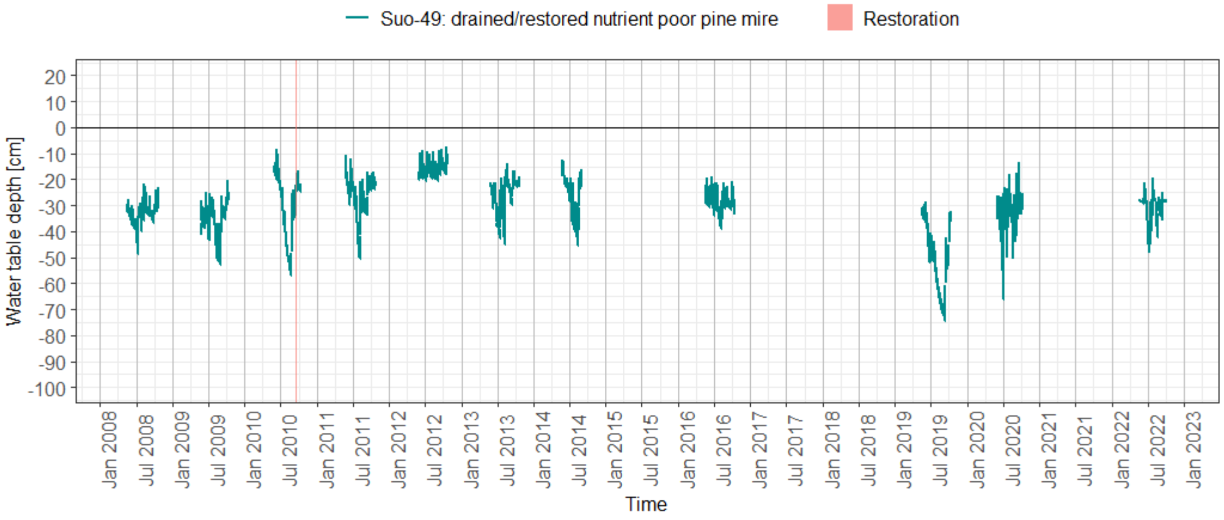
Suo-49: drained/restored nutrient poor pine mire
Restoration
Water table depth [cm]
20
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-10
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-30
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-60
-70
-80
-90
-100
Jan 2008
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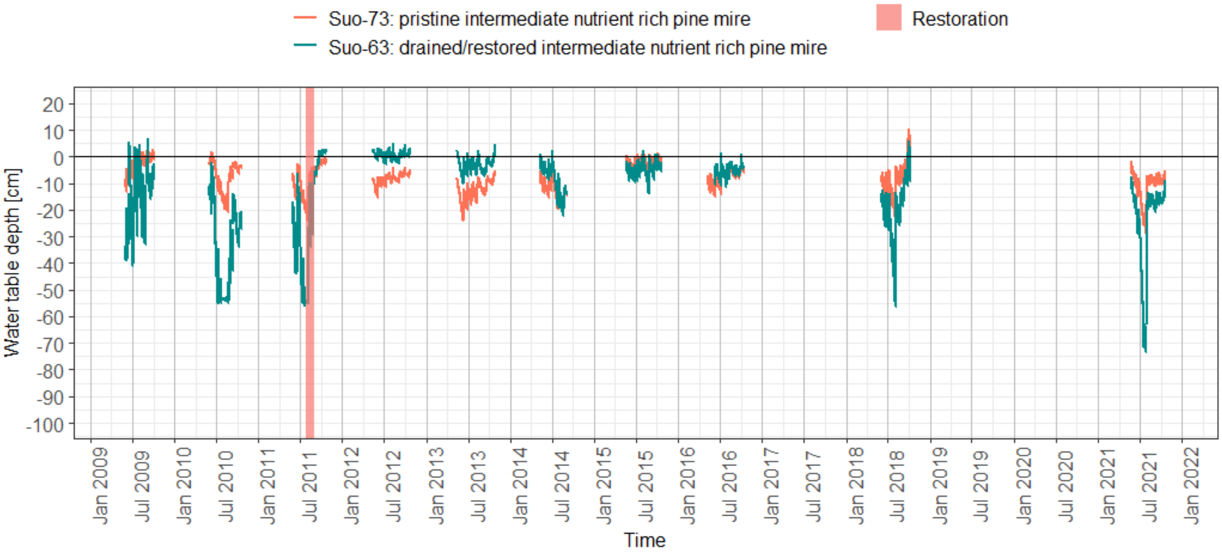
Suo-73: pristine intermediate nutrient rich pine mire
Suo-63: drained/restored intermediate nutrient rich pine mire
Restoration
Water table depth [cm]
20
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0
-10
-20
-30
-40
-50
-60
-70
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Jan 2009
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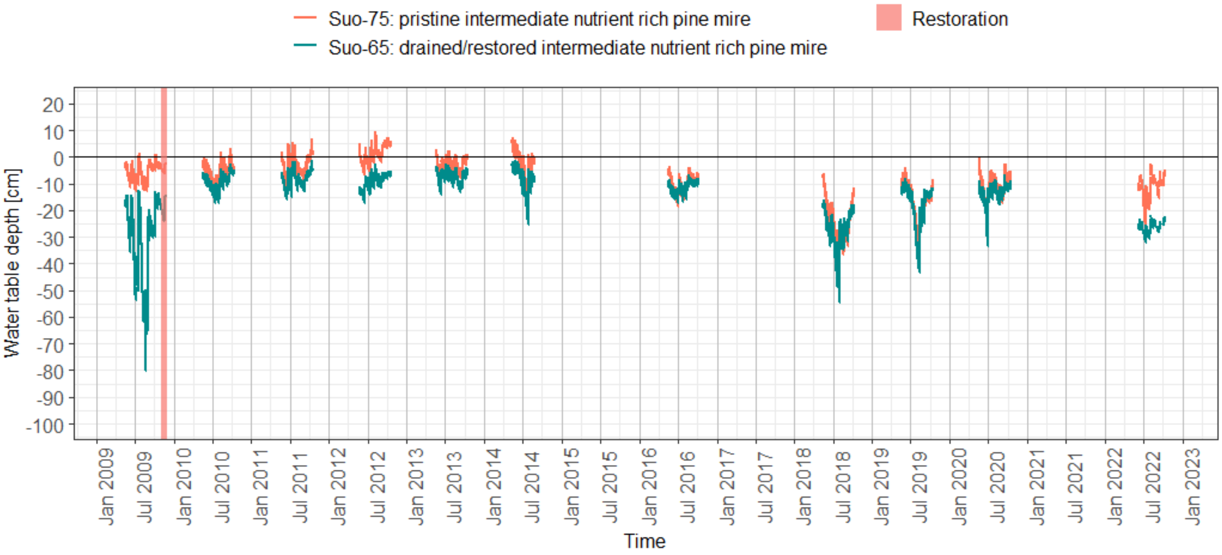
Suo-75: pristine intermediate nutrient rich pine mire
Suo-65: drained/restored intermediate nutrient rich pine mire
Restoration
Water table depth [cm]
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-20
-30
-40
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-60
-70
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Jan 2009
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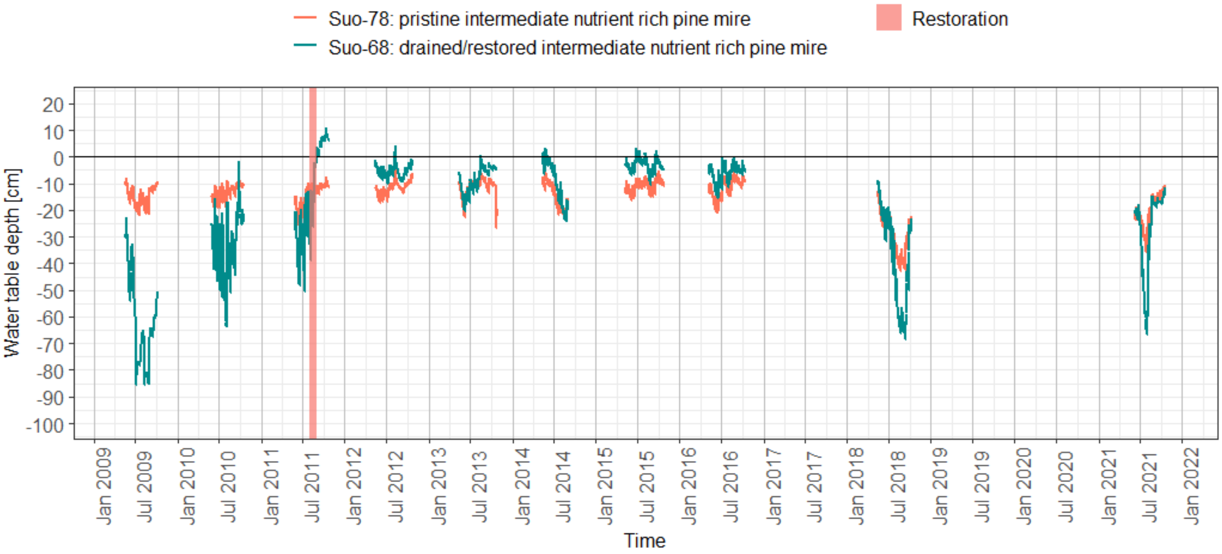
Suo-78: pristine intermediate nutrient rich pine mire
Suo-68: drained/restored intermediate nutrient rich pine mire
Restoration
Water table depth [cm]
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-20
-30
-40
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Jan 2009
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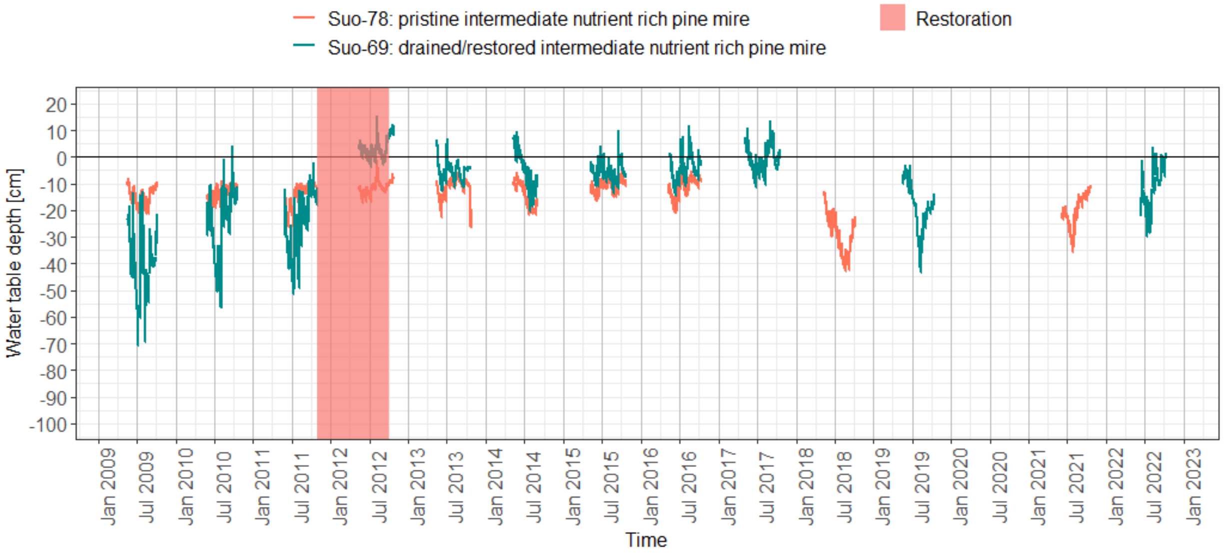
Suo-78: pristine intermediate nutrient rich pine mire
Suo-69: drained/restored intermediate nutrient rich pine mire
Restoration
Water table depth [cm]
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-20
-30
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Jan 2009
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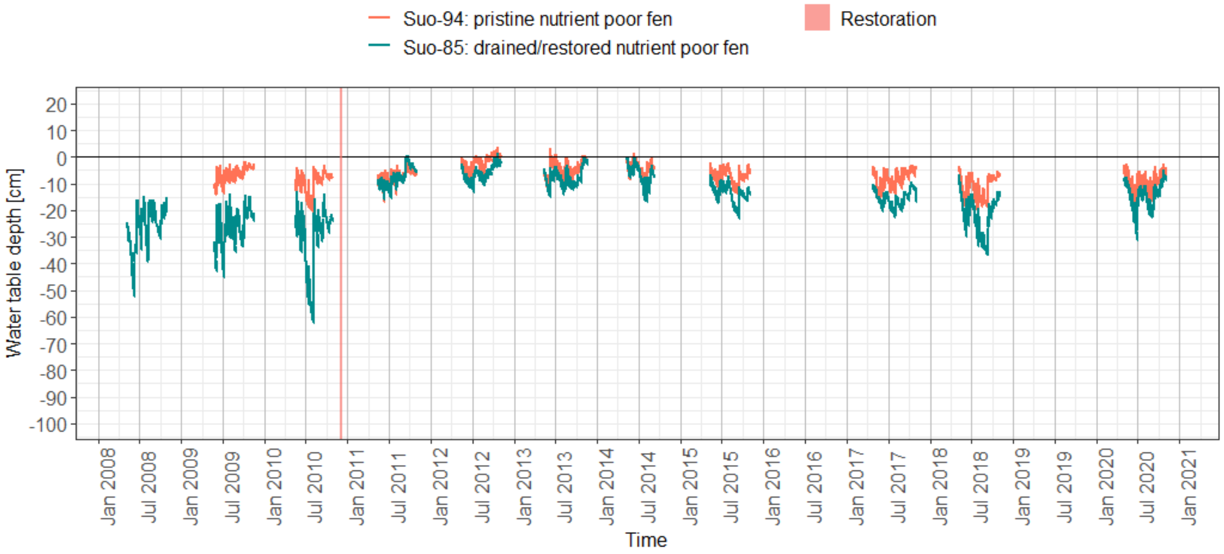
Suo-94: pristine nutrient poor fen
Suo-85: drained/restored nutrient poor fen
Restoration
Water table depth [cm]
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Jan 2008
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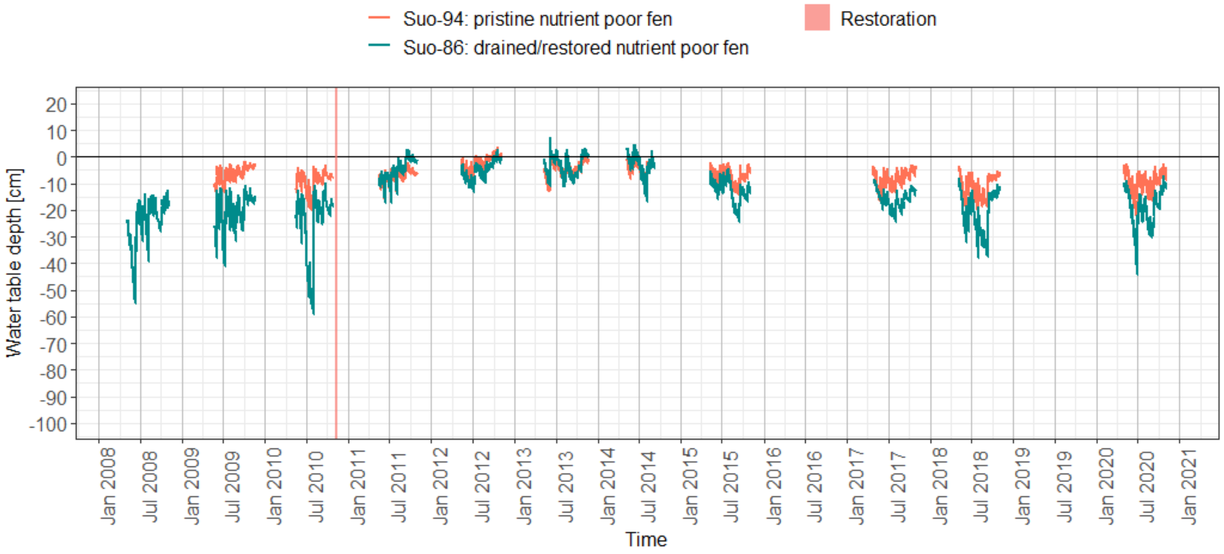
Suo-94: pristine nutrient poor fen
Suo-86: drained/restored nutrient poor fen
Restoration
Water table depth [cm]
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Jan 2008
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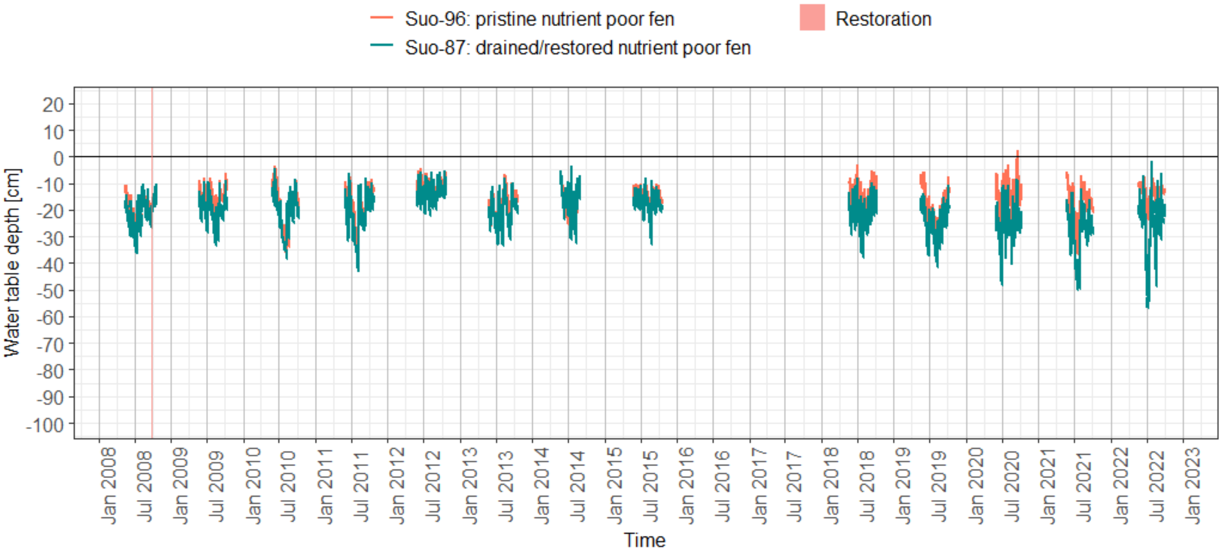

Suo-96: pristine nutrient poor fen
Suo-87: drained/restored nutrient poor fen
Restoration
Water table depth [cm]
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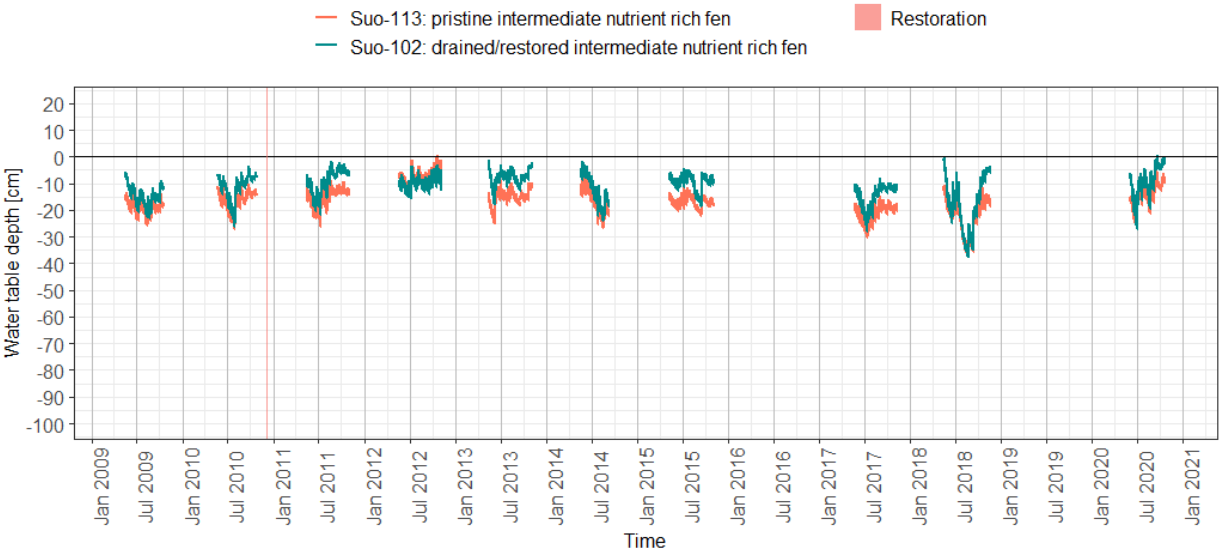

Suo-113: pristine intermediate nutrient rich fen
Suo-102: drained/restored intermediate nutrient rich fen
Restoration
Water table depth [cm]
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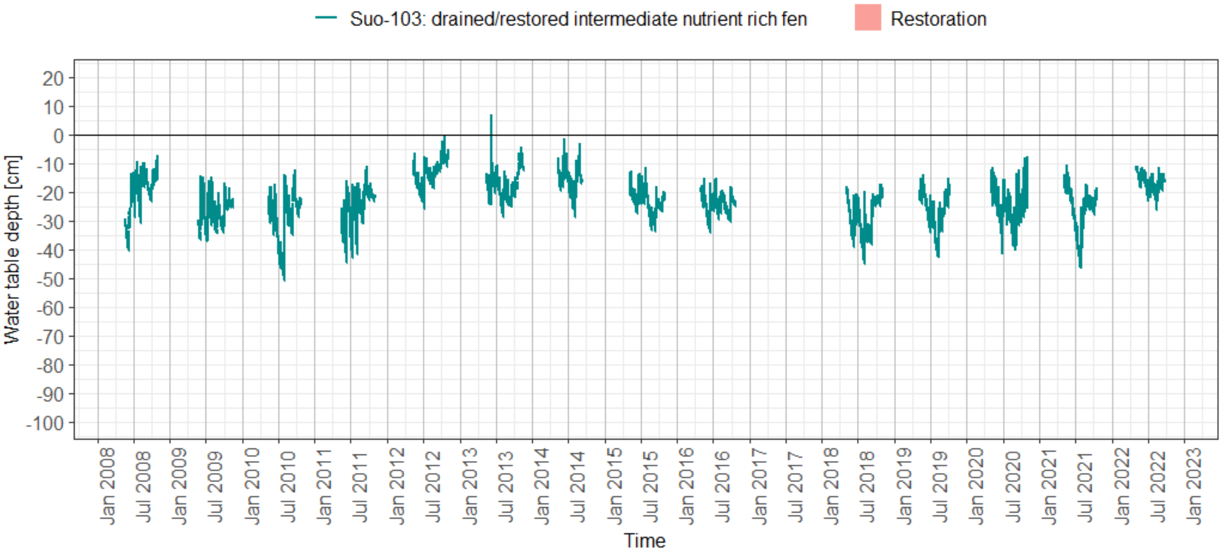

Suo-103: drained/restored intermediate nutrient rich fen
Restoration
Water table depth [cm]
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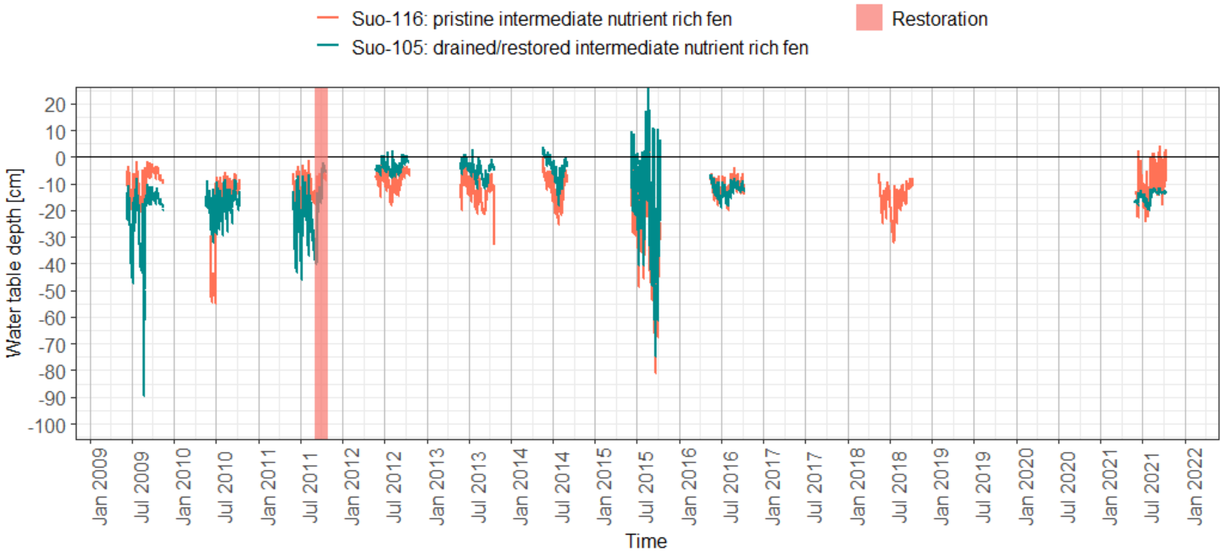
Time


Suo-116: pristine intermediate nutrient rich fen
Suo-105: drained/restored intermediate nutrient rich fen
Restoration
Water table depth [cm]
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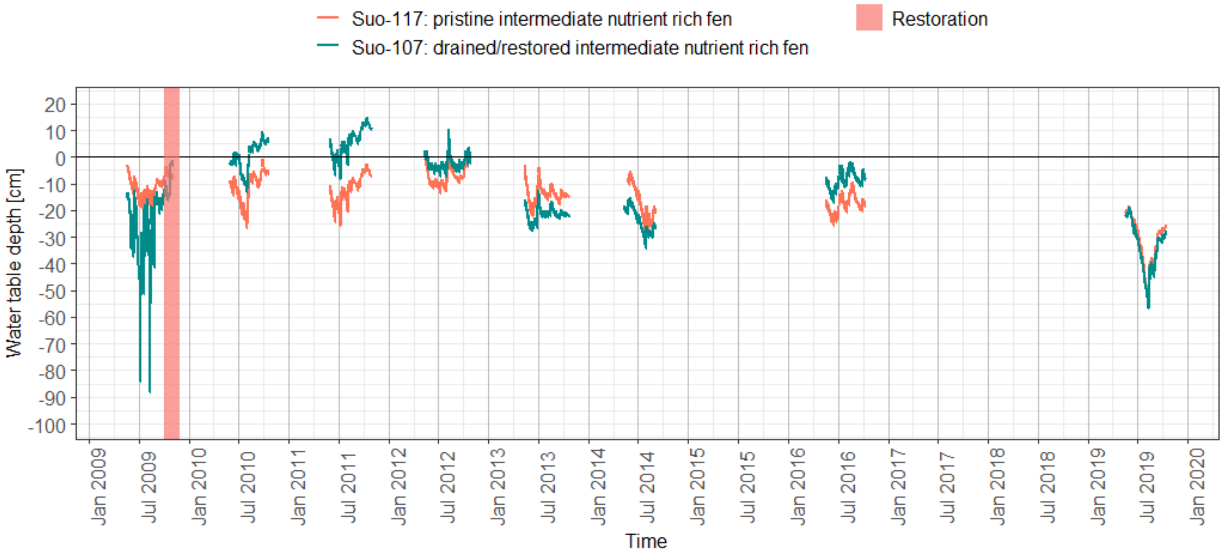
Suo-117: pristine intermediate nutrient rich fen
Suo-107: drained/restored intermediate nutrient rich fen
Restoration
Water table depth [cm]
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-30
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-50
-60
-70
-80
-90
-100
Jan 2009
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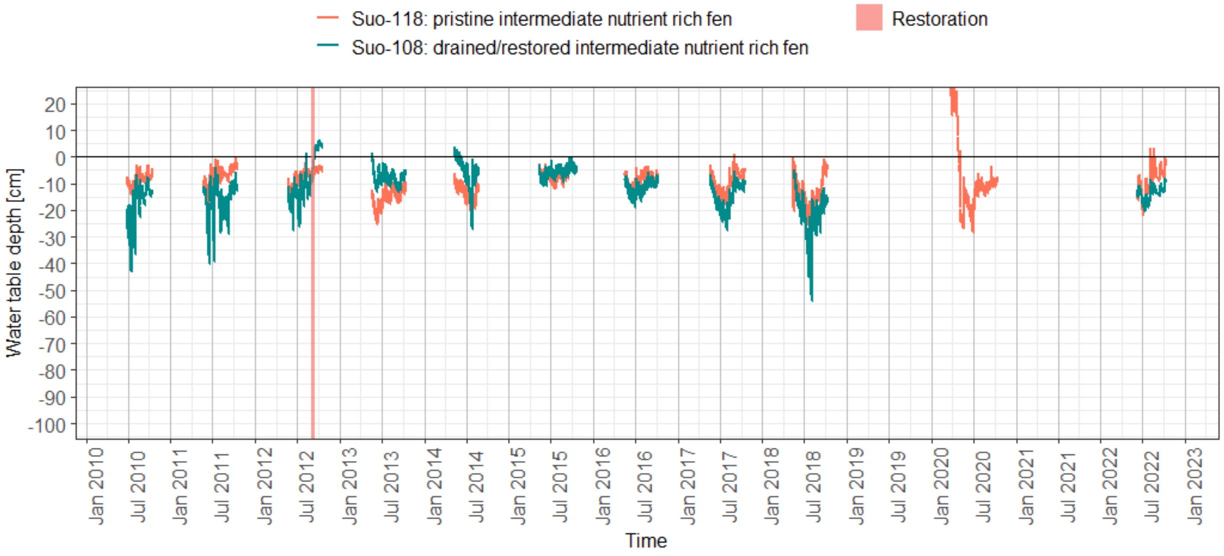
Suo-118: pristine intermediate nutrient rich fen
Suo-108: drained/restored intermediate nutrient rich fen
Restoration
Water table depth [cm]
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Jan 2022
Jul 2022
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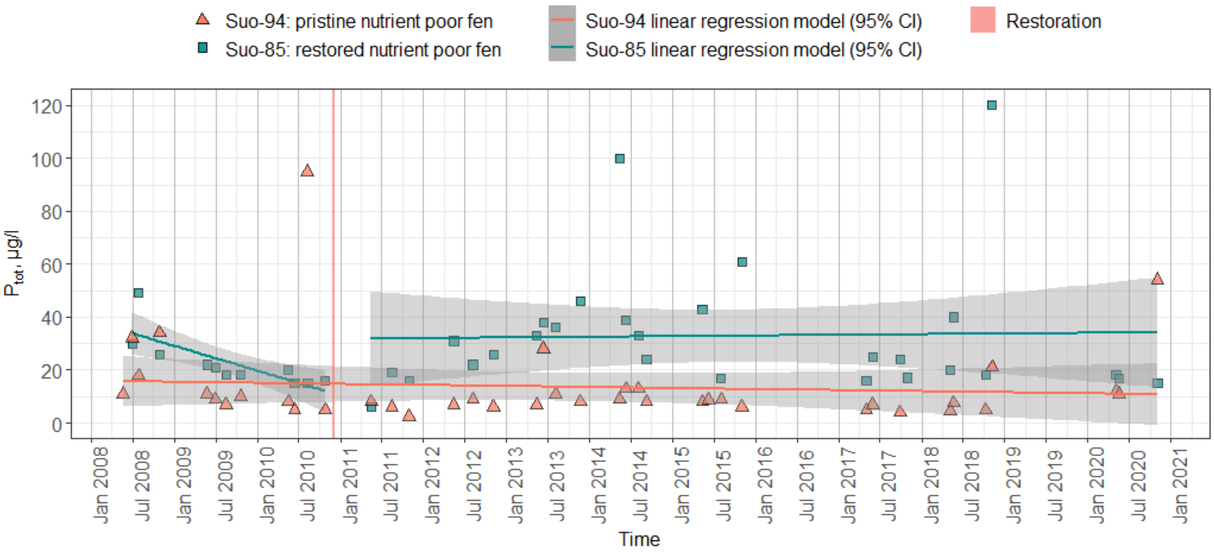
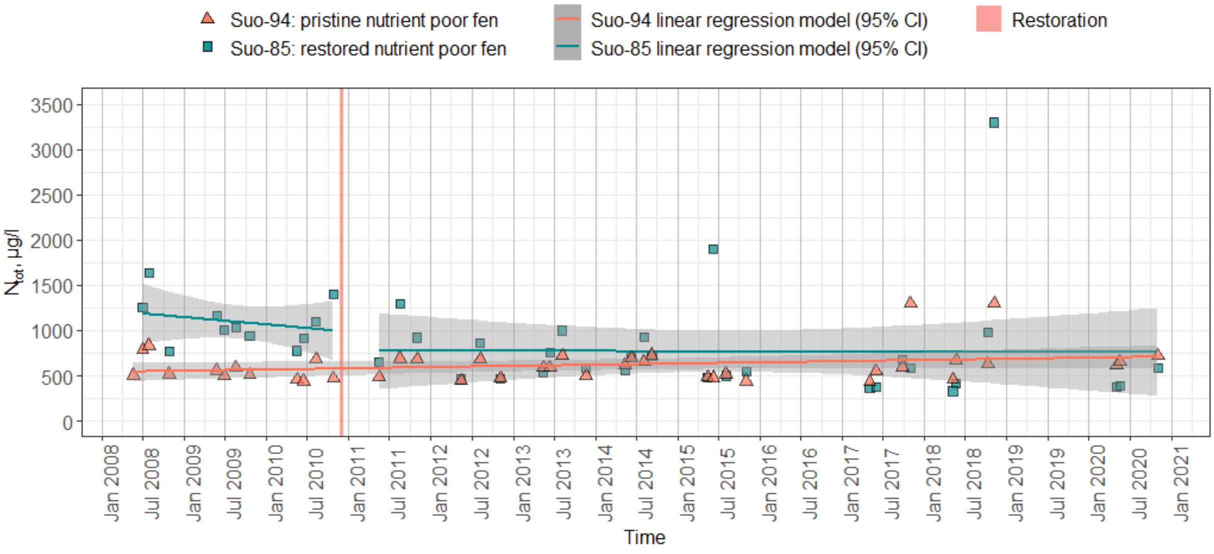
Time

Appendix 2A. 10-year water quality observations in the peatland monitoring network – Fens






Suo-94: pristine nutrient poor fen
Suo-85: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-85 linear regression model (95% CI)
Restoration
pH
4.50
4.25
4.00
3.75
3.50
Jan 2008
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Jan 2021
Time


Suo-94: pristine nutrient poor fen
Suo-85: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-85 linear regression model (95% CI)
Restoration
EC, mS/m
10
9
8
7
6
5
4
3
2
1
0
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
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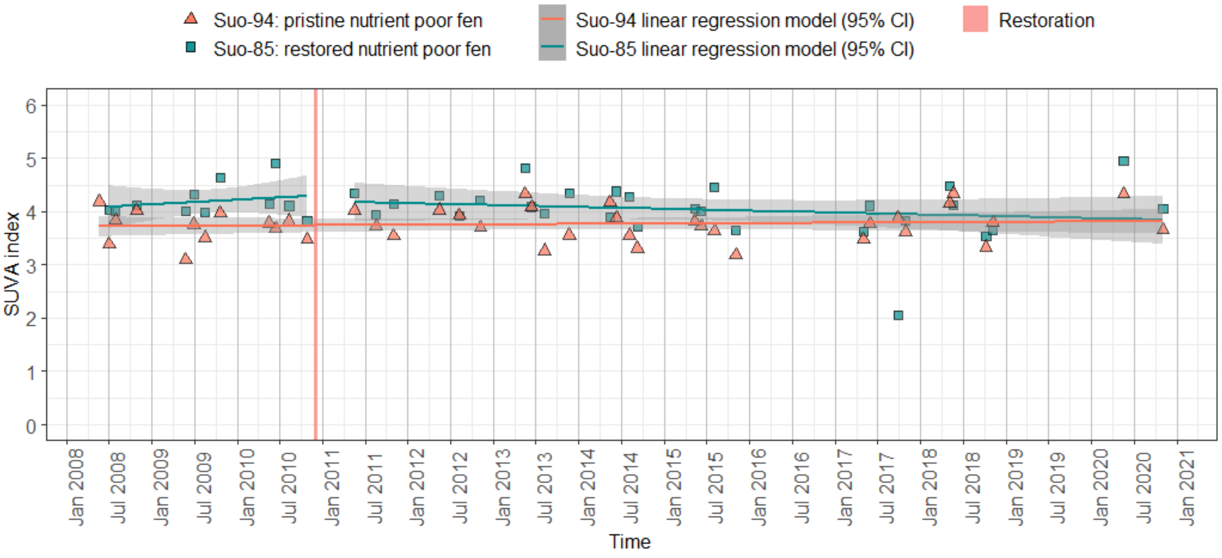
Suo-94: pristine nutrient poor fen
Suo-85: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-85 linear regression model (95% CI)
Restoration
SUVA index
6
5
4
3
2
1
0
Jan 2008
Jul 2008
Jan 2009
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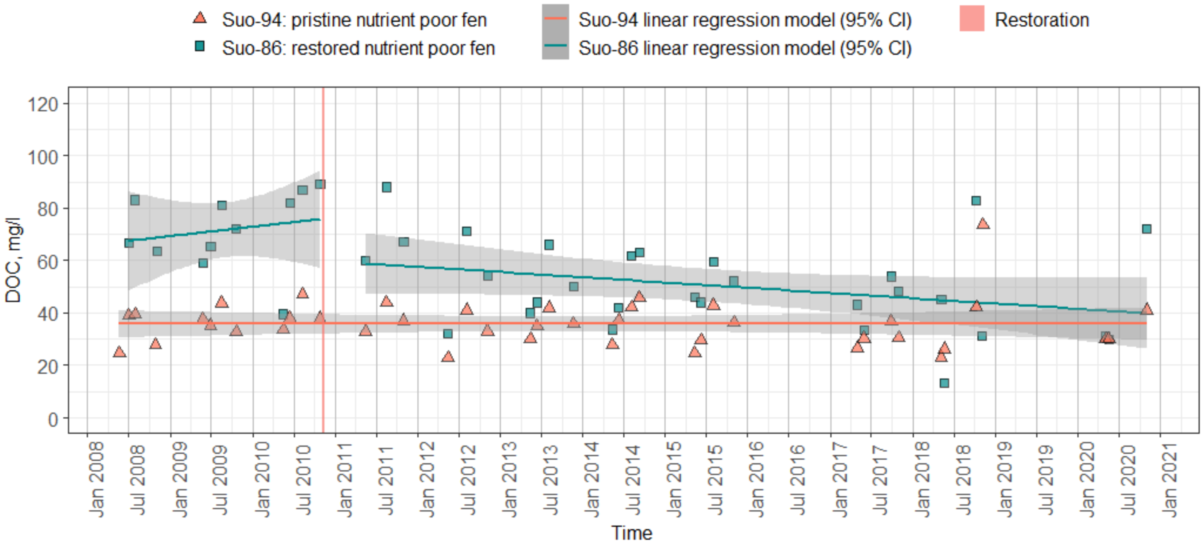
Suo-94: pristine nutrient poor fen
Suo-86: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-86 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
120
Jan 2008
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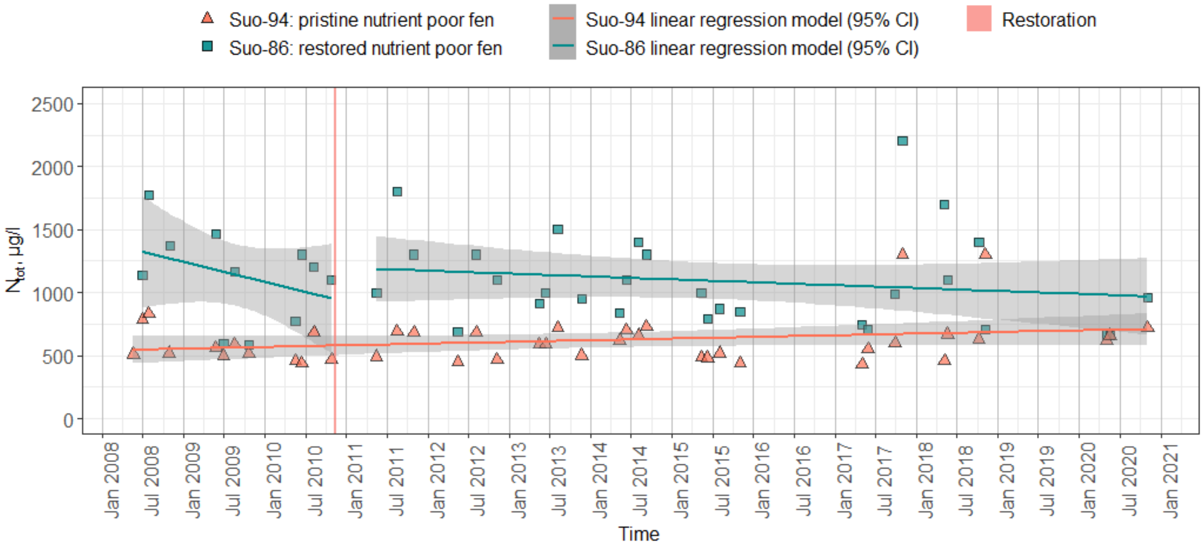
Suo-94: pristine nutrient poor fen
Suo-86: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-86 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
500
1000
1500
2000
2500
Jan 2008
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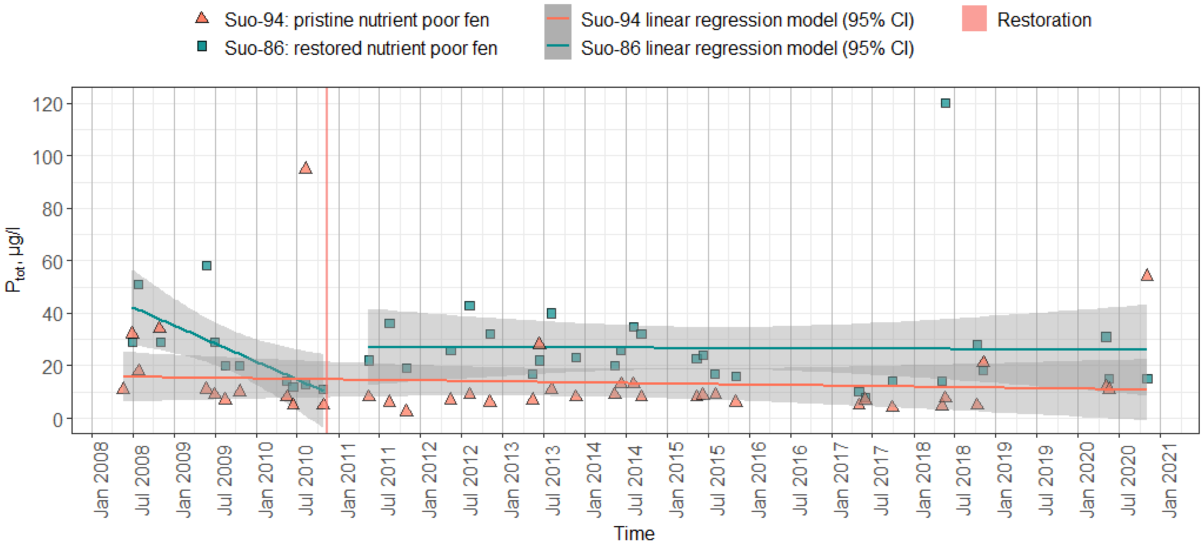
Suo-94: pristine nutrient poor fen
Suo-86: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-86 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
20
40
60
80
100
120
Jan 2008
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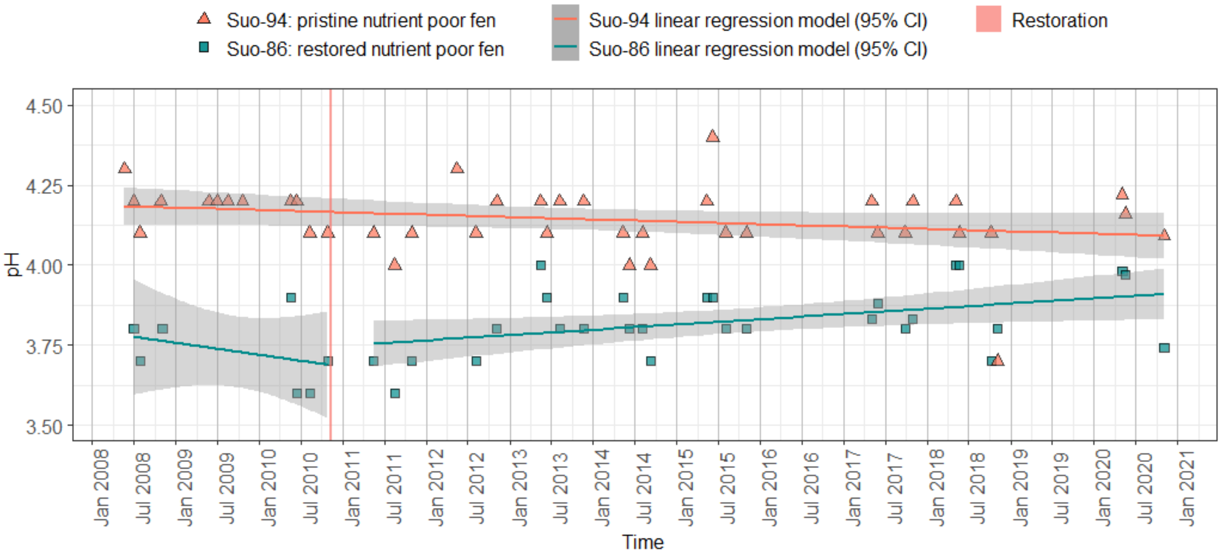
Suo-94: pristine nutrient poor fen
Suo-86: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-86 linear regression model (95% CI)
Restoration
pH
4.50
4.25
4.00
3.75
3.50
Jan 2008
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Jan 2021
Time


Suo-94: pristine nutrient poor fen
Suo-86: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-86 linear regression model (95% CI)
Restoration
EC, mS/m
11
10
9
8
7
6
5
4
3
2
1
0
Jan 2008
Jul 2008
Jan 2009
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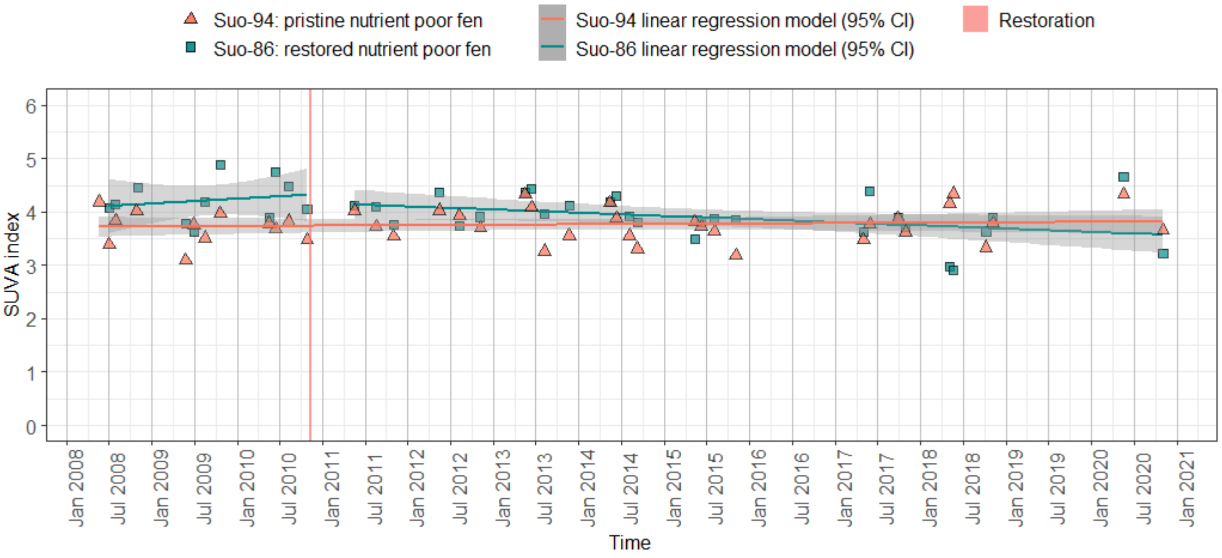
Suo-94: pristine nutrient poor fen
Suo-86: restored nutrient poor fen
Suo-94 linear regression model (95% CI)
Suo-86 linear regression model (95% CI)
Restoration
SUVA index
6
5
4
3
2
1
0
Jan 2008
Jul 2008
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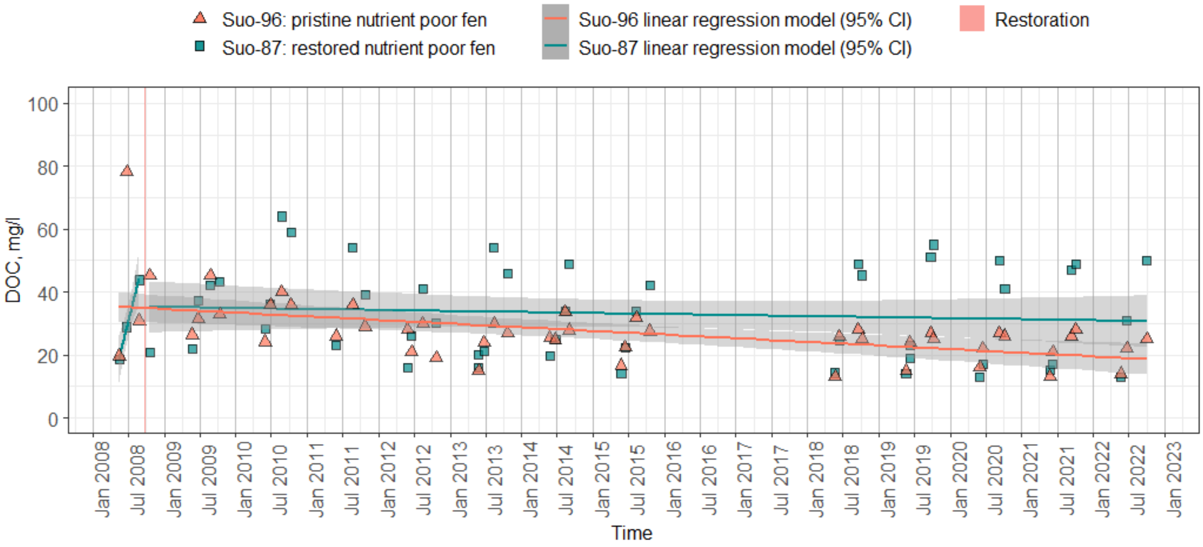
Suo-96: pristine nutrient poor fen
Suo-87: restored nutrient poor fen
Suo-96 linear regression model (95% CI)
Suo-87 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
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Jan 2008
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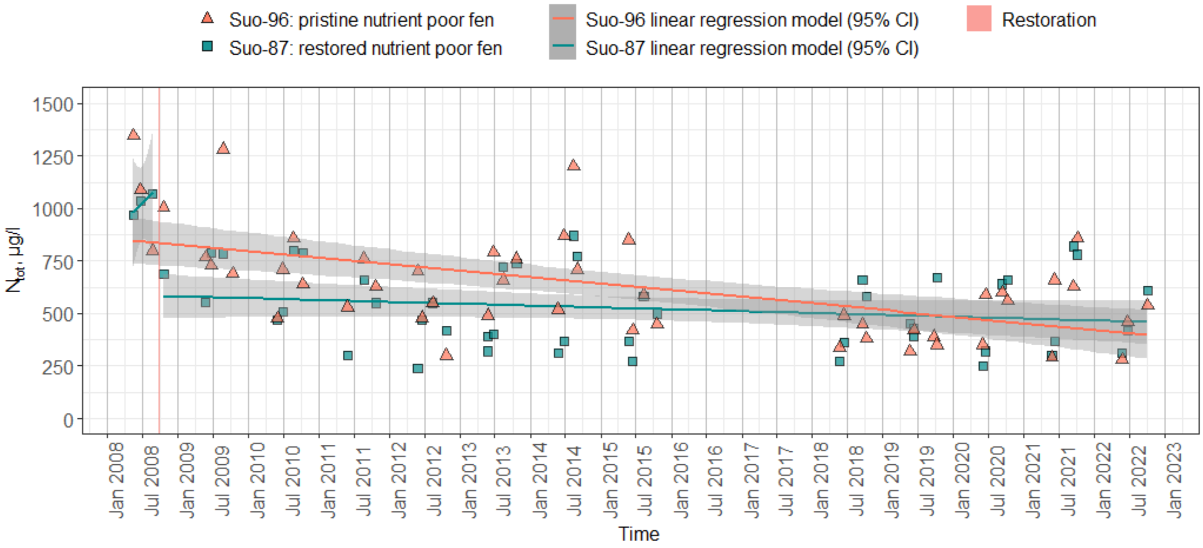
Time


Suo-96: pristine nutrient poor fen
Suo-87: restored nutrient poor fen
Suo-96 linear regression model (95% CI)
Suo-87 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
250
500
750
1000
1250
1500
Jan 2008
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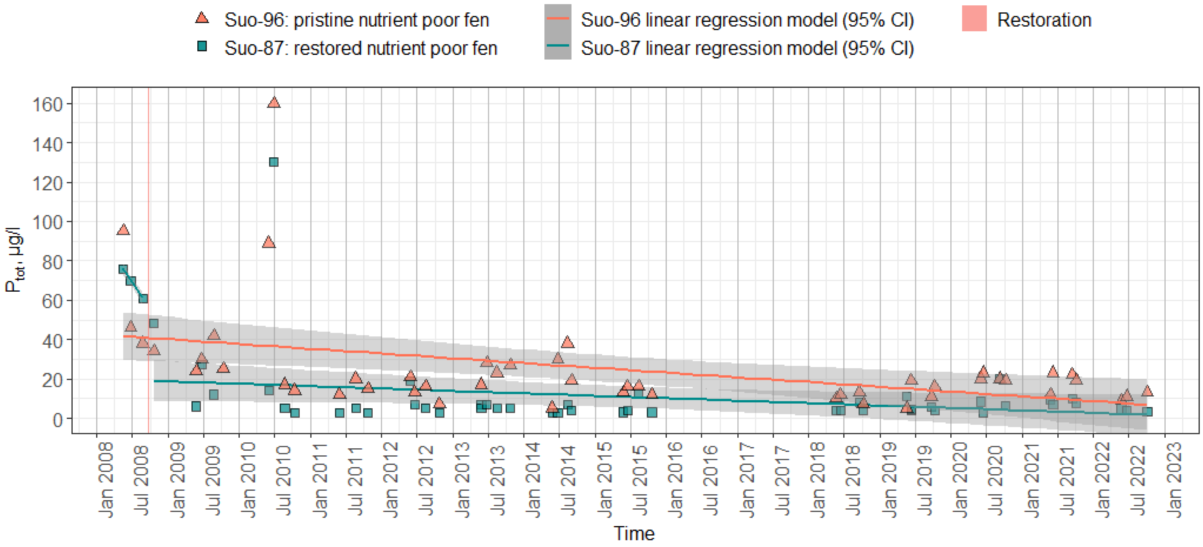
Time


Suo-96: pristine nutrient poor fen
Suo-87: restored nutrient poor fen
Suo-96 linear regression model (95% CI)
Suo-87 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
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Jan 2008
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Time


Suo-96: pristine nutrient poor fen
Suo-87: restored nutrient poor fen
Suo-96 linear regression model (95% CI)
Suo-87 linear regression model (95% CI)
Restoration
pH
4.50
4.25
4.00
3.75
3.50
Jan 2008
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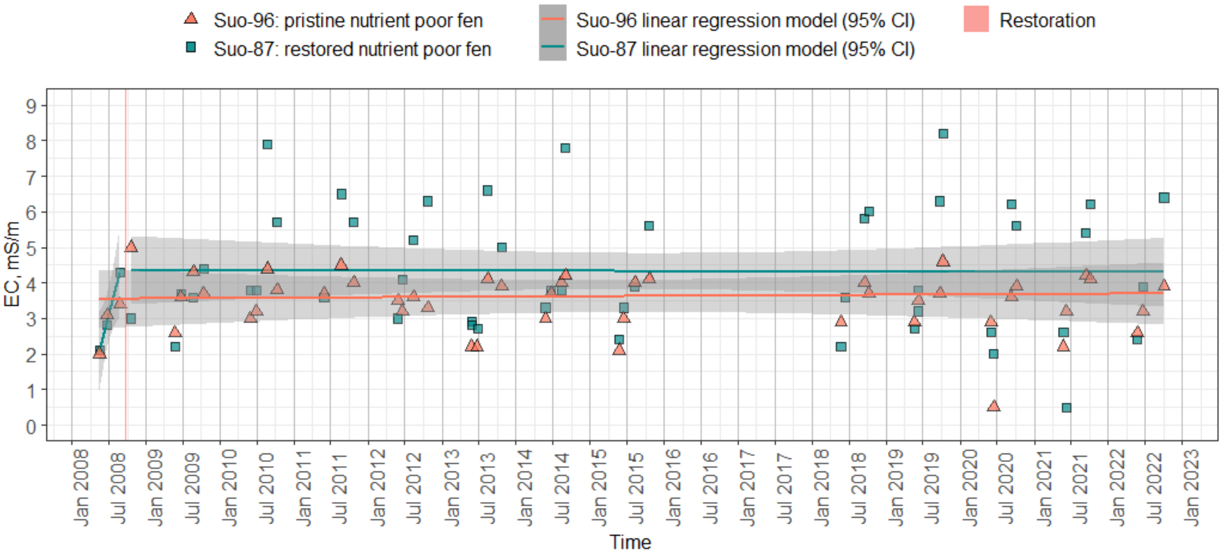
Time


Suo-96: pristine nutrient poor fen
Suo-87: restored nutrient poor fen
Suo-96 linear regression model (95% CI)
Suo-87 linear regression model (95% CI)
Restoration
EC, mS/m
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Jan 2008
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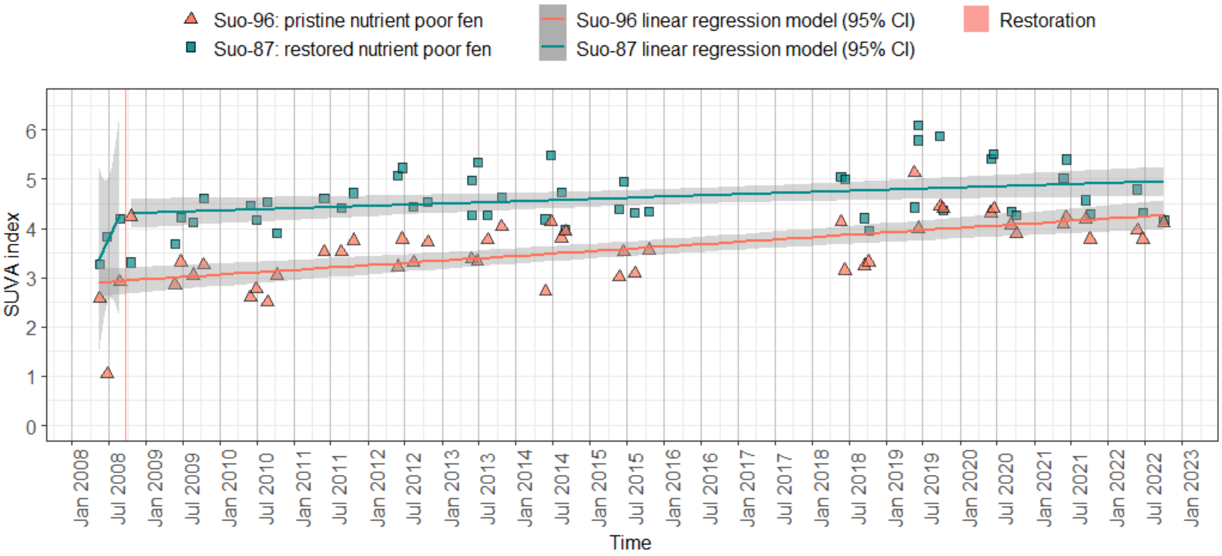
Time


Suo-96: pristine nutrient poor fen
Suo-87: restored nutrient poor fen
Suo-96 linear regression model (95% CI)
Suo-87 linear regression model (95% CI)
Restoration
SUVA index
6
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3
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Jan 2008
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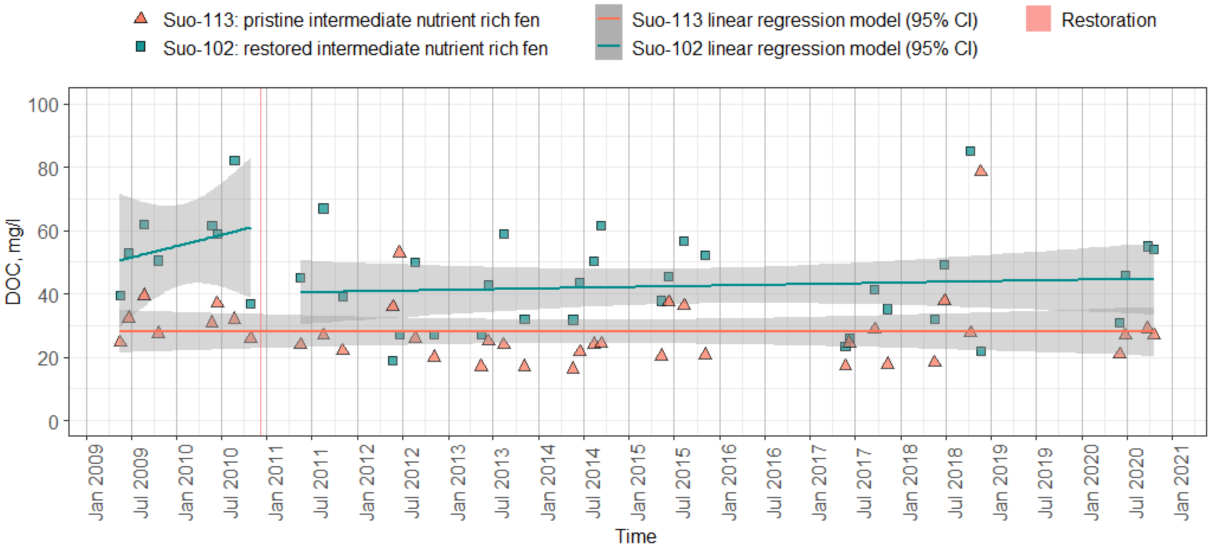
Jan 2023
Time


Suo-113: pristine intermediate nutrient rich fen
Suo-102: restored intermediate nutrient rich fen
Suo-113 linear regression model (95% CI)
Suo-102 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
Jan 2009
Jul 2009
Jan 2010
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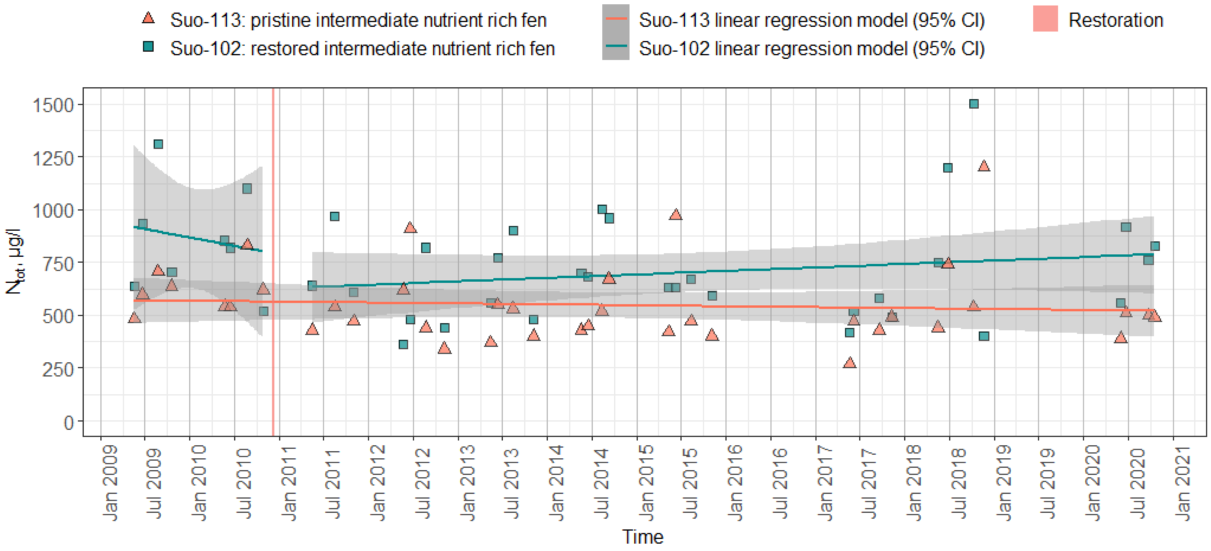
Time


Suo-113: pristine intermediate nutrient rich fen
Suo-102: restored intermediate nutrient rich fen
Suo-113 linear regression model (95% CI)
Suo-102 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
250
500
750
1000
1250
1500
Jan 2009
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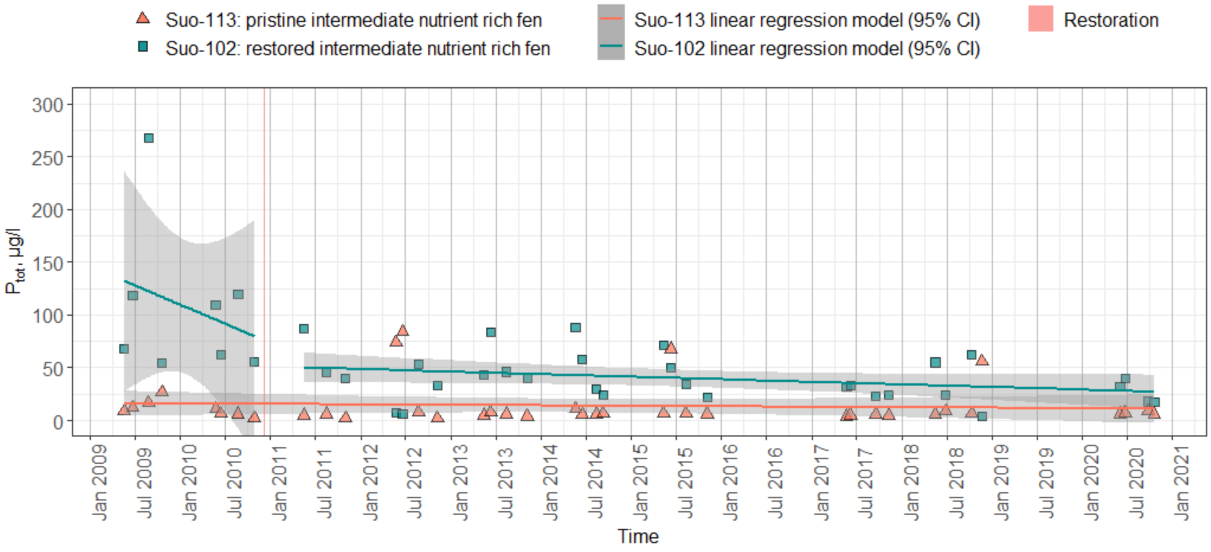
Suo-113: pristine intermediate nutrient rich fen
Suo-102: restored intermediate nutrient rich fen
Suo-113 linear regression model (95% CI)
Suo-102 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
50
100
150
200
250
300
Jan 2009
Jul 2009
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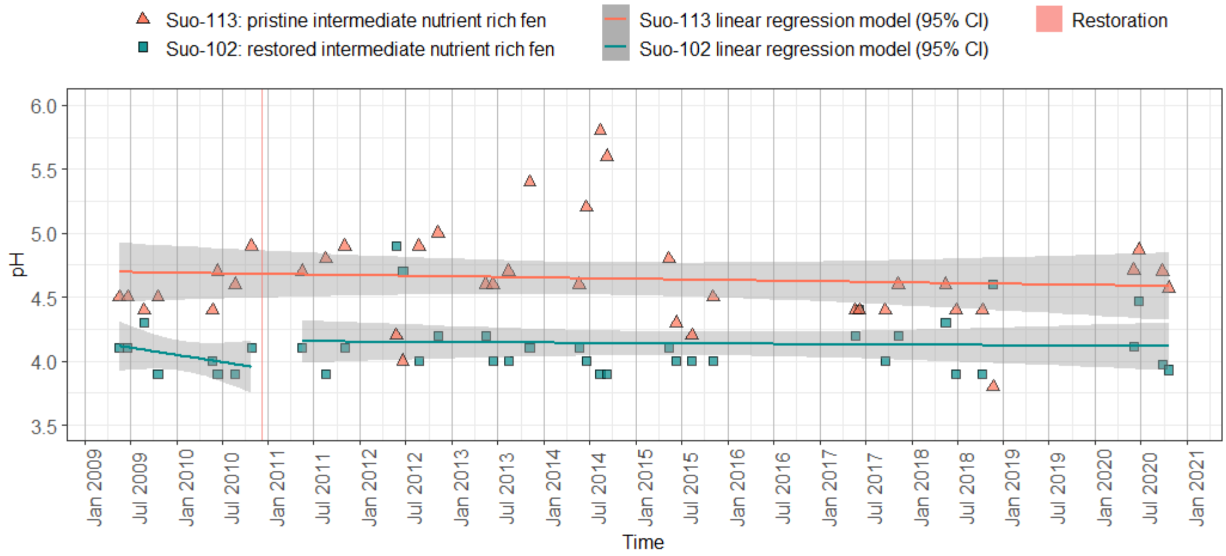
Suo-113: pristine intermediate nutrient rich fen
Suo-102: restored intermediate nutrient rich fen
Suo-113 linear regression model (95% CI)
Suo-102 linear regression model (95% CI)
Restoration
pH
6.0
5.5
5.0
4.5
4.0
3.5
Jan 2009
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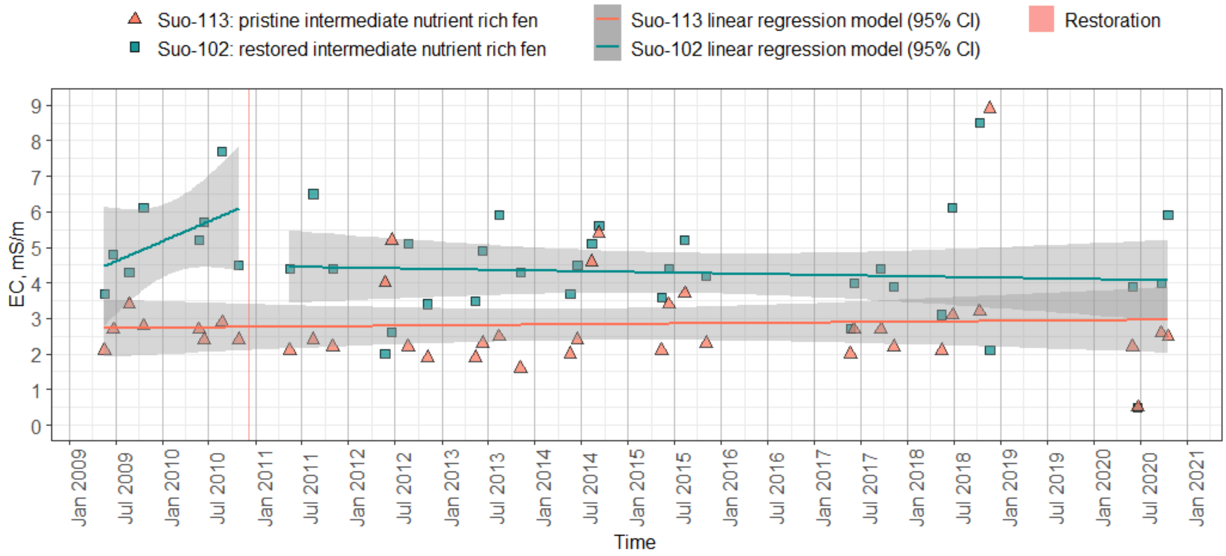
Suo-113: pristine intermediate nutrient rich fen
Suo-102: restored intermediate nutrient rich fen
Suo-113 linear regression model (95% CI)
Suo-102 linear regression model (95% CI)
Restoration
EC, mS/m
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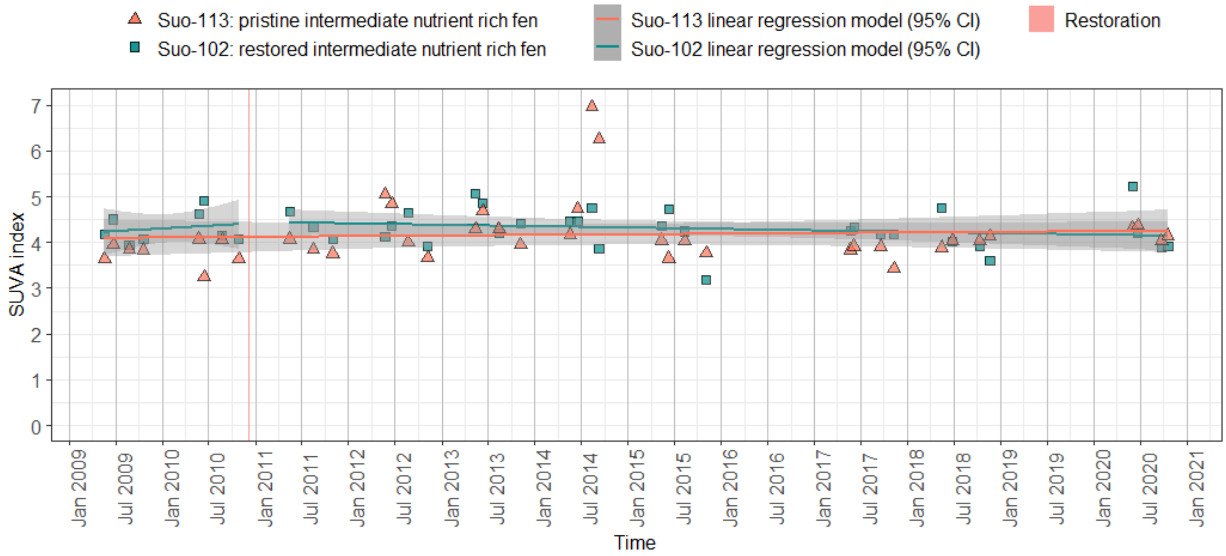
Suo-113: pristine intermediate nutrient rich fen
Suo-102: restored intermediate nutrient rich fen
Suo-113 linear regression model (95% CI)
Suo-102 linear regression model (95% CI)
Restoration
SUVA index
7
6
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Jan 2009
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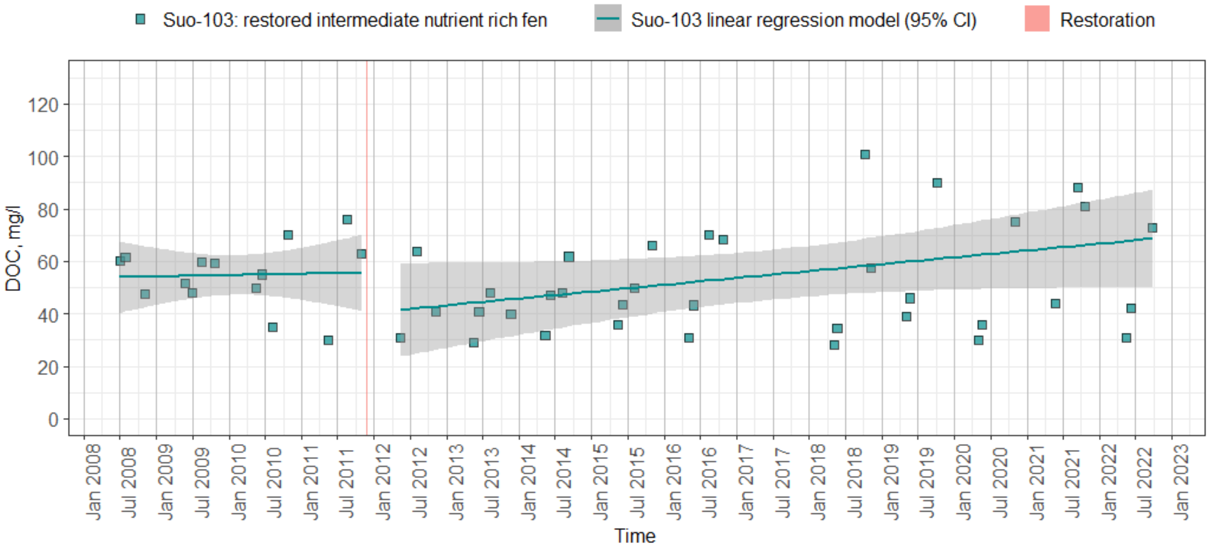
Suo-103: restored intermediate nutrient rich fen
Suo-103 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
120
Jan 2008
Jul 2008
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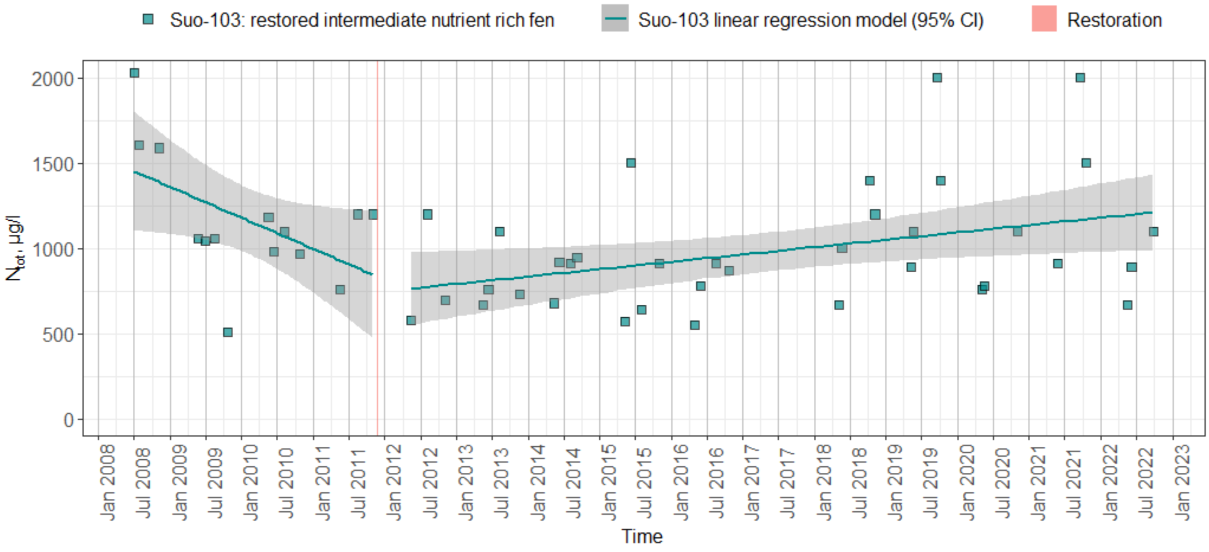
Time


Suo-103: restored intermediate nutrient rich fen
Suo-103 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
500
1000
1500
2000
Jan 2008
Jul 2008
Jan 2009
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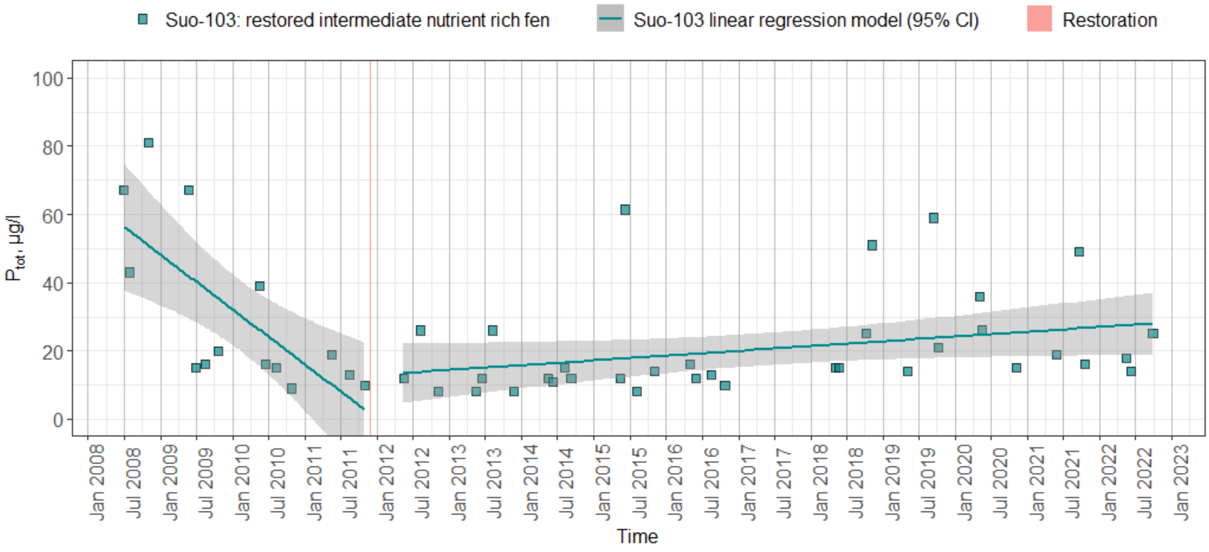
Time


Suo-103: restored intermediate nutrient rich fen
Suo-103 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
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Jan 2008
Jul 2008
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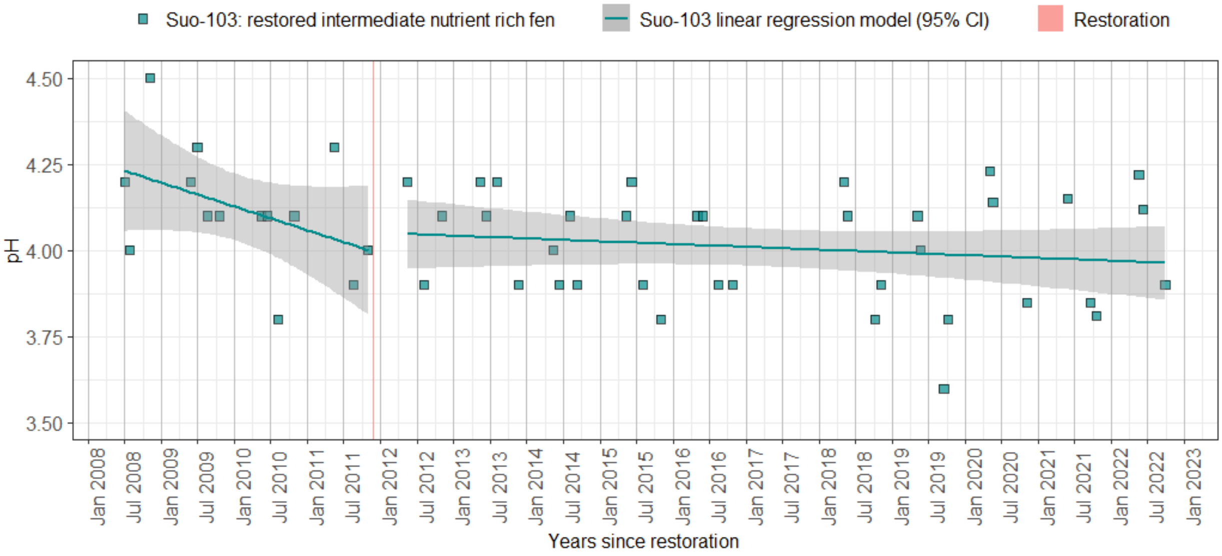
Suo-103: restored intermediate nutrient rich fen
Suo-103 linear regression model (95% CI)
Restoration
pH
4.50
4.25
4.00
3.75
3.50
Jan 2008
Jul 2008
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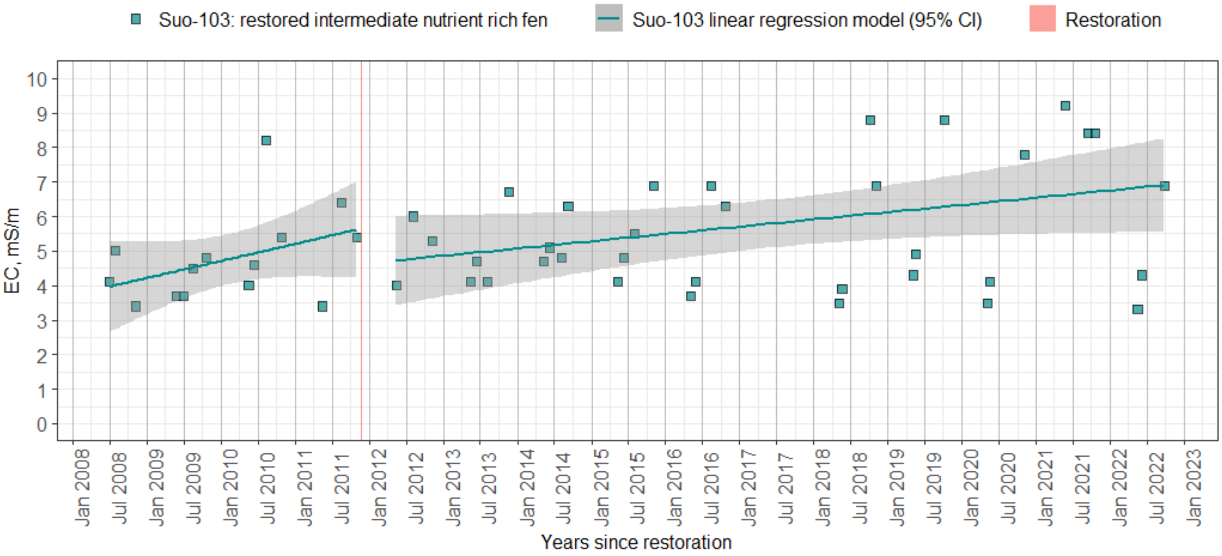
Jan 2023
Years since restoration


Suo-103: restored intermediate nutrient rich fen
Suo-103 linear regression model (95% CI)
Restoration
EC, mS/m
10
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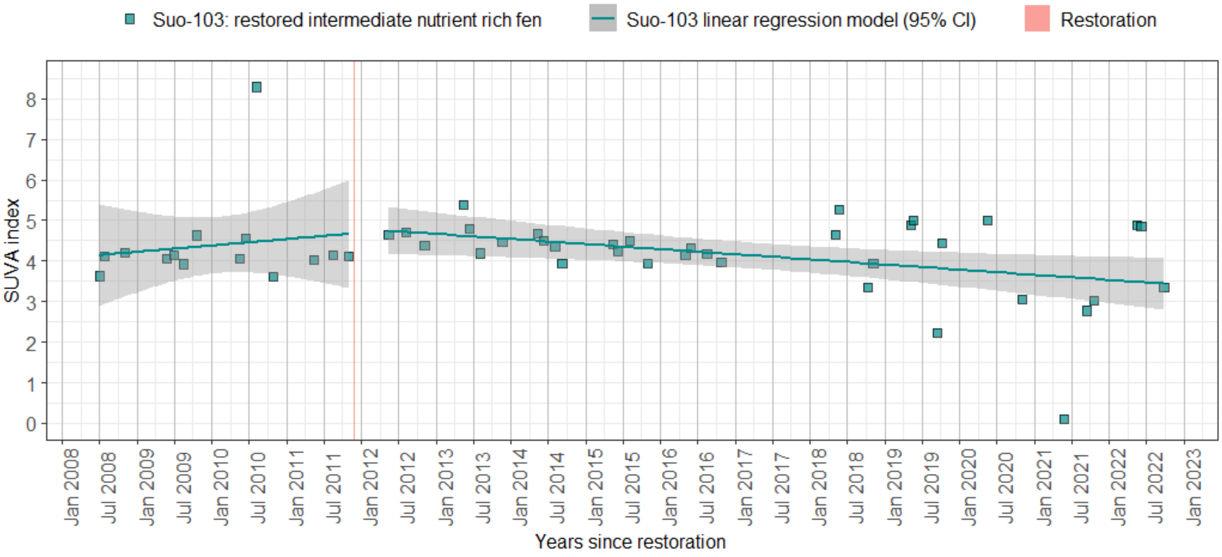
Years since restoration


Suo-103: restored intermediate nutrient rich fen
Suo-103 linear regression model (95% CI)
Restoration
SUVA index
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Jan 2008
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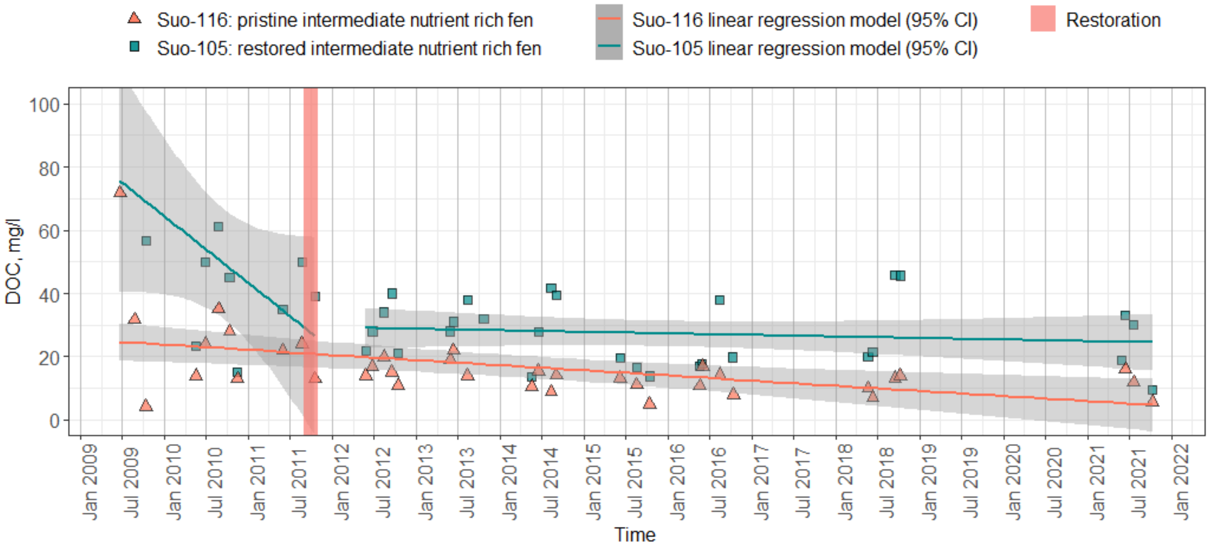
Years since restoration


Suo-116: pristine intermediate nutrient rich fen
Suo-105: restored intermediate nutrient rich fen
Suo-116 linear regression model (95% CI)
Suo-105 linear regression model (95% CI)
Restoration
DOC, mg/l
100
80
60
40
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Jan 2009
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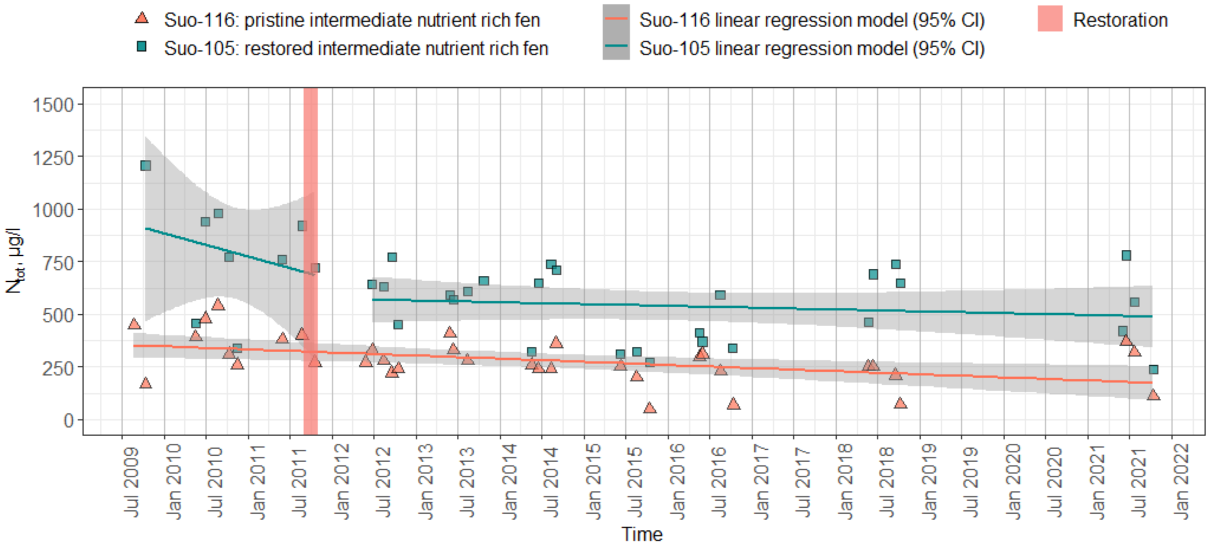
Time


Suo-116: pristine intermediate nutrient rich fen
Suo-105: restored intermediate nutrient rich fen
Suo-116 linear regression model (95% CI)
Suo-105 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
1500
1250
1000
750
500
250
0
Jul 2009
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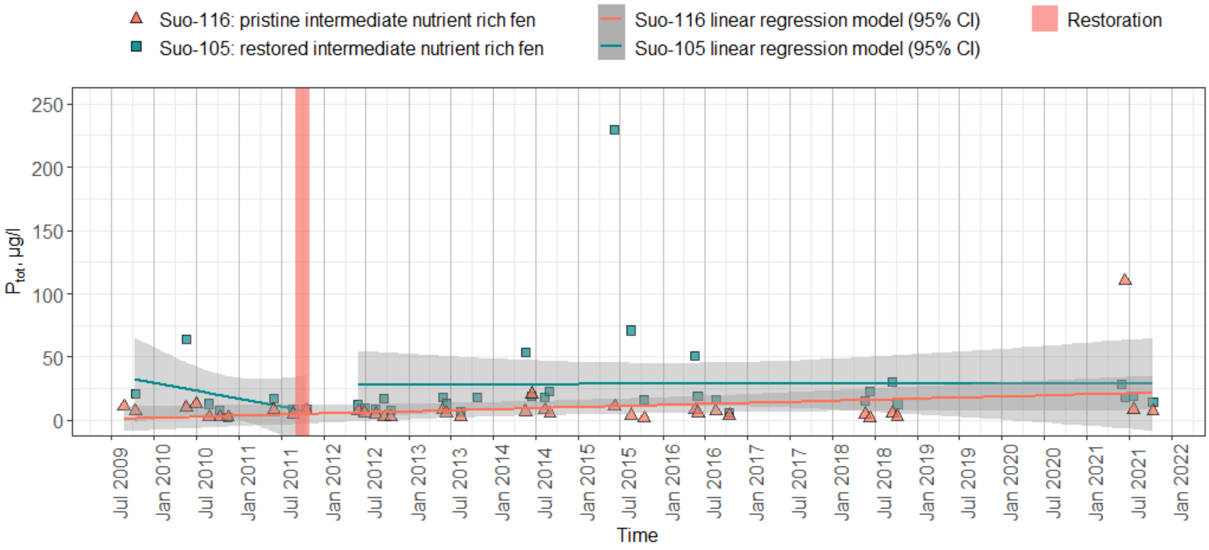
Suo-116: pristine intermediate nutrient rich fen
Suo-105: restored intermediate nutrient rich fen
Suo-116 linear regression model (95% CI)
Suo-105 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
250
200
150
100
50
0
Jul 2009
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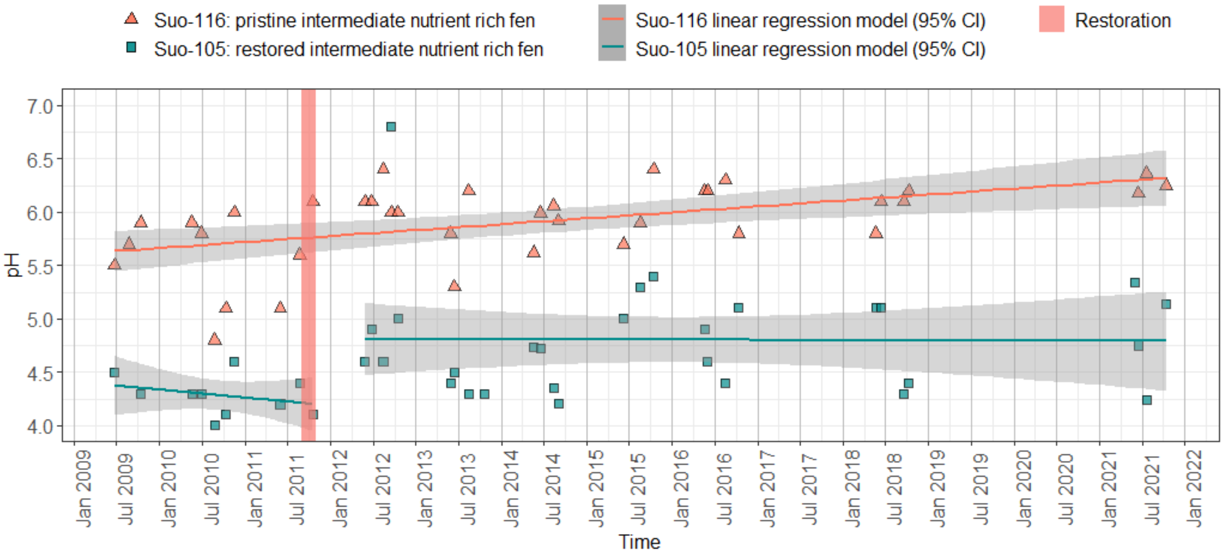
Time


Suo-116: pristine intermediate nutrient rich fen
Suo-105: restored intermediate nutrient rich fen
Suo-116 linear regression model (95% CI)
Suo-105 linear regression model (95% CI)
Restoration
pH
7.0
6.5
6.0
5.5
5.0
4.5
4.0
Jan 2009
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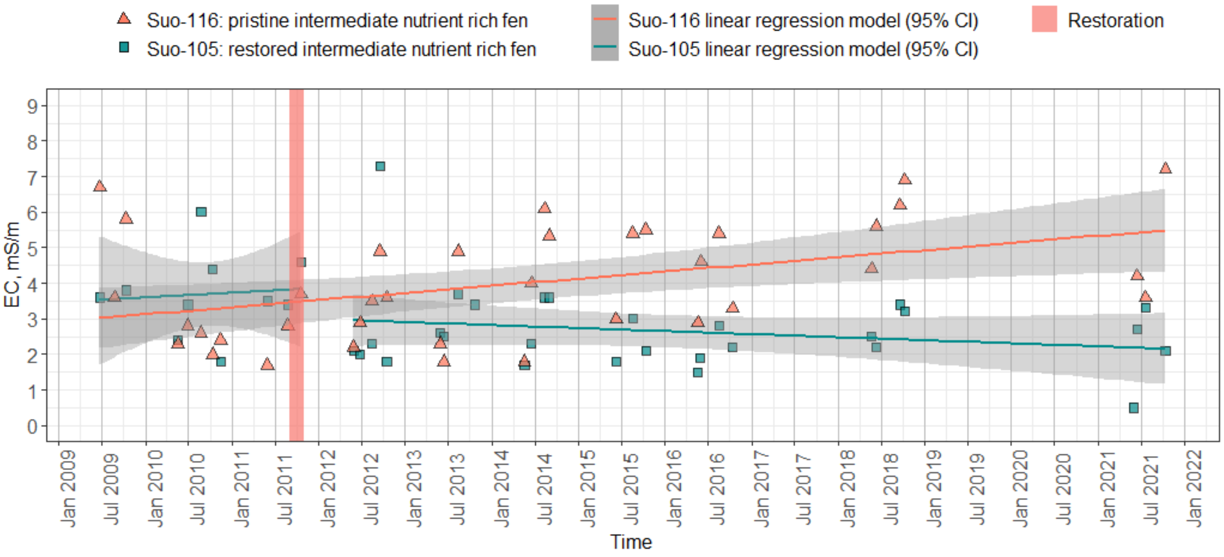
Suo-116: pristine intermediate nutrient rich fen
Suo-105: restored intermediate nutrient rich fen
Suo-116 linear regression model (95% CI)
Suo-105 linear regression model (95% CI)
Restoration
EC, mS/m
9
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Jan 2009
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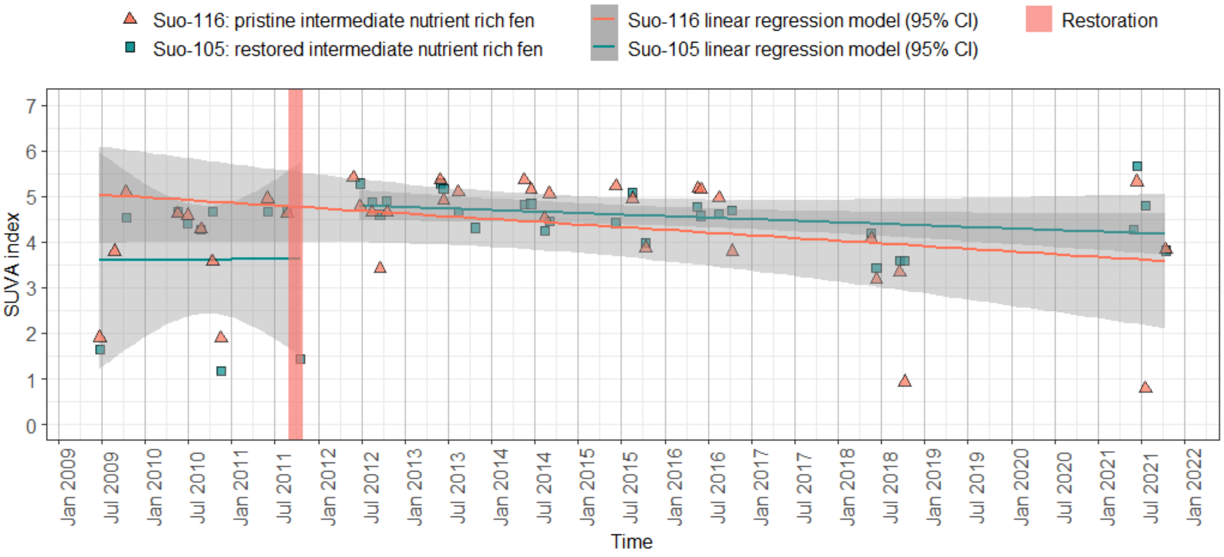
Suo-116: pristine intermediate nutrient rich fen
Suo-105: restored intermediate nutrient rich fen
Suo-116 linear regression model (95% CI)
Suo-105 linear regression model (95% CI)
Restoration
SUVA index
7
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Jan 2009
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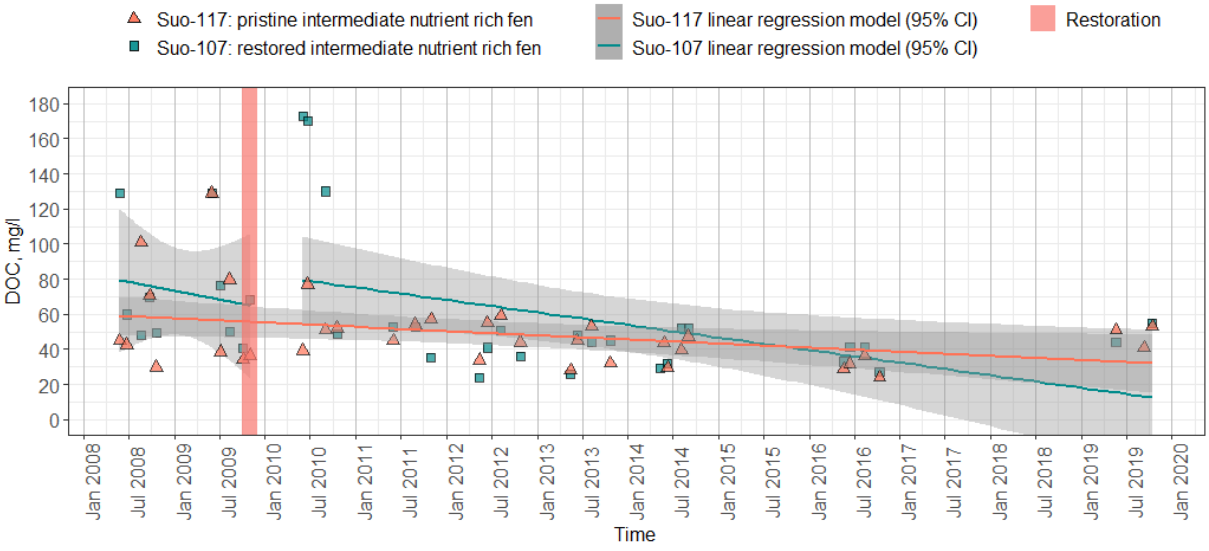
Time


Suo-117: pristine intermediate nutrient rich fen
Suo-107: restored intermediate nutrient rich fen
Suo-117 linear regression model (95% CI)
Suo-107 linear regression model (95% CI)
Restoration
DOC, mg/l
180
160
140
120
100
80
60
40
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0
Jan 2008
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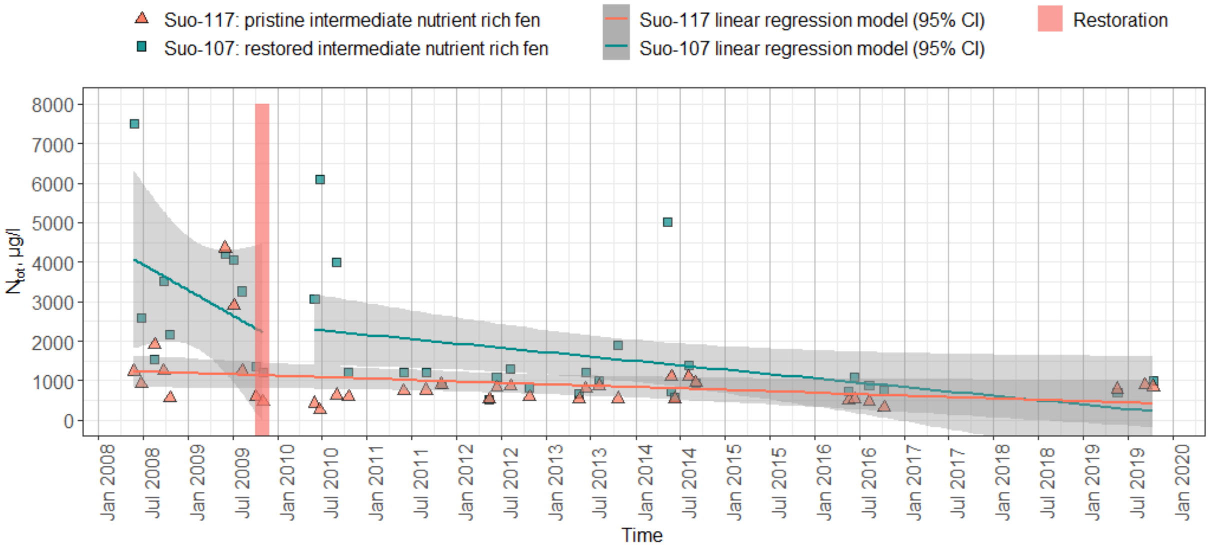
Suo-117: pristine intermediate nutrient rich fen
Suo-107: restored intermediate nutrient rich fen
Suo-117 linear regression model (95% CI)
Suo-107 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
8000
7000
6000
5000
4000
3000
2000
1000
0
Jan 2008
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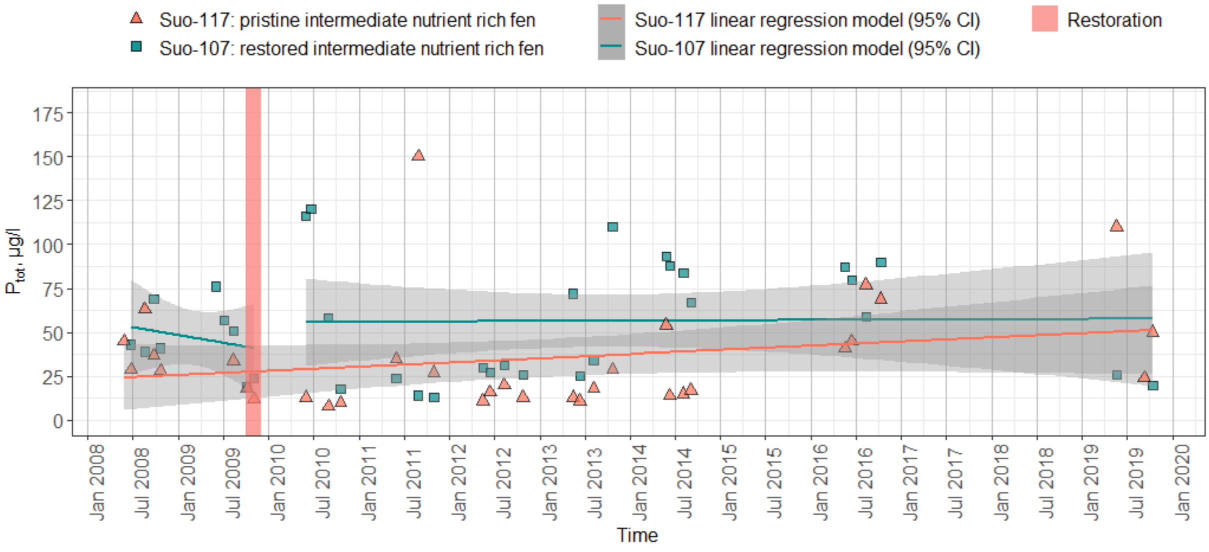
Time


Suo-117: pristine intermediate nutrient rich fen
Suo-107: restored intermediate nutrient rich fen
Suo-117 linear regression model (95% CI)
Suo-107 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
175
150
125
100
75
50
25
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Jan 2008
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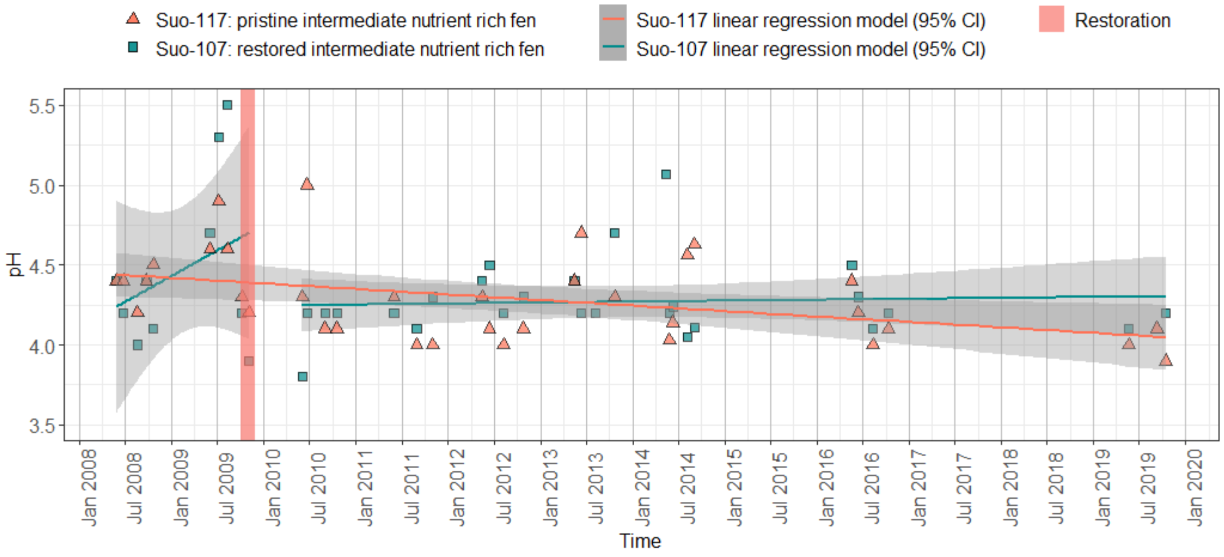
Jan 2020
Time


Suo-117: pristine intermediate nutrient rich fen
Suo-107: restored intermediate nutrient rich fen
Suo-117 linear regression model (95% CI)
Suo-107 linear regression model (95% CI)
Restoration
pH
5.5
5.0
4.5
4.0
3.5
Jan 2008
Jul 2008
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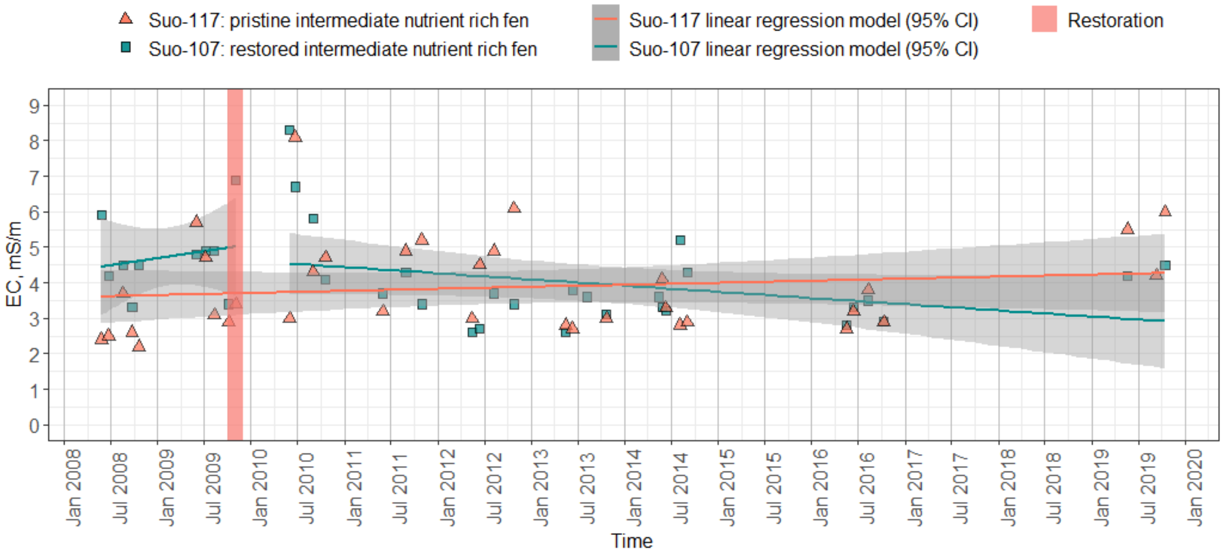
Time


Suo-117: pristine intermediate nutrient rich fen
Suo-107: restored intermediate nutrient rich fen
Suo-117 linear regression model (95% CI)
Suo-107 linear regression model (95% CI)
Restoration
EC, mS/m
9
8
7
6
5
4
3
2
1
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Jan 2008
Jul 2008
Jan 2009
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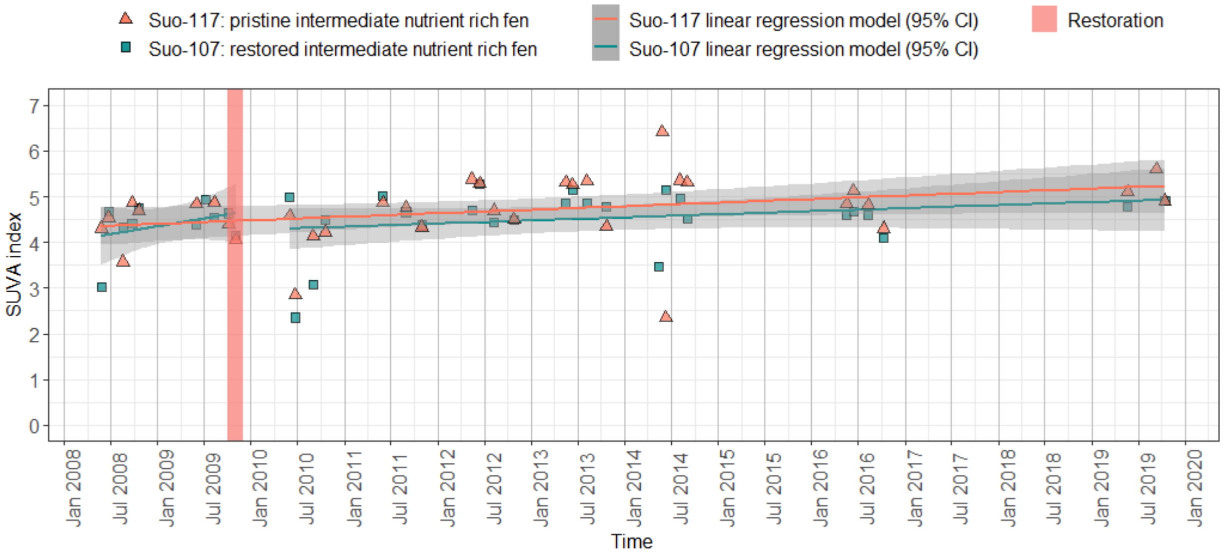
Time


Suo-117: pristine intermediate nutrient rich fen
Suo-107: restored intermediate nutrient rich fen
Suo-117 linear regression model (95% CI)
Suo-107 linear regression model (95% CI)
Restoration
SUVA index
7
6
5
4
3
2
1
0
Jan 2008
Jul 2008
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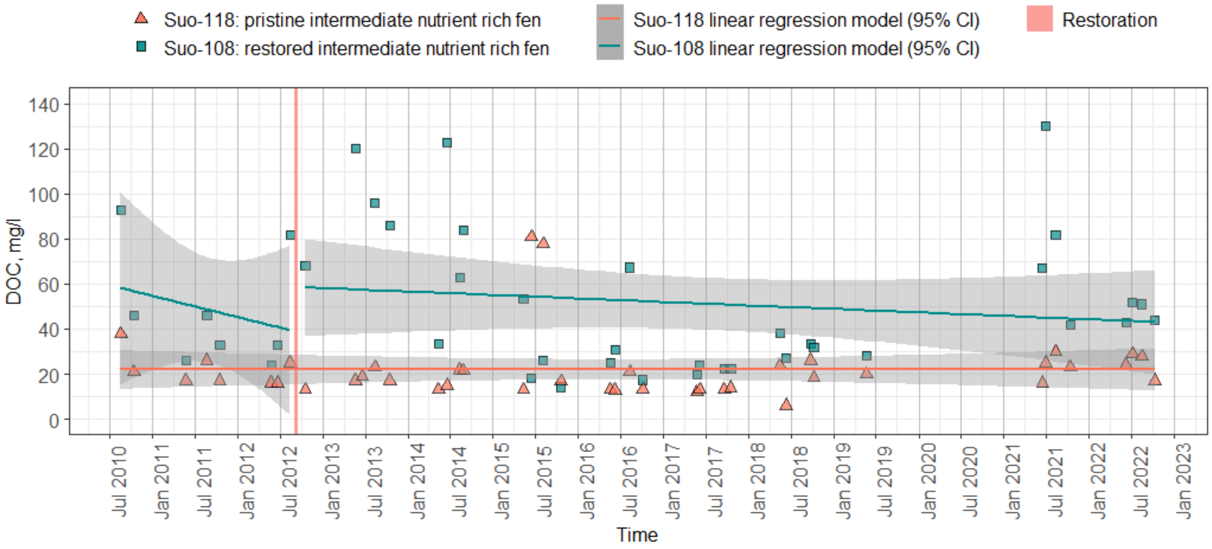
Suo-118: pristine intermediate nutrient rich fen
Suo-108: restored intermediate nutrient rich fen
Suo-118 linear regression model (95% CI)
Suo-108 linear regression model (95% CI)
Restoration
DOC, mg/l
140
120
100
80
60
40
20
0
Jul 2010
Jan 2011
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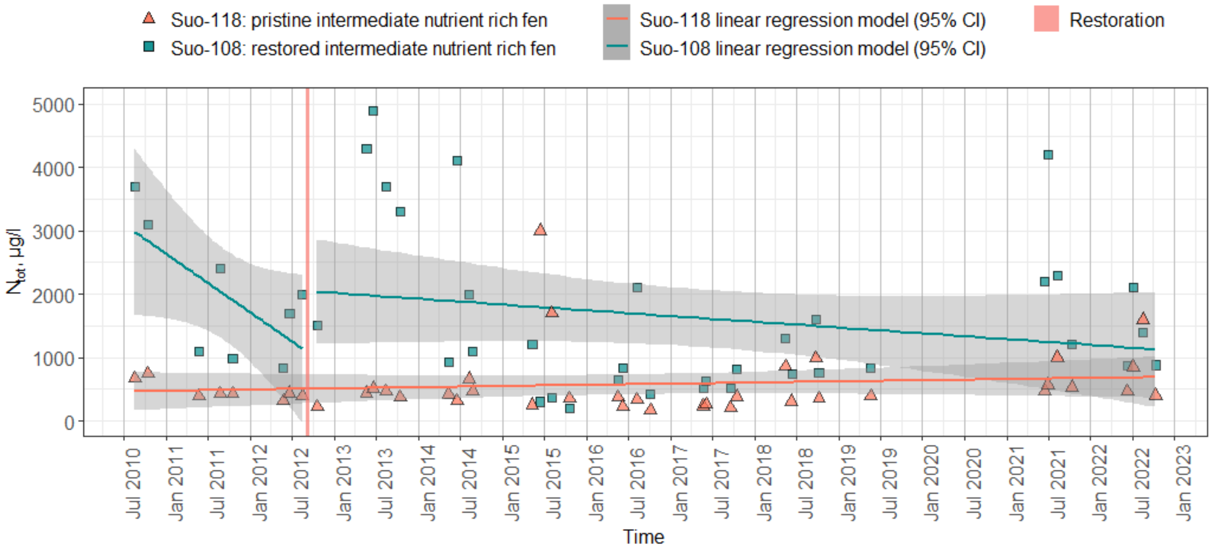
Time


Suo-118: pristine intermediate nutrient rich fen
Suo-108: restored intermediate nutrient rich fen
Suo-118 linear regression model (95% CI)
Suo-108 linear regression model (95% CI)
Restoration
N$_{tot}$, µg/l
5000
4000
3000
2000
1000
0
Jul 2010
Jan 2011
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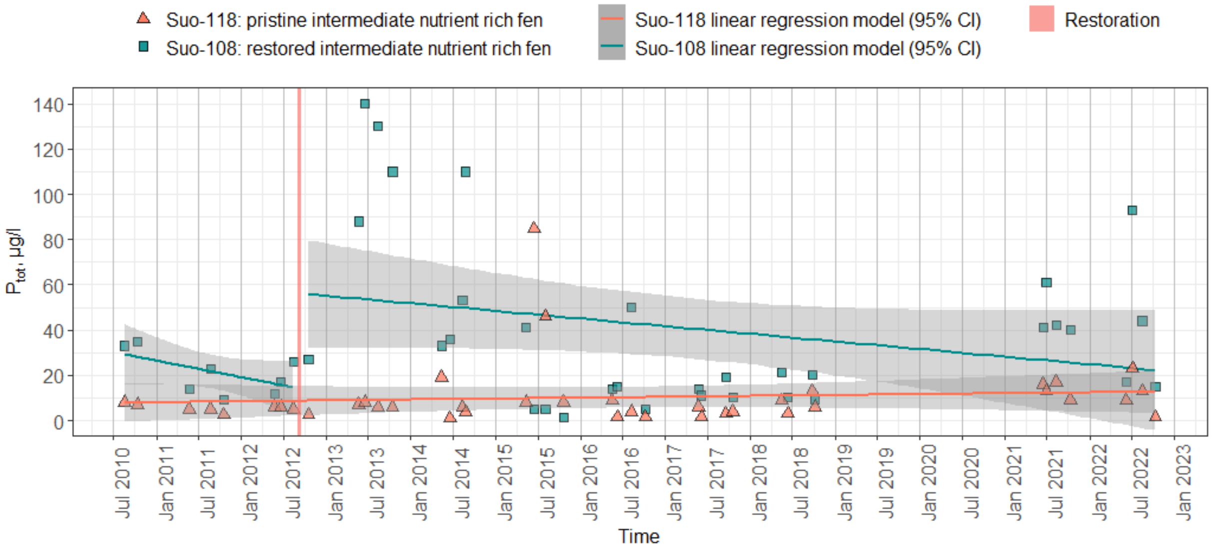
Time


Suo-118: pristine intermediate nutrient rich fen
Suo-108: restored intermediate nutrient rich fen
Suo-118 linear regression model (95% CI)
Suo-108 linear regression model (95% CI)
Restoration
P$_{tot}$, µg/l
140
120
100
80
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Jul 2010
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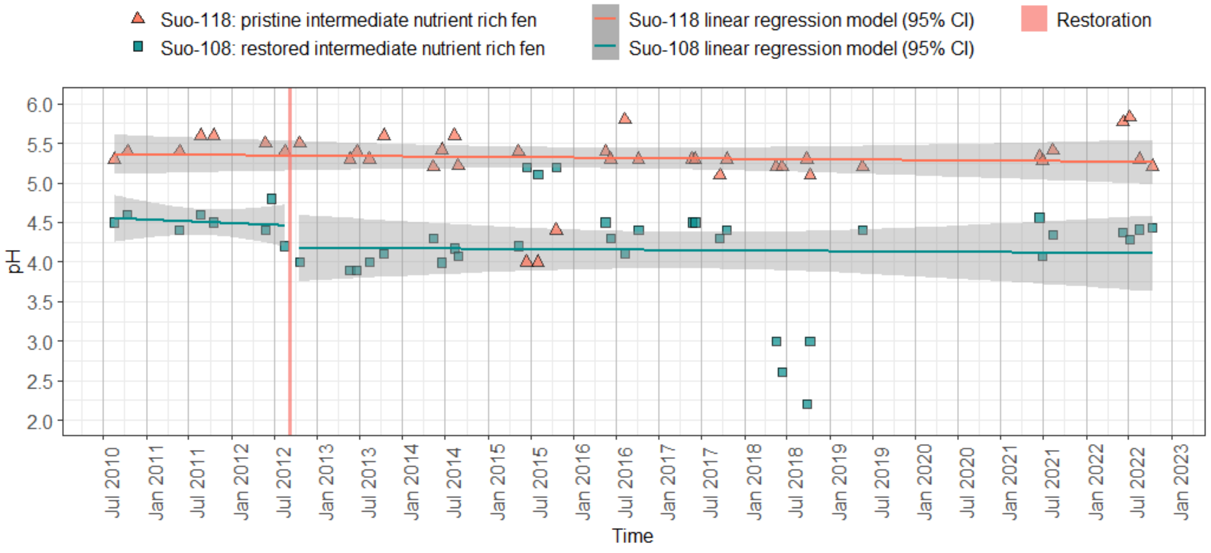
Time


Suo-118: pristine intermediate nutrient rich fen
Suo-108: restored intermediate nutrient rich fen
Suo-118 linear regression model (95% CI)
Suo-108 linear regression model (95% CI)
Restoration
pH
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
Jul 2010
Jan 2011
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Jul 2022
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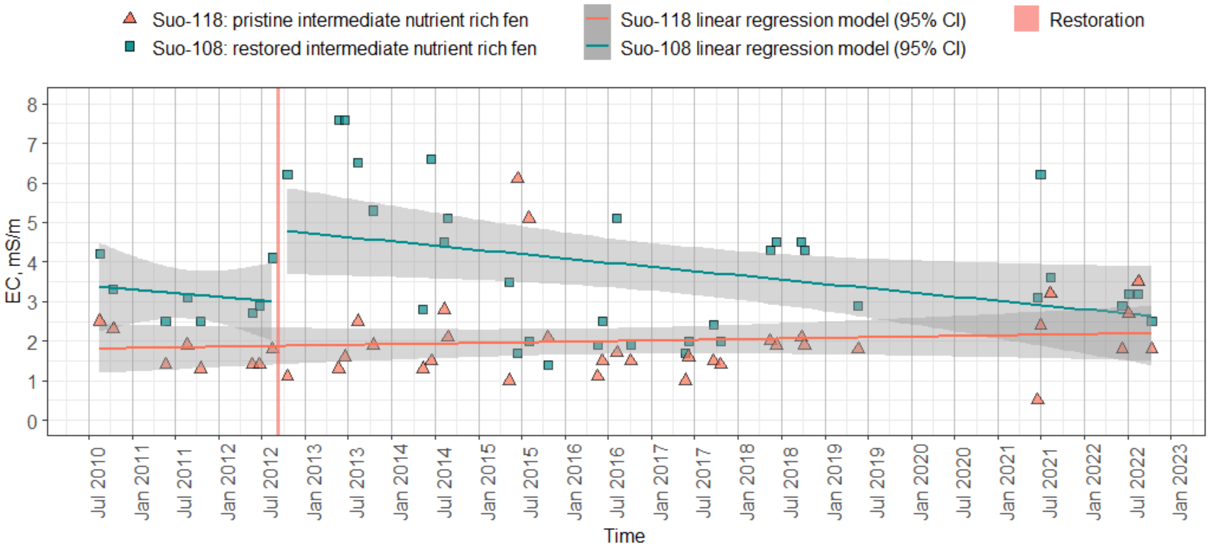
Time


Suo-118: pristine intermediate nutrient rich fen
Suo-108: restored intermediate nutrient rich fen
Suo-118 linear regression model (95% CI)
Suo-108 linear regression model (95% CI)
Restoration
EC, mS/m
8
7
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4
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Jul 2010
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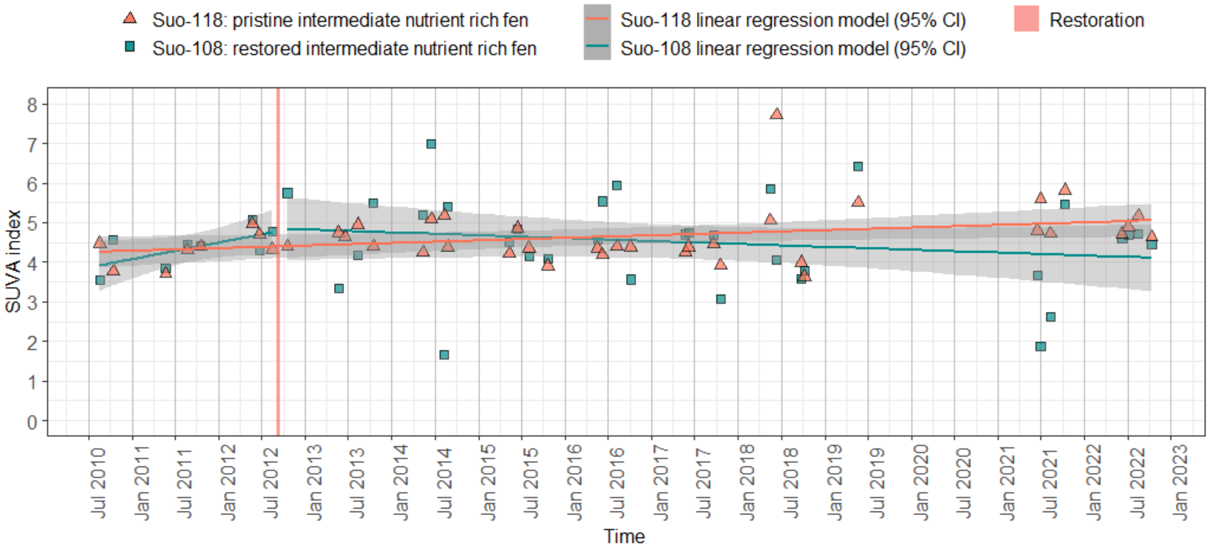
Time


Suo-118: pristine intermediate nutrient rich fen
Suo-108: restored intermediate nutrient rich fen
Suo-118 linear regression model (95% CI)
Suo-108 linear regression model (95% CI)
Restoration
SUVA index
8
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Jul 2010
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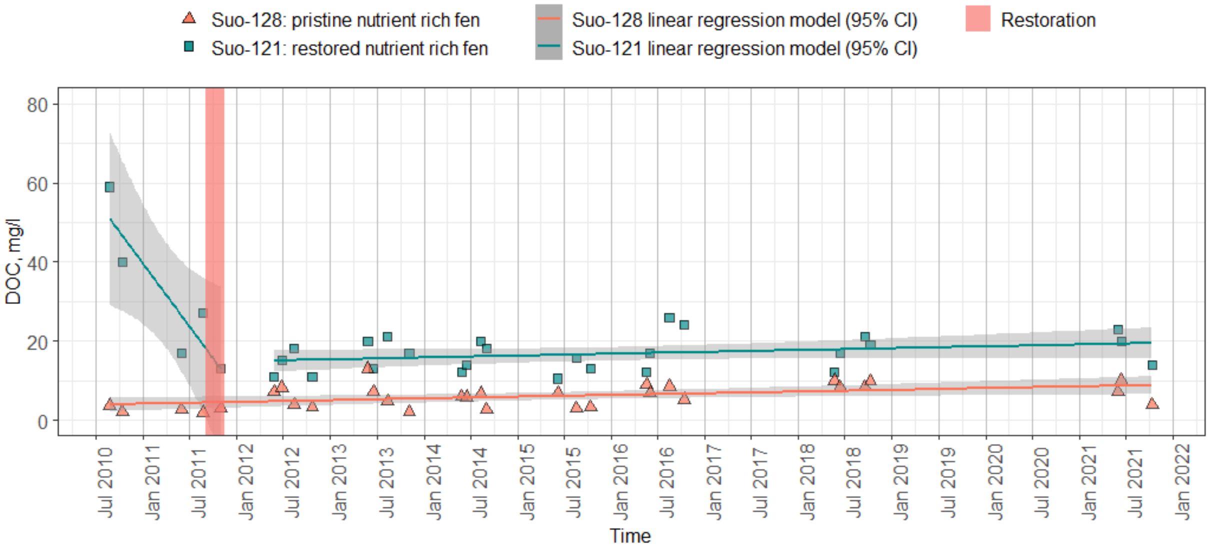
Time


Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
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Jul 2010
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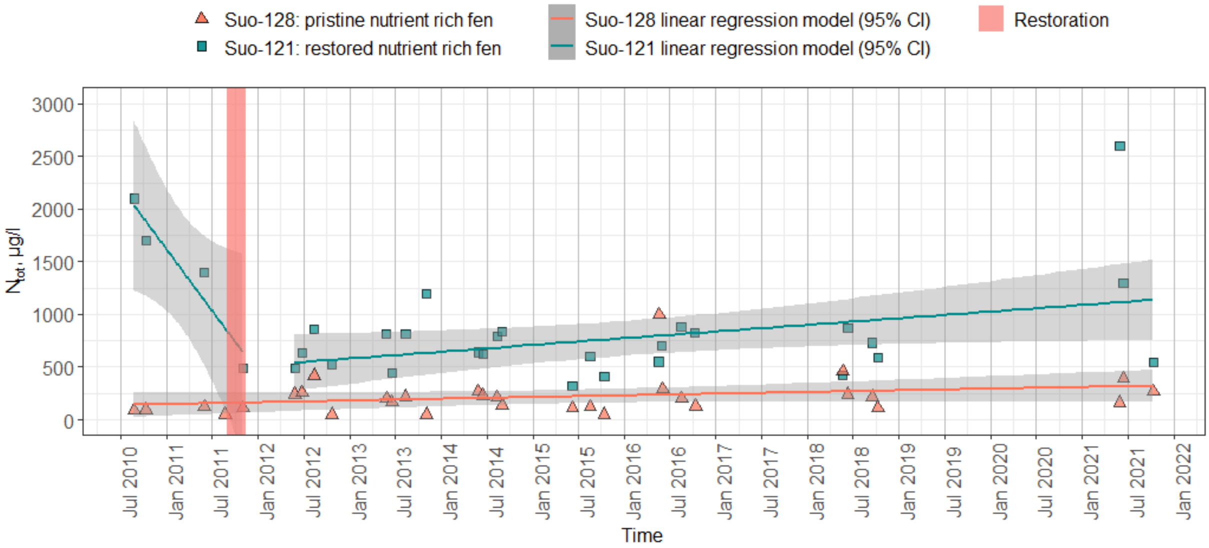
Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
N$_{tot}$, µg/l
0
500
1000
1500
2000
2500
3000
Jul 2010
Jan 2011
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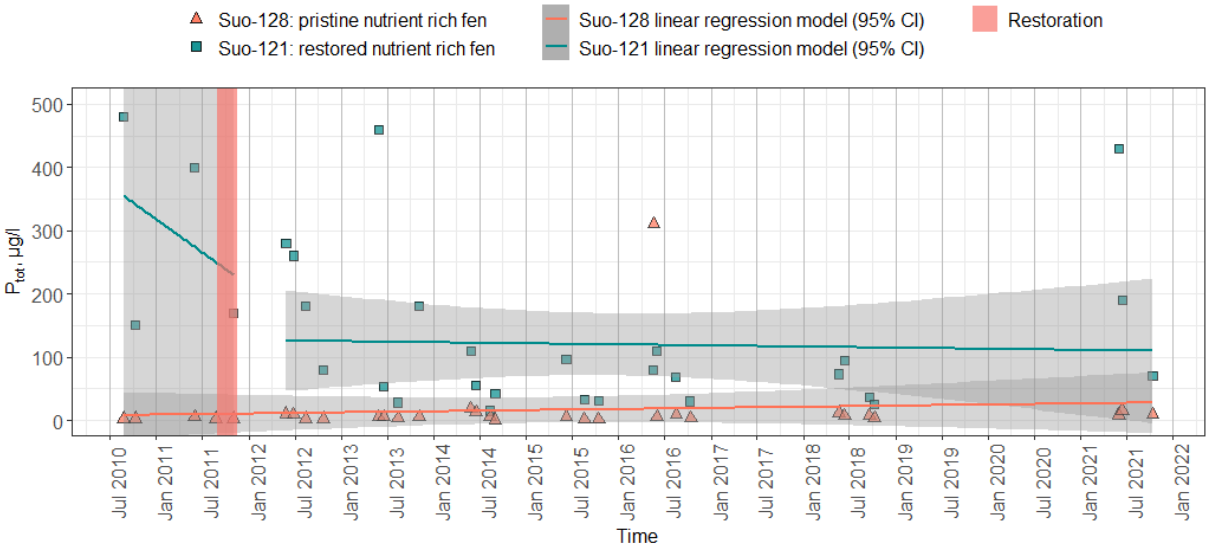
Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
P$_{tot}$, µg/l
0
100
200
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Jul 2010
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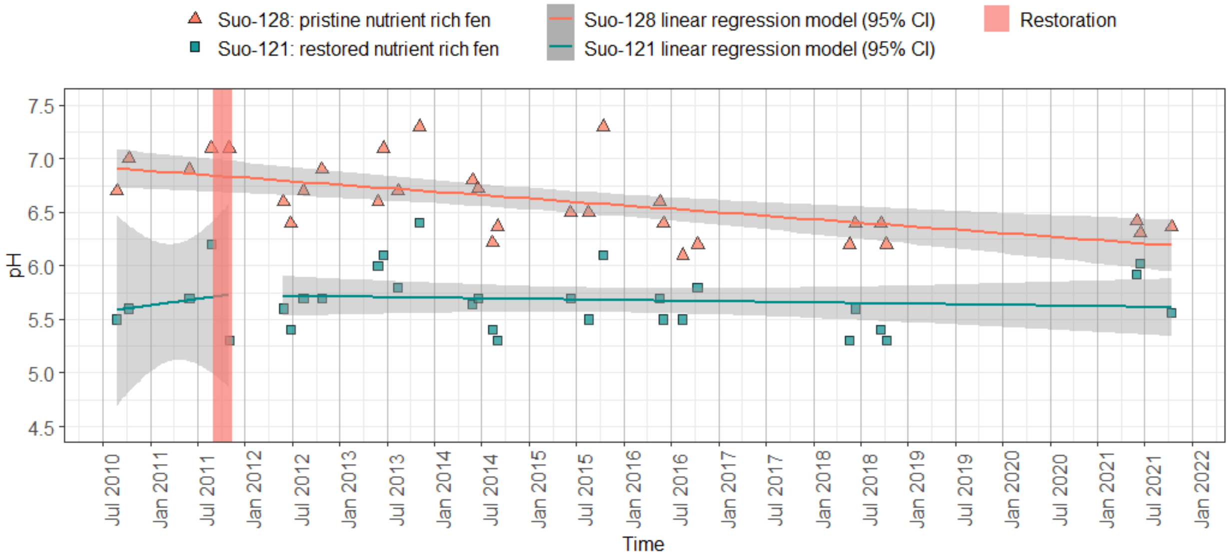
Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
pH
7.5
7.0
6.5
6.0
5.5
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Jul 2010
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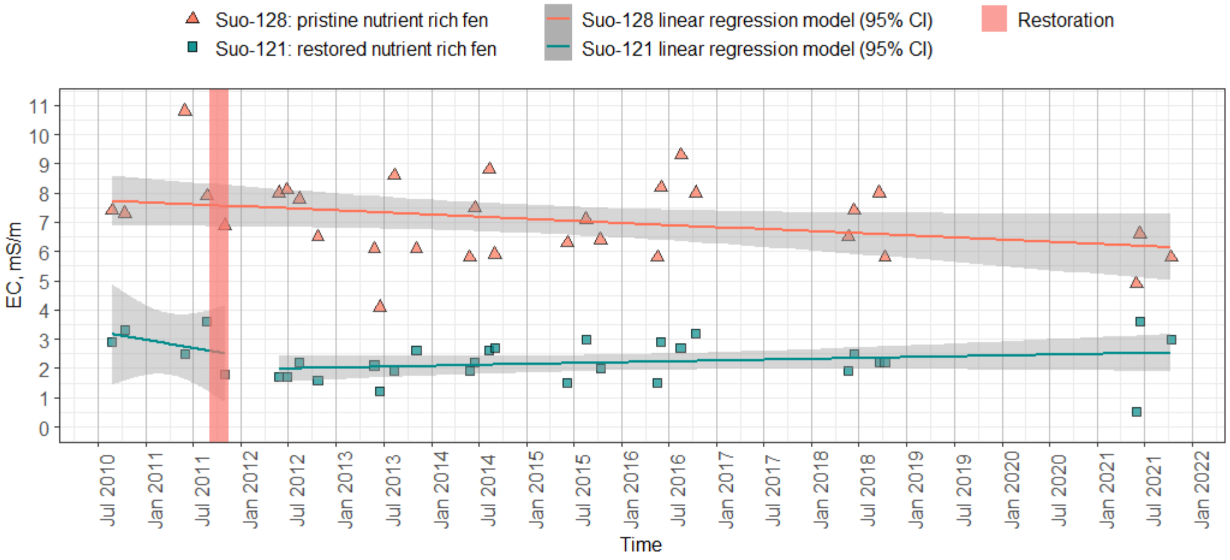
Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
EC, mS/m
11
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Jul 2010
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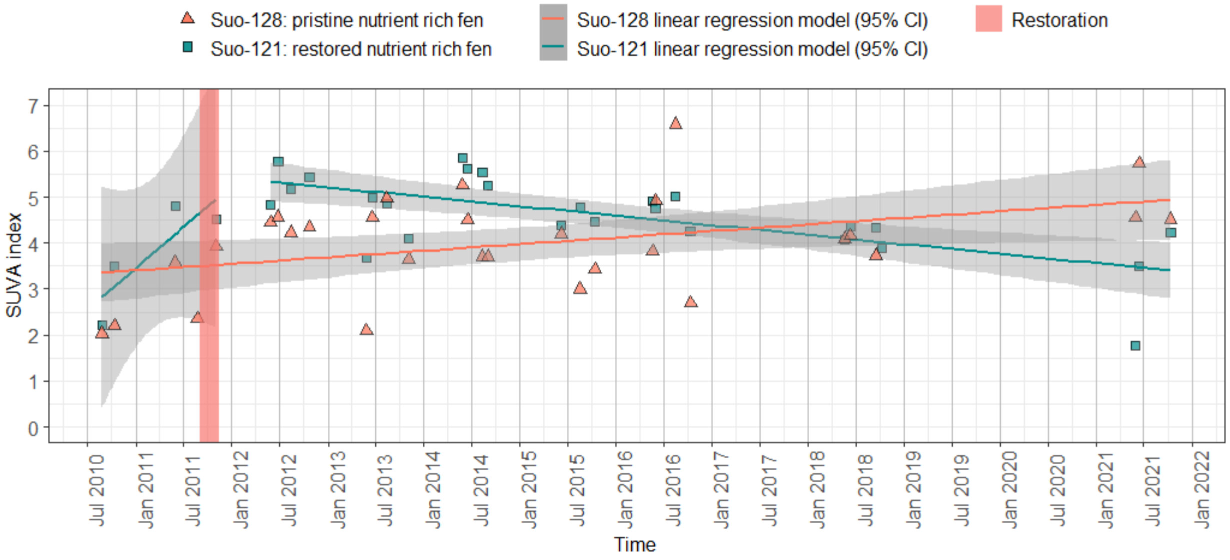
Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
SUVA index
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Jul 2010
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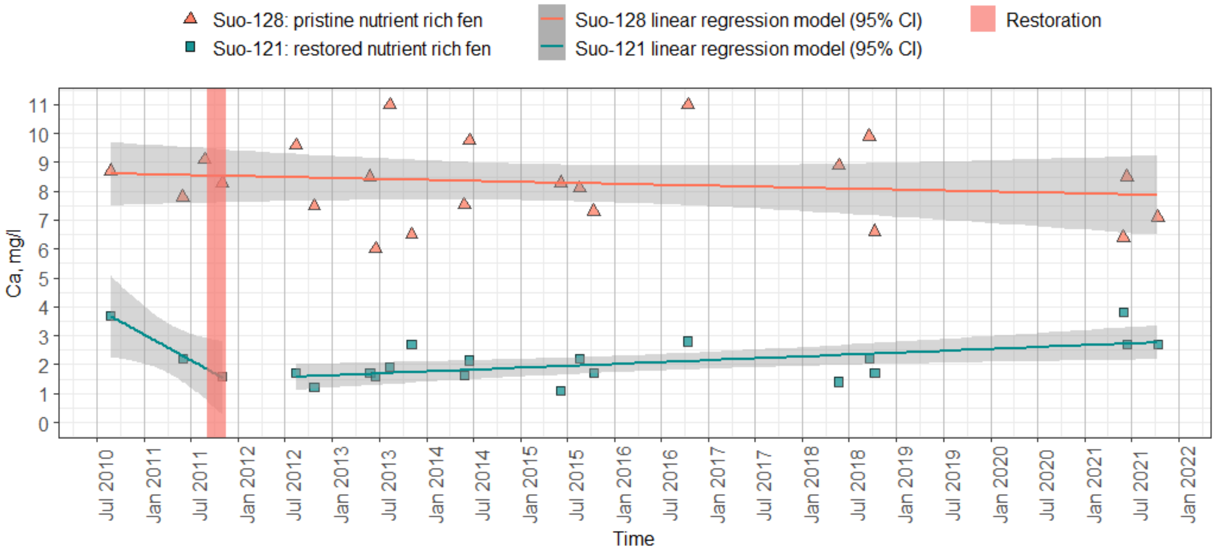

Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
Ca, mg/l
0
1
2
3
4
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11
Jul 2010
Jan 2011
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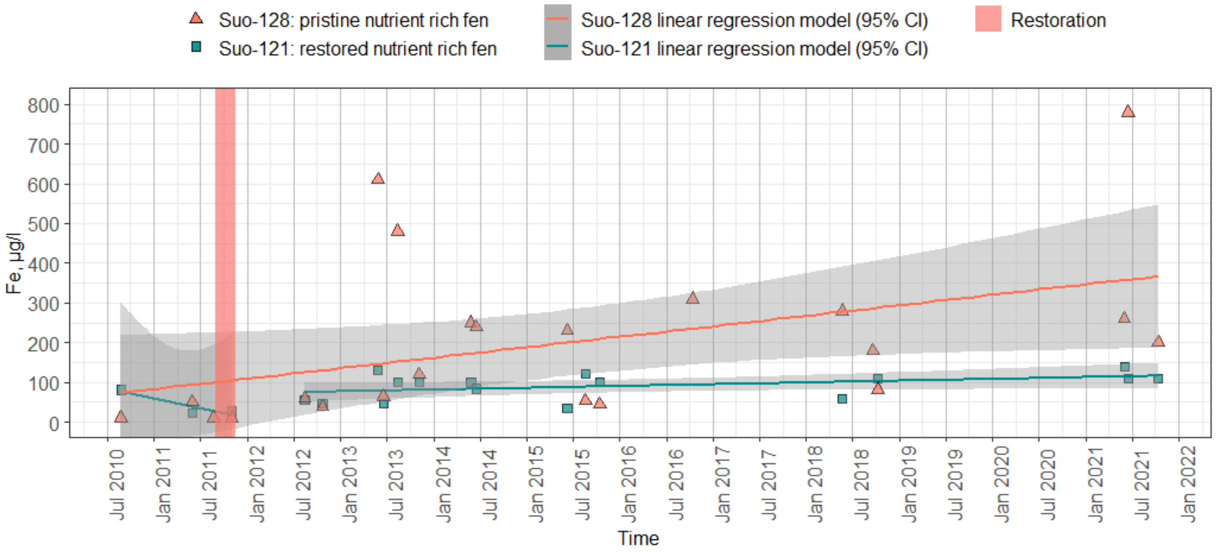

Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
Fe, µg/l
0
100
200
300
400
500
600
700
800
Jul 2010
Jan 2011
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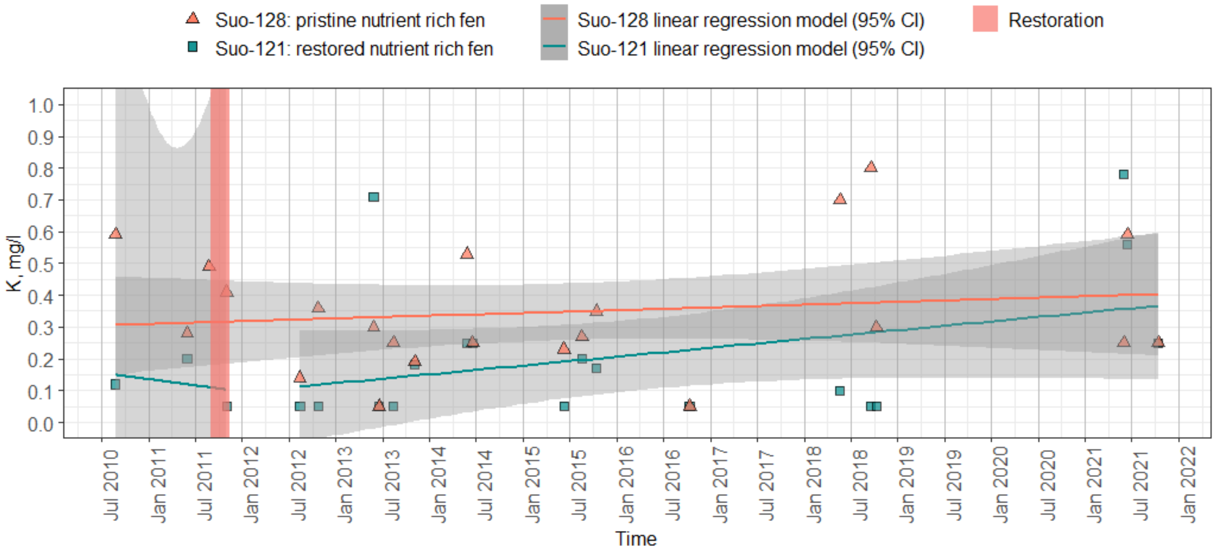

Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
K, mg/l
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Jul 2010
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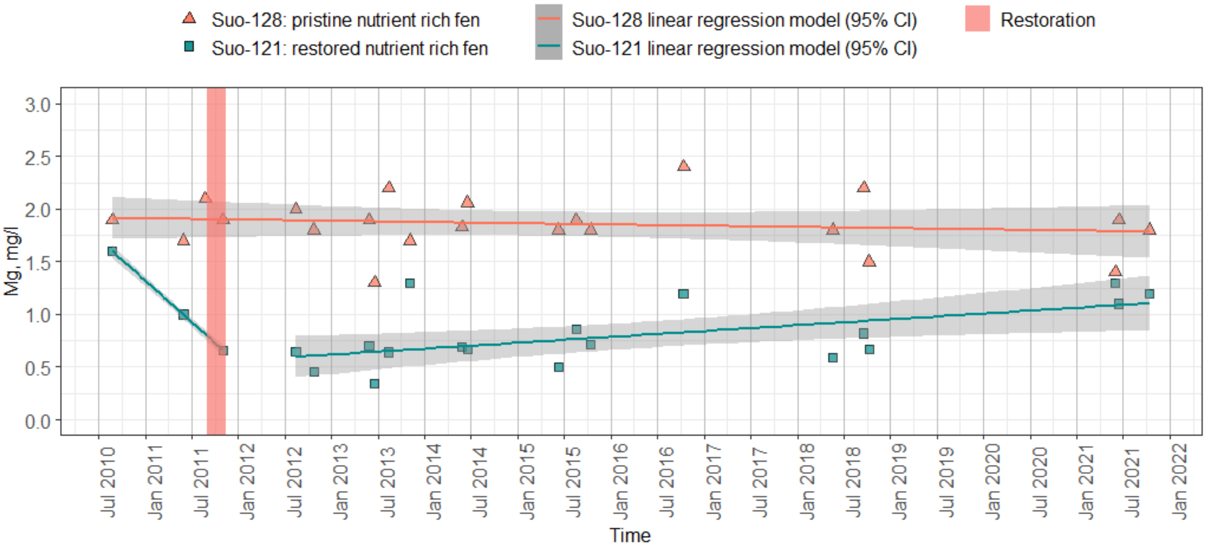

Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
Mg, mg/l
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Jul 2010
Jan 2011
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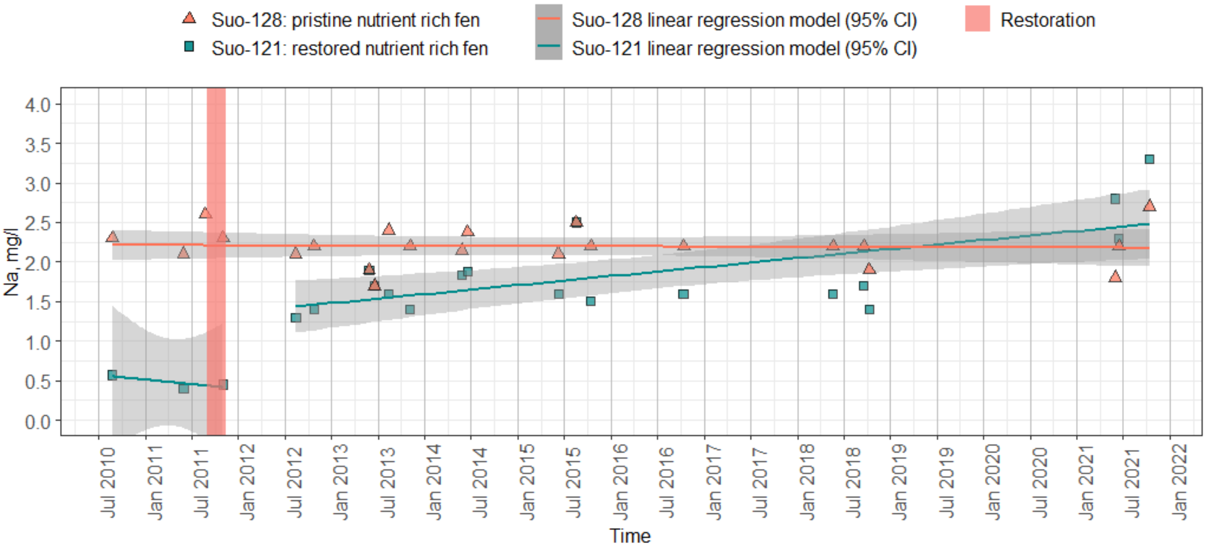
Jan 2022
Time



Suo-128: pristine nutrient rich fen
Suo-121: restored nutrient rich fen
Suo-128 linear regression model (95% CI)
Suo-121 linear regression model (95% CI)
Restoration
Na, mg/l
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Jul 2010
Jan 2011
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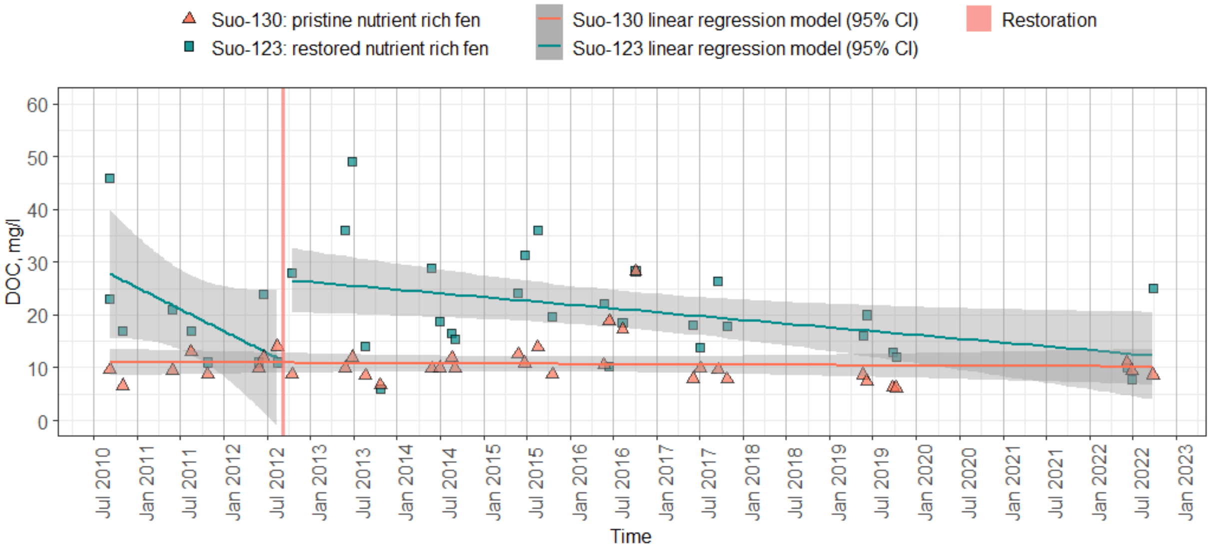
Time



Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
DOC, mg/l
0
10
20
30
40
50
60
Jul 2010
Jan 2011
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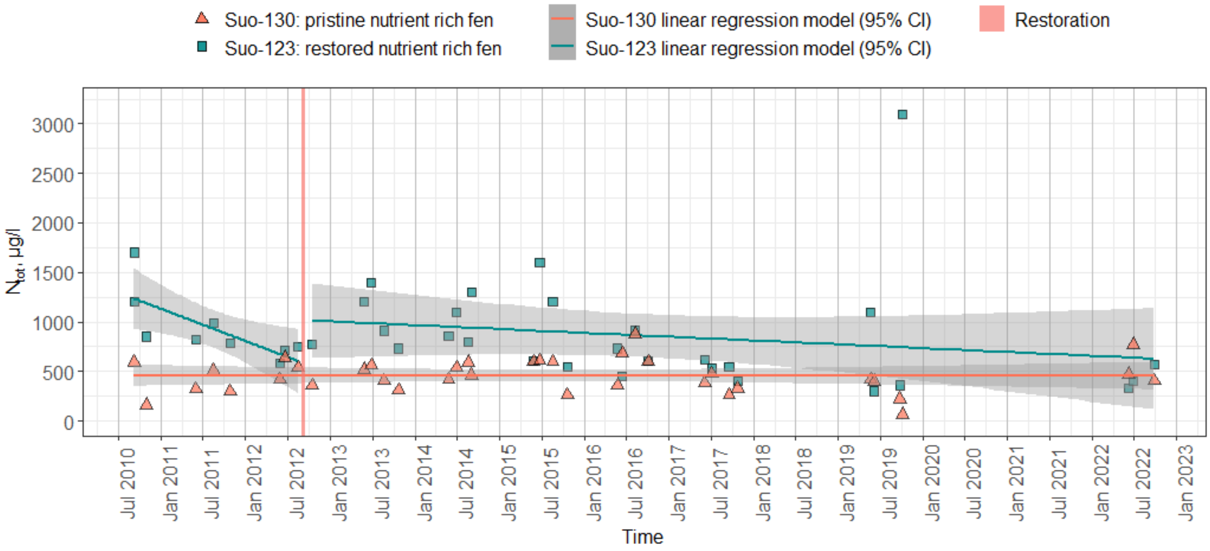
Jul 2022
Jan 2023
Time



Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
500
1000
1500
2000
2500
3000
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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Jan 2014
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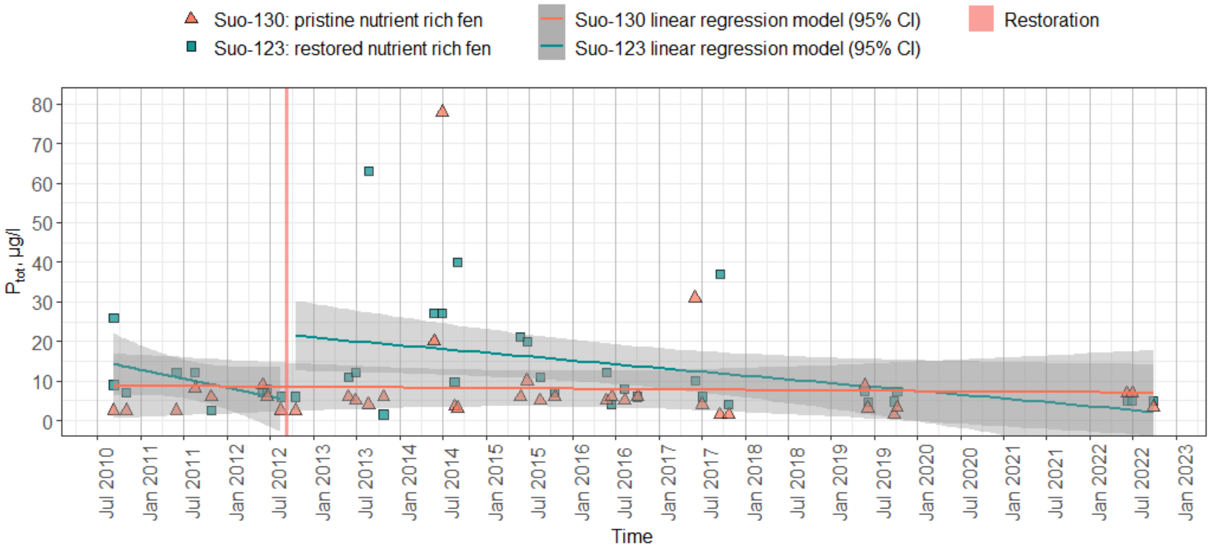
Time



Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
10
20
30
40
50
60
70
80
Jul 2010
Jan 2011
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Jul 2022
Jan 2023
Time


Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
pH
7.5
7.0
6.5
6.0
5.5
5.0
4.5
Jul 2010
Jan 2011
Jul 2011
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Jul 2022
Jan 2023
Time


Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
EC, mS/m
16
14
12
10
8
6
4
2
0
Jul 2010
Jan 2011
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Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time


Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
SUVA index
8
7
6
5
4
3
2
1
0
Jul 2010
Jan 2011
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Jan 2022
Jul 2022
Jan 2023
Time


Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
Ca, mg/l
0
5
10
15
20
25
30
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
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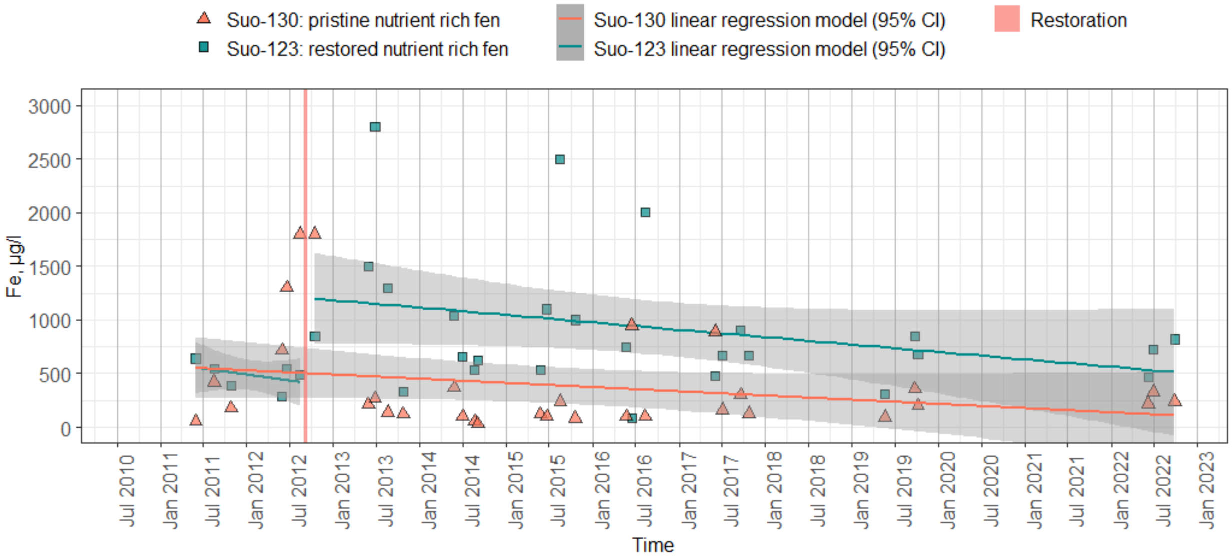
Jan 2023
Time


Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
Fe, µg/l
0
500
1000
1500
2000
2500
3000
Jul 2010
Jan 2011
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Jan 2013
Jul 2013
Jan 2014
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Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time


Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
K, mg/l
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Jul 2010
Jan 2011
Jul 2011
Jan 2012
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Jul 2018
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time


Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
Mg, mg/l
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
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Jul 2013
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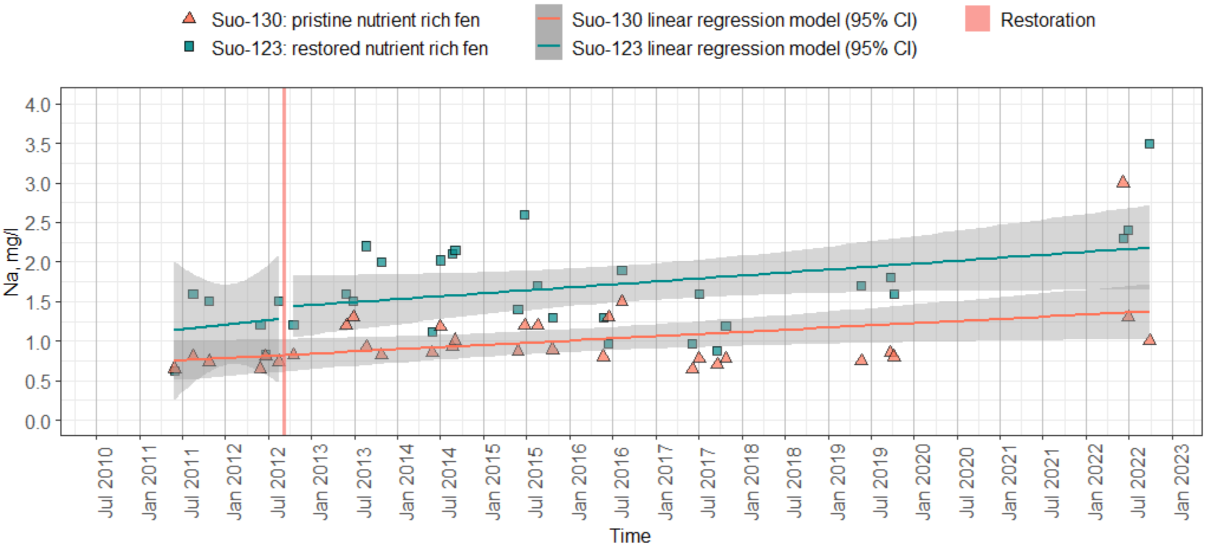
Jul 2020
Jan 2021
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time


Suo-130: pristine nutrient rich fen
Suo-123: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
Na, mg/l
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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Jul 2019
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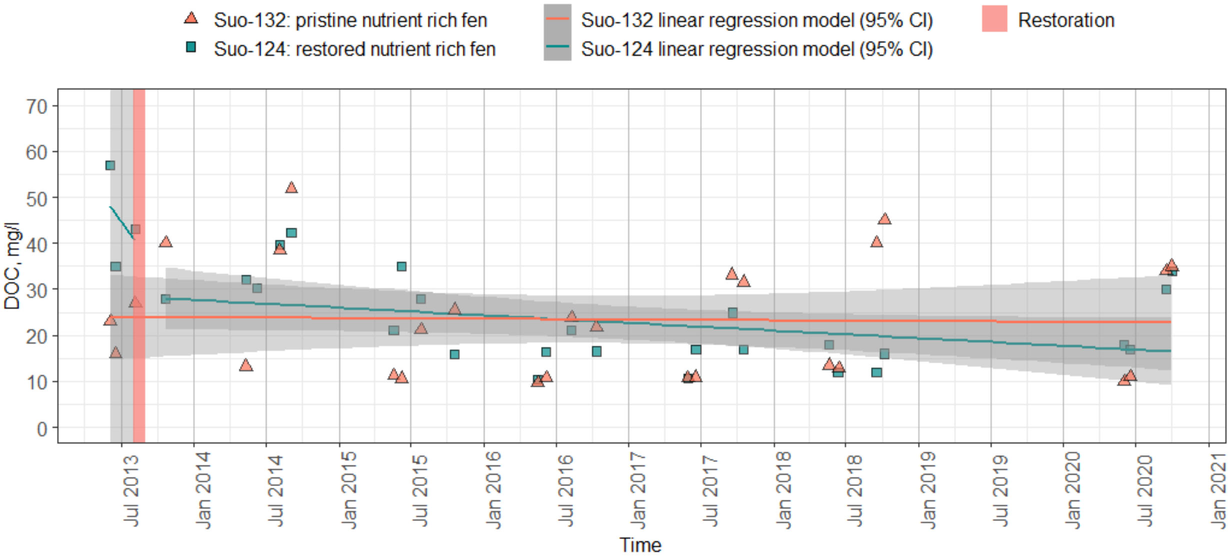
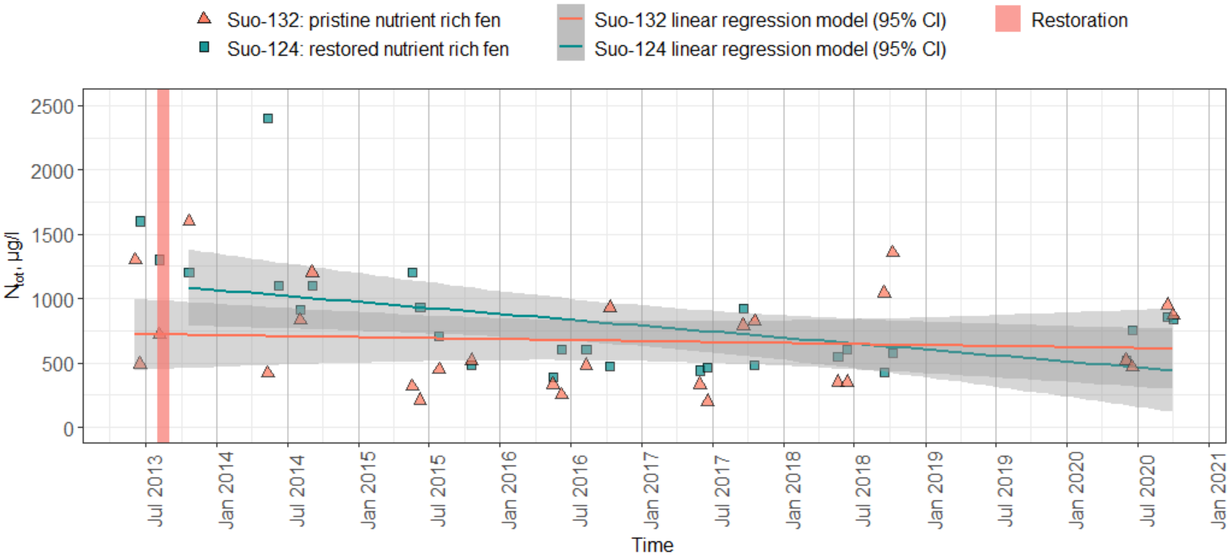
Jul 2020
Jan 2021
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
DOC, mg/l
70
60
50
40
30
20
10
0
Jul 2013
Jan 2014
Jul 2014
Jan 2015
Jul 2015
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
2500
2000
1500
1000
500
0
Jul 2013
Jan 2014
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Jan 2015
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Jul 2016
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Jan 2018
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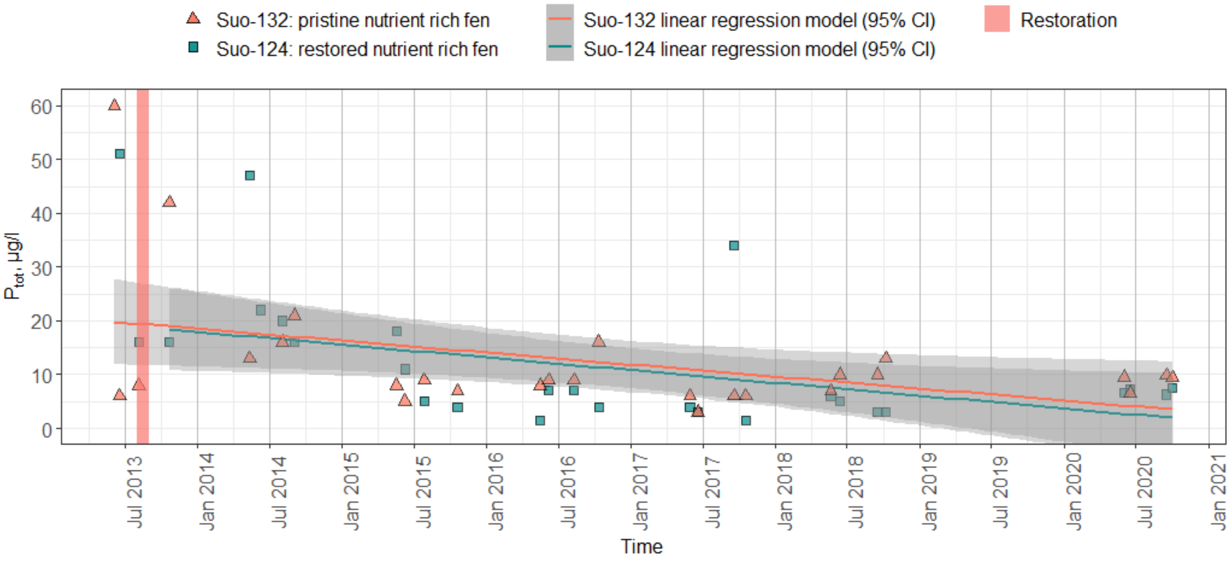
Jan 2020
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
60
50
40
30
20
10
0
Jul 2013
Jan 2014
Jul 2014
Jan 2015
Jul 2015
Jan 2016
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Jan 2017
Jul 2017
Jan 2018
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Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
pH
8.0
7.5
7.0
6.5
6.0
5.5
Jul 2013
Jan 2014
Jul 2014
Jan 2015
Jul 2015
Jan 2016
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Jan 2017
Jul 2017
Jan 2018
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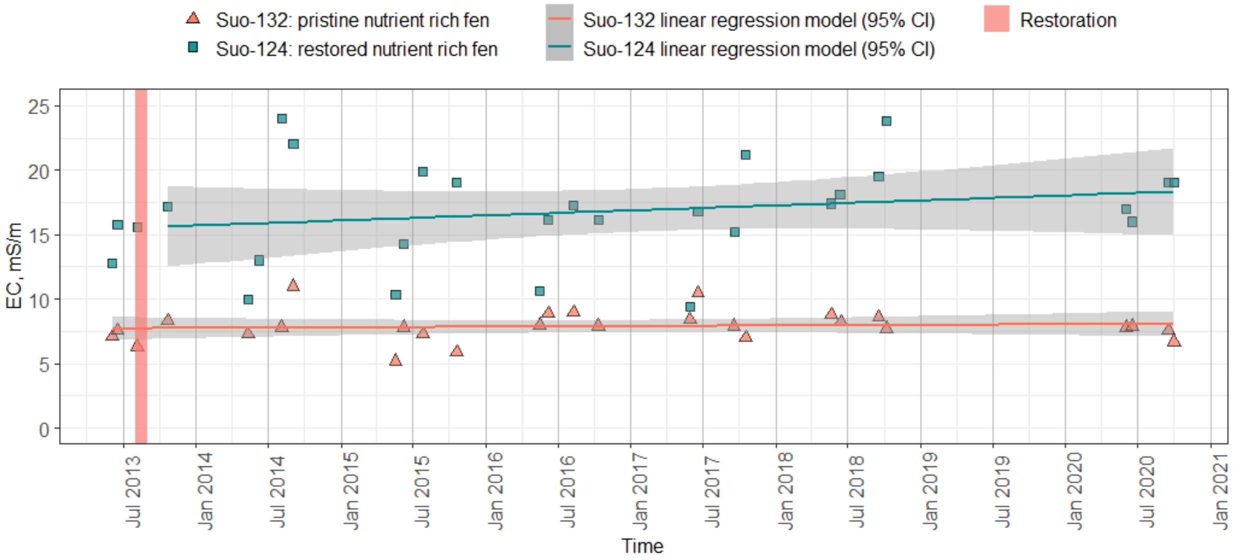
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
EC, mS/m
25
20
15
10
5
0
Jul 2013
Jan 2014
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Jan 2015
Jul 2015
Jan 2016
Jul 2016
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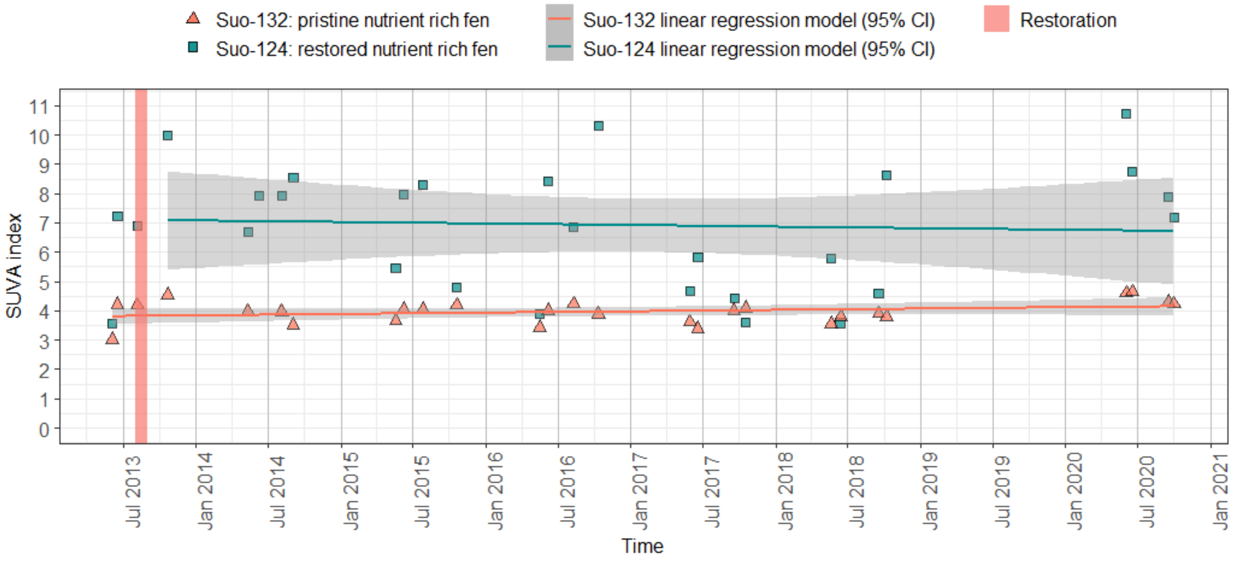
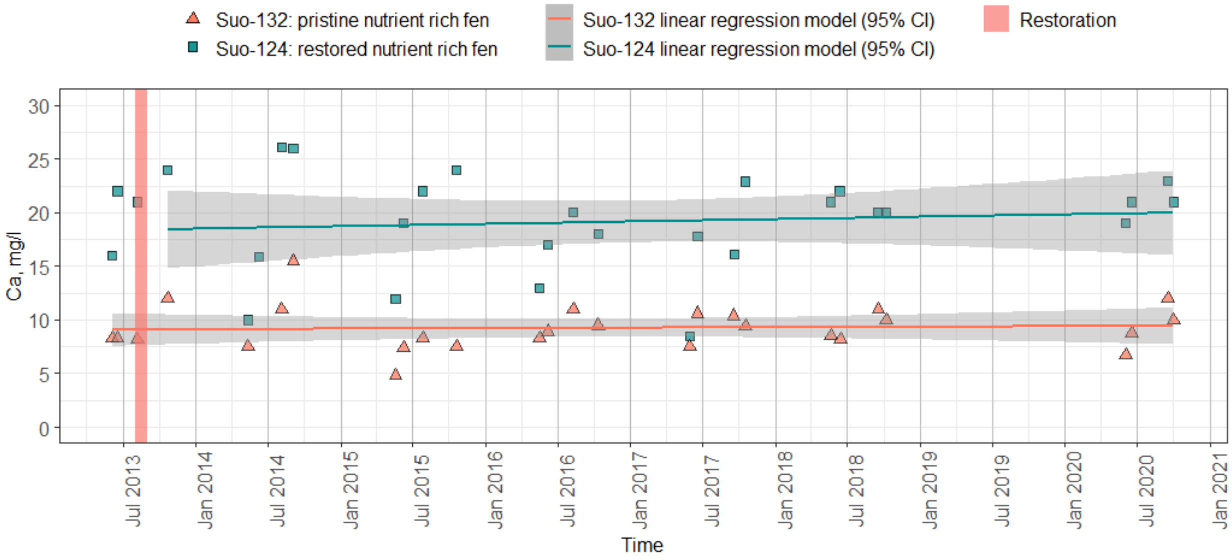
Jan 2020
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
SUVA index
11
10
9
8
7
6
5
4
3
2
1
0
Jul 2013
Jan 2014
Jul 2014
Jan 2015
Jul 2015
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
Ca, mg/l
0
5
10
15
20
25
30
Jul 2013
Jan 2014
Jul 2014
Jan 2015
Jul 2015
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
Fe, µg/l
0
5000
10000
15000
20000
25000
30000
35000
Jul 2013
Jan 2014
Jul 2014
Jan 2015
Jul 2015
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
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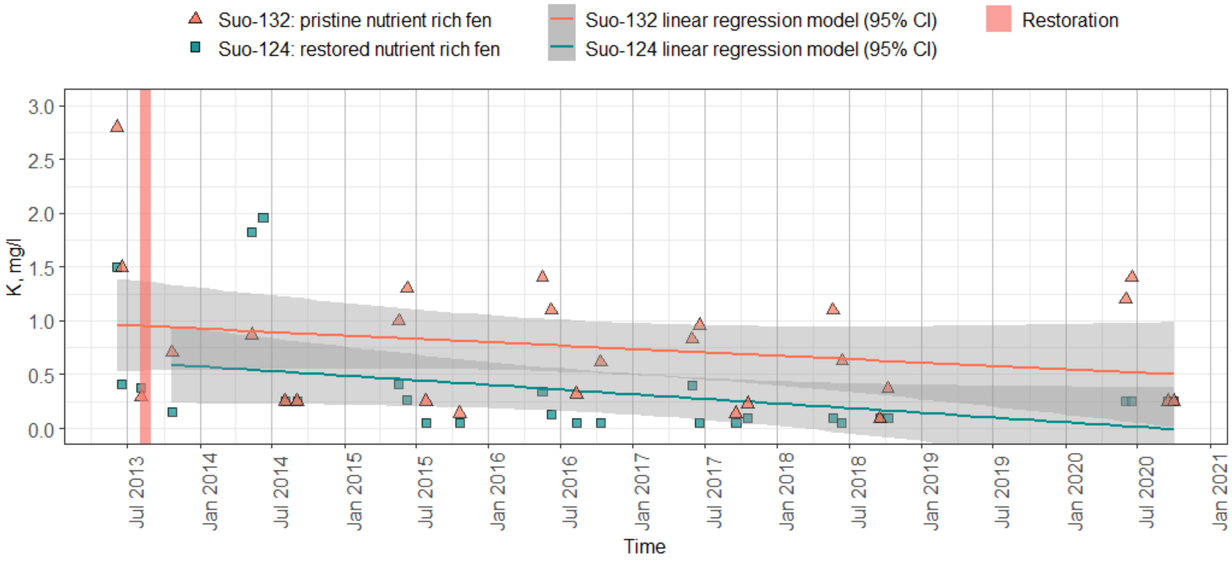
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
K, mg/l
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Jul 2013
Jan 2014
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Jan 2015
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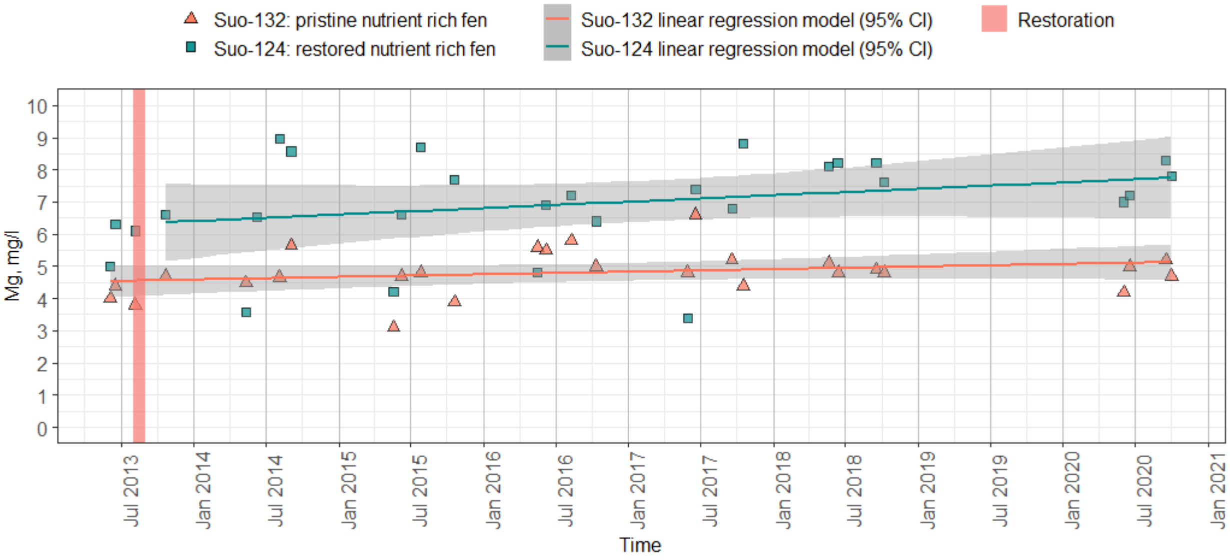
Jul 2020
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-132 linear regression model (95% CI)
Suo-124 linear regression model (95% CI)
Restoration
Mg, mg/l
0
1
2
3
4
5
6
7
8
9
10
Jul 2013
Jan 2014
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Jan 2015
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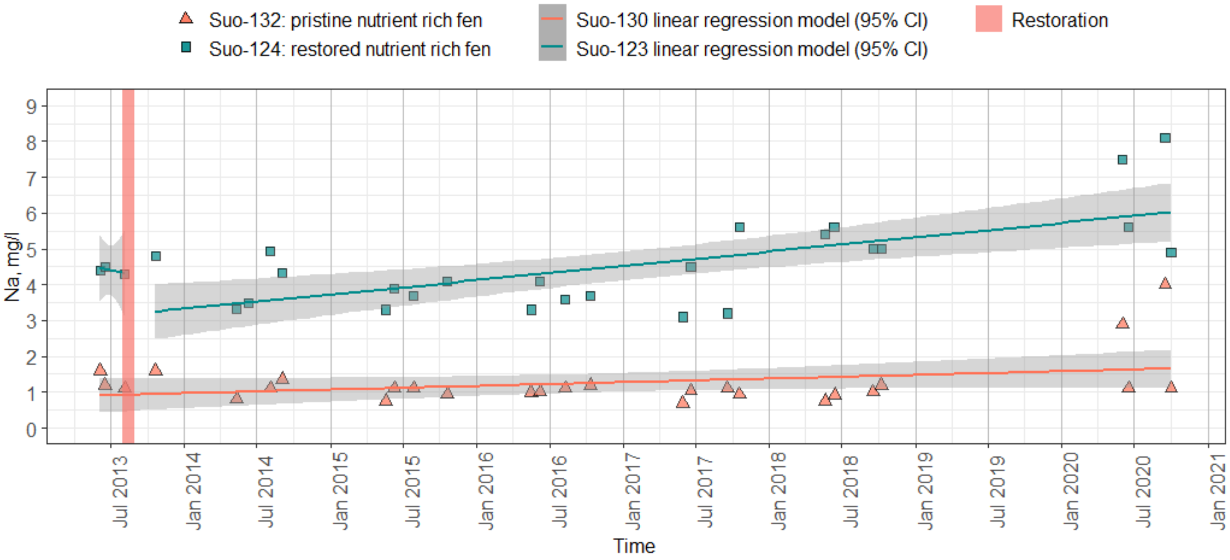
Jan 2021
Time


Suo-132: pristine nutrient rich fen
Suo-124: restored nutrient rich fen
Suo-130 linear regression model (95% CI)
Suo-123 linear regression model (95% CI)
Restoration
Na, mg/l
0
1
2
3
4
5
6
7
8
9
Jul 2013
Jan 2014
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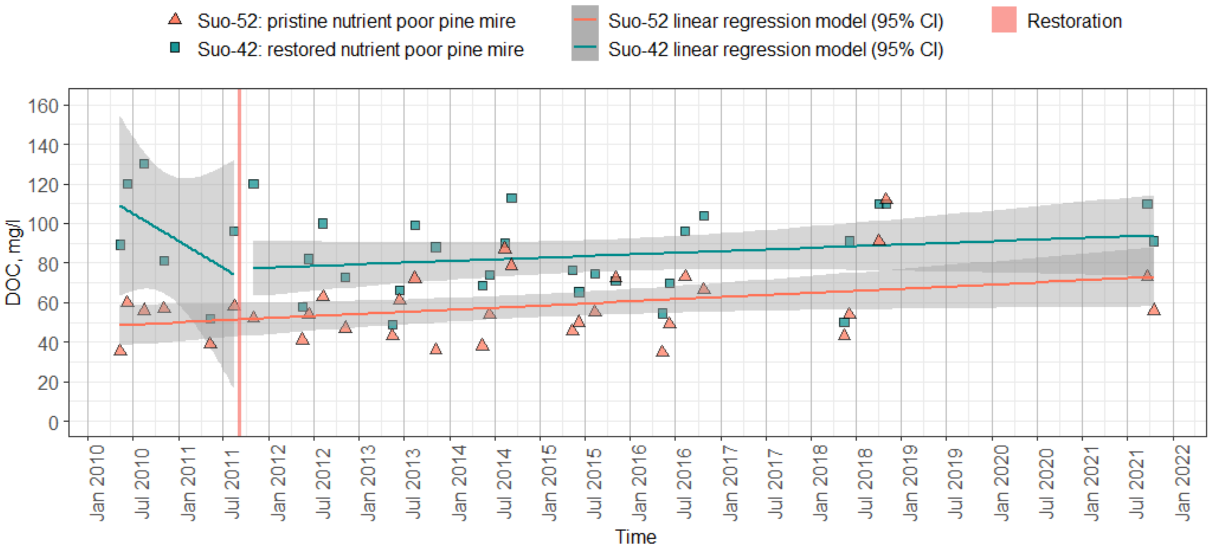
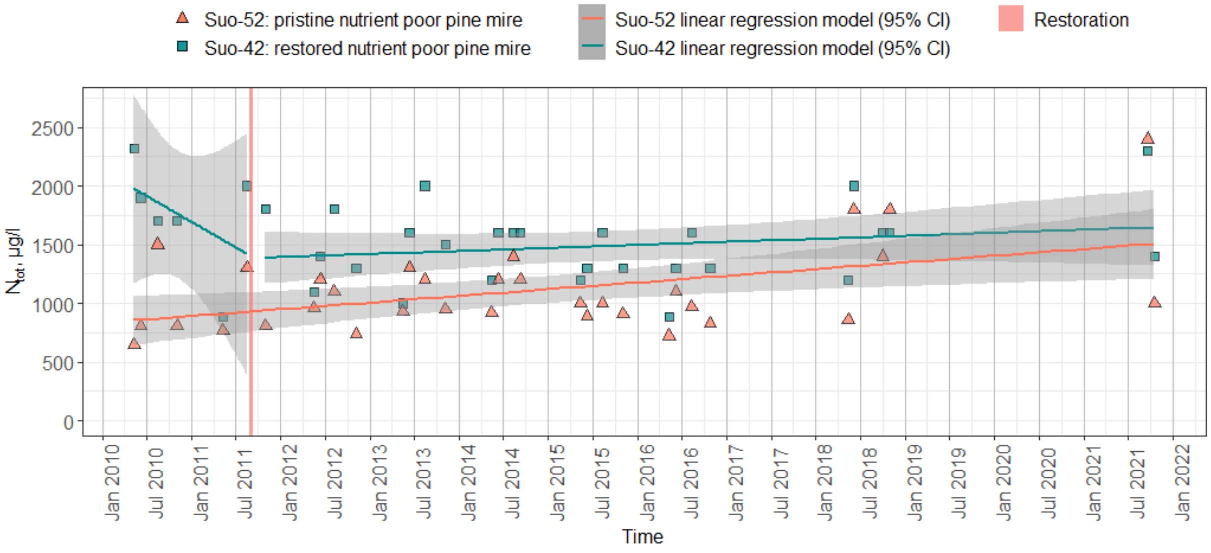
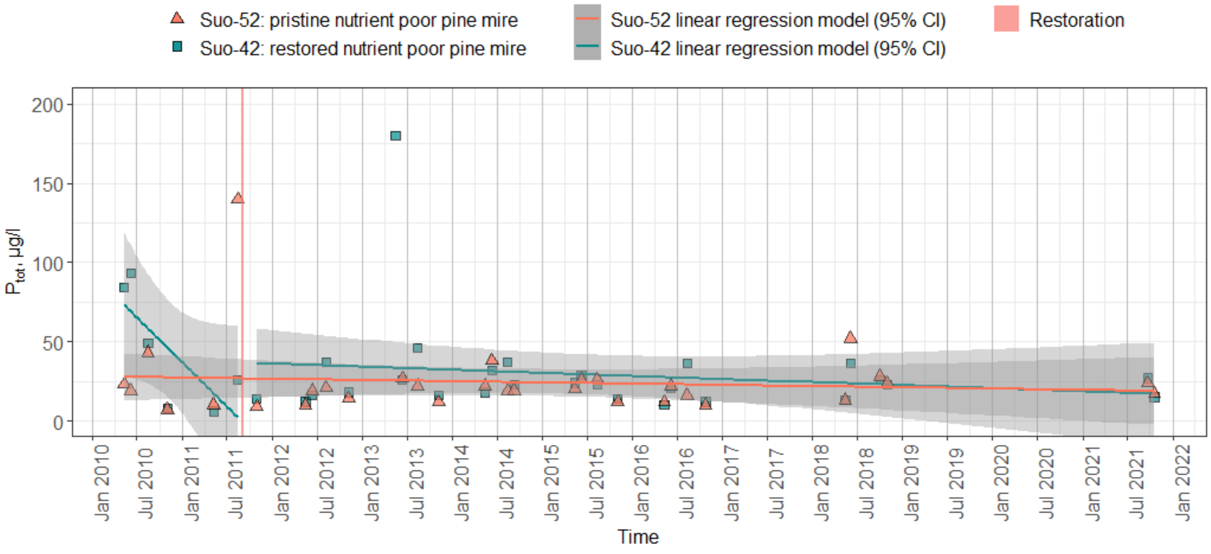
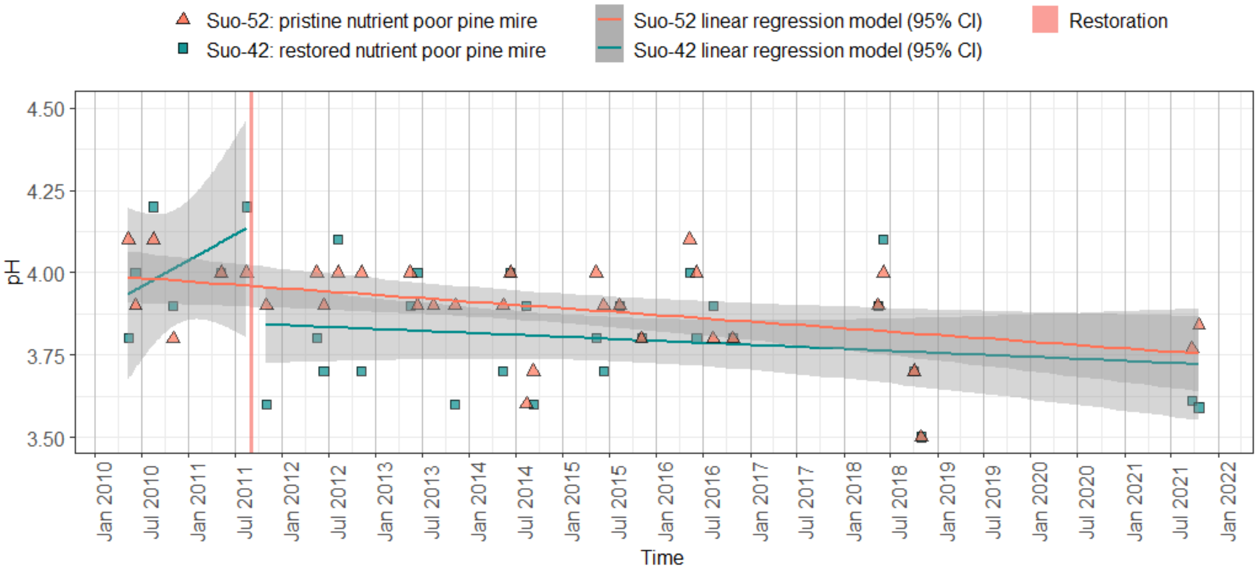
Jul 2020
Jan 2021
Time

Appendix 2B. 10-year water quality observations in the peatland monitoring network – Pine mires








Suo-52: pristine nutrient poor pine mire
Suo-42: restored nutrient poor pine mire
Suo-52 linear regression model (95% CI)
Suo-42 linear regression model (95% CI)
Restoration
pH
4.50
4.25
4.00
3.75
3.50
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
Jul 2013
Jan 2014
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Jan 2020
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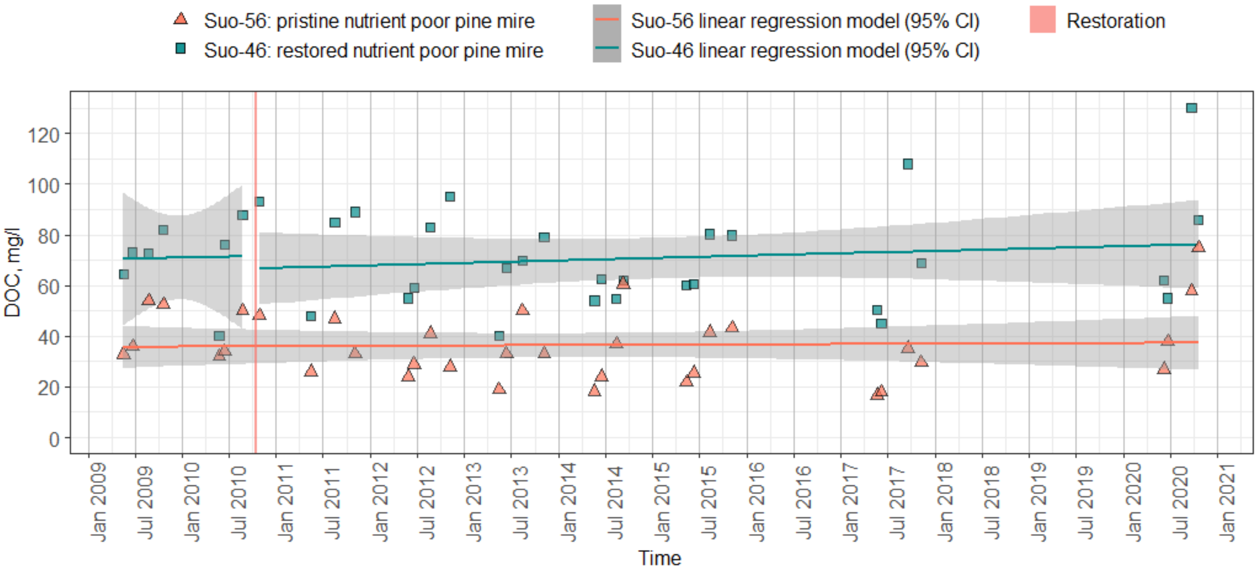
Jan 2021
Jul 2021
Jan 2022
Time


Suo-56: pristine nutrient poor pine mire
Suo-46: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-46 linear regression model (95% CI)
Restoration
DOC, mg/l
120
100
80
60
40
20
0
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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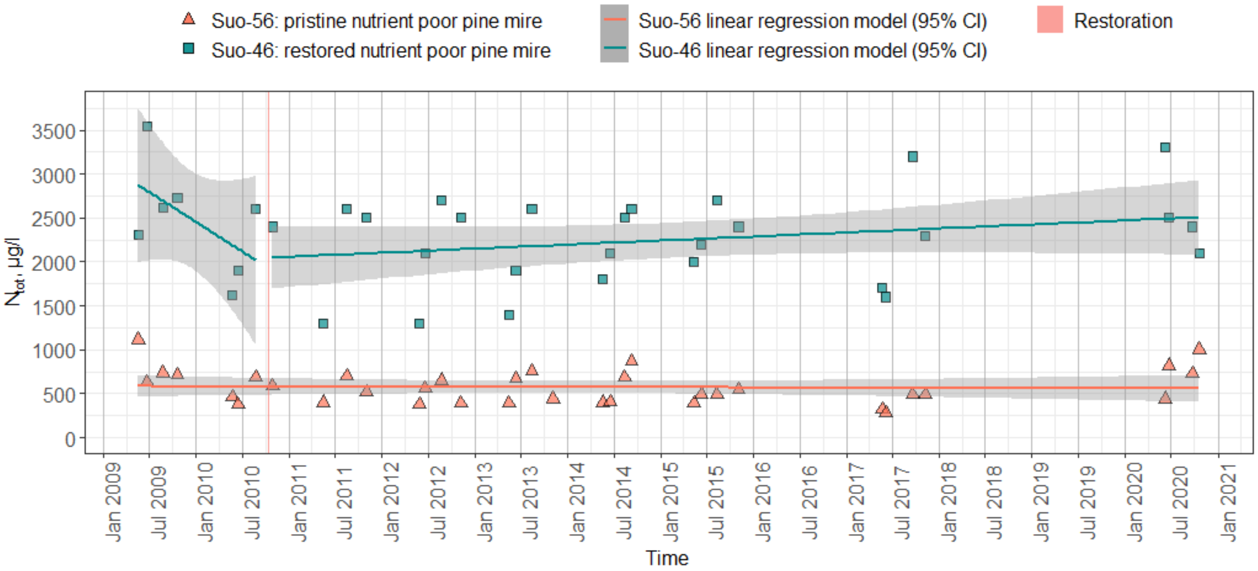
Jan 2019
Jul 2019
Jan 2020
Jul 2020
Jan 2021
Time


Suo-56: pristine nutrient poor pine mire
Suo-46: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-46 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
3500
3000
2500
2000
1500
1000
500
0
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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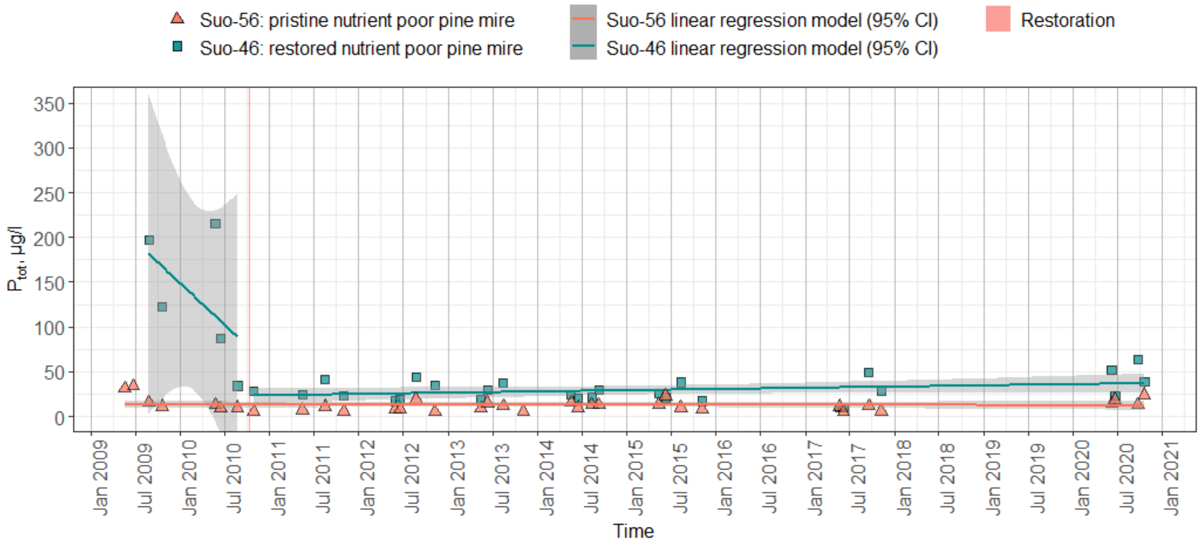
Jan 2020
Jul 2020
Jan 2021
Time


Suo-56: pristine nutrient poor pine mire
Suo-46: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-46 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
50
100
150
200
250
300
350
Time
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
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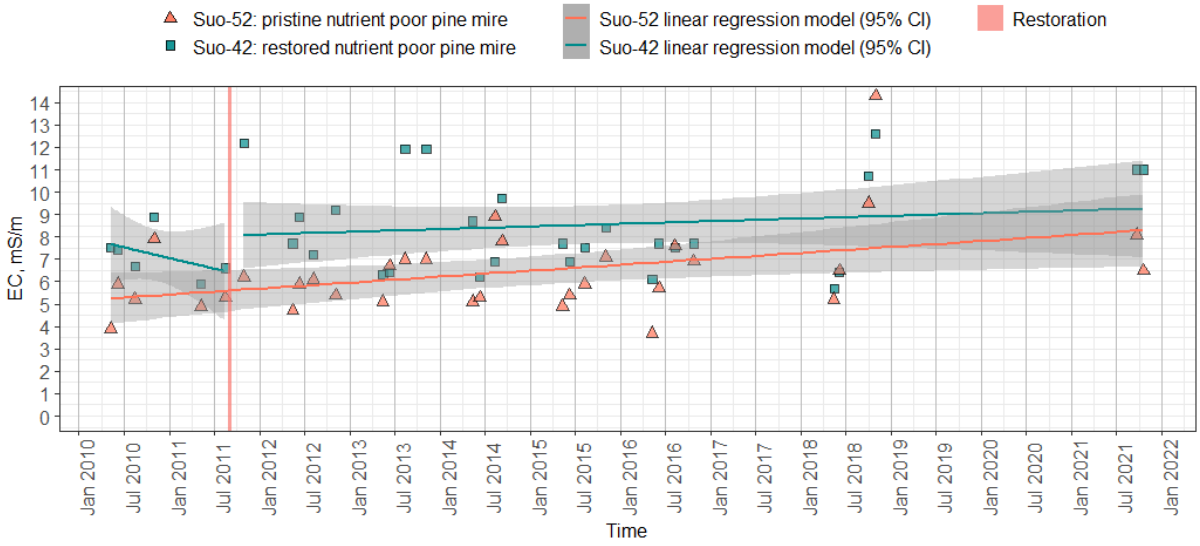
Jul 2020
Jan 2021


Suo-52: pristine nutrient poor pine mire
Suo-42: restored nutrient poor pine mire
Suo-52 linear regression model (95% CI)
Suo-42 linear regression model (95% CI)
Restoration
EC, mS/m
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Time
Jan 2010
Jul 2010
Jan 2011
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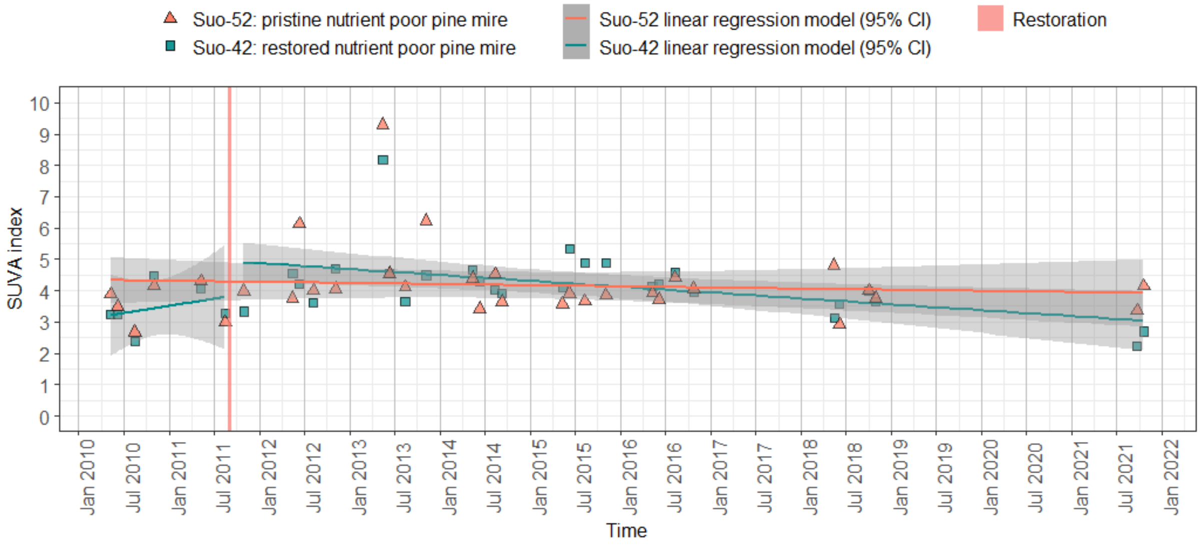
Jan 2021
Jul 2021
Jan 2022


Suo-52: pristine nutrient poor pine mire
Suo-42: restored nutrient poor pine mire
Suo-52 linear regression model (95% CI)
Suo-42 linear regression model (95% CI)
Restoration
SUVA index
0
1
2
3
4
5
6
7
8
9
10
Time
Jan 2010
Jul 2010
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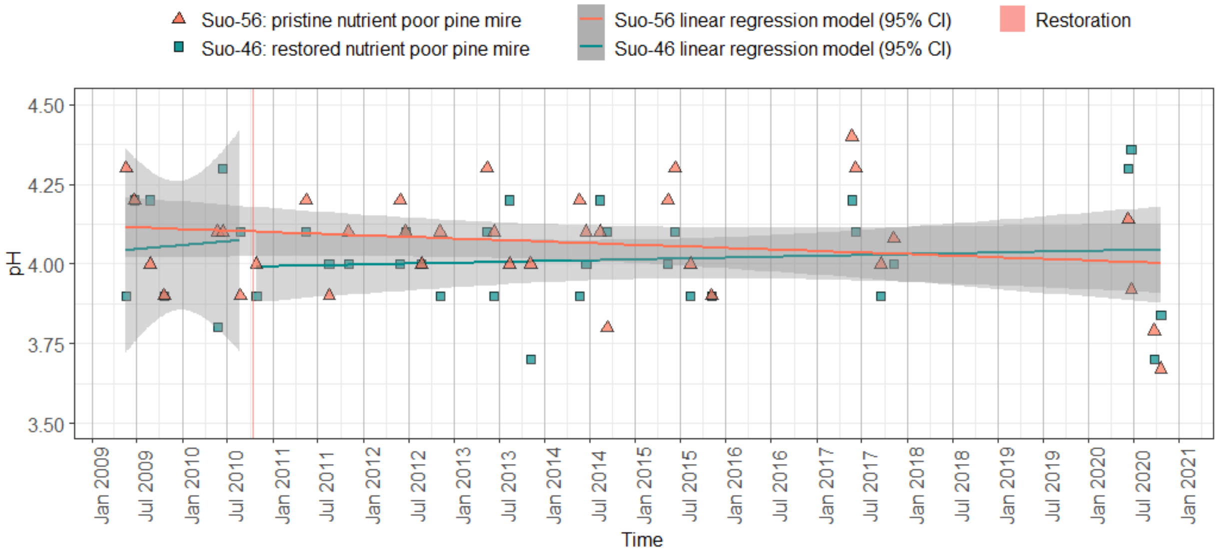
Jan 2021
Jul 2021
Jan 2022


Suo-56: pristine nutrient poor pine mire
Suo-46: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-46 linear regression model (95% CI)
Restoration
pH
4.50
4.25
4.00
3.75
3.50
Jan 2009
Jul 2009
Jan 2010
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Jan 2012
Jul 2012
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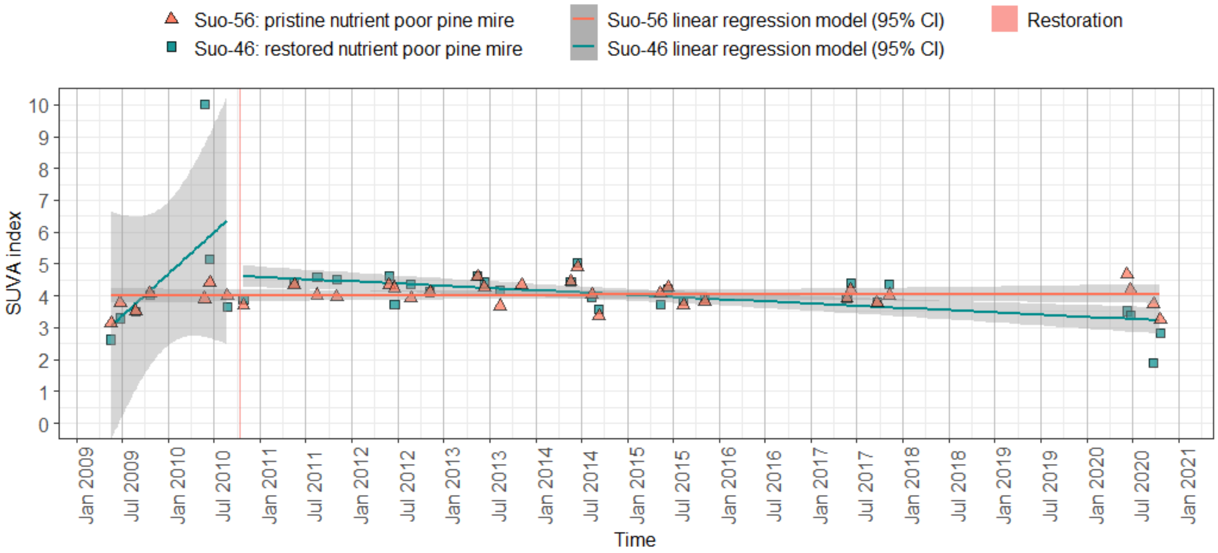
Jul 2020
Jan 2021
Time


Suo-56: pristine nutrient poor pine mire
Suo-46: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-46 linear regression model (95% CI)
Restoration
SUVA index
10
9
8
7
6
5
4
3
2
1
0
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
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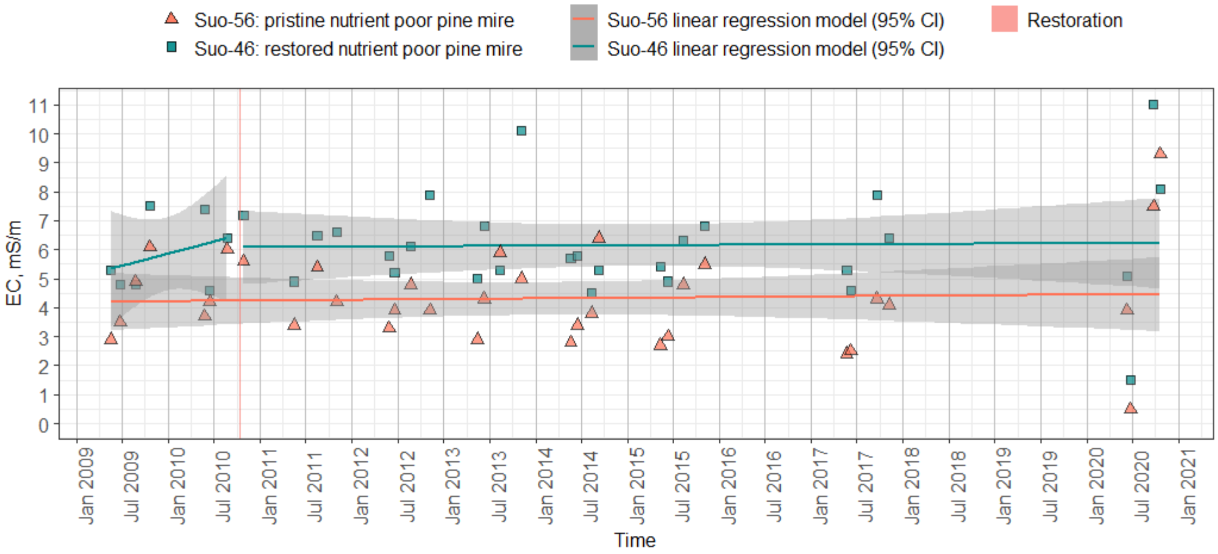
Jan 2020
Jul 2020
Jan 2021
Time


Suo-56: pristine nutrient poor pine mire
Suo-46: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-46 linear regression model (95% CI)
Restoration
EC, mS/m
11
10
9
8
7
6
5
4
3
2
1
0
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
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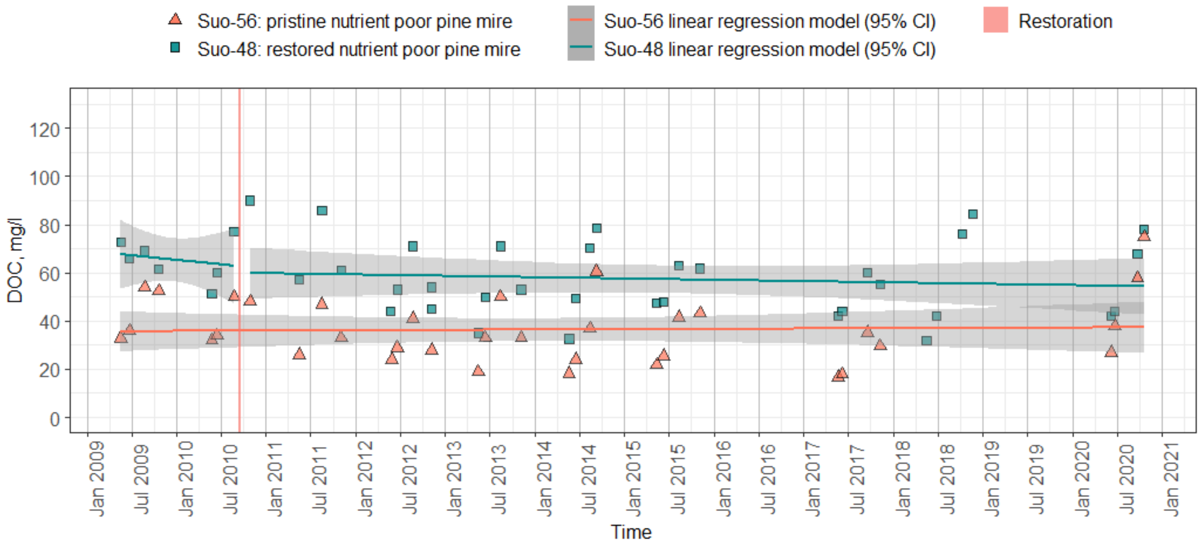
Jul 2020
Jan 2021
Time



Suo-56: pristine nutrient poor pine mire
Suo-48: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-48 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
120
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
Jul 2013
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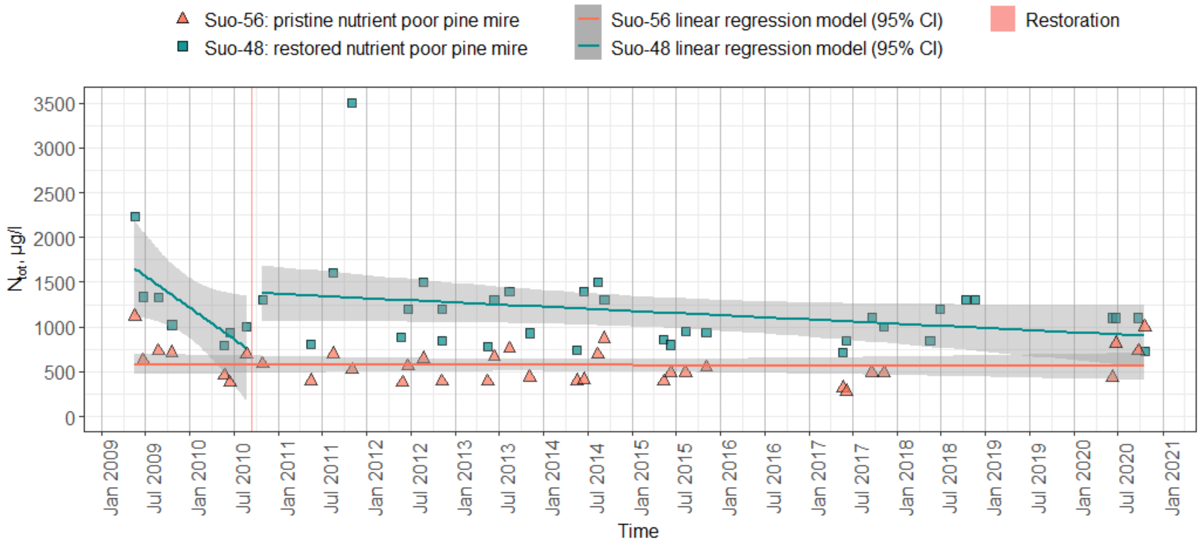
Jan 2020
Jul 2020
Jan 2021
Time



Suo-56: pristine nutrient poor pine mire
Suo-48: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-48 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
500
1000
1500
2000
2500
3000
3500
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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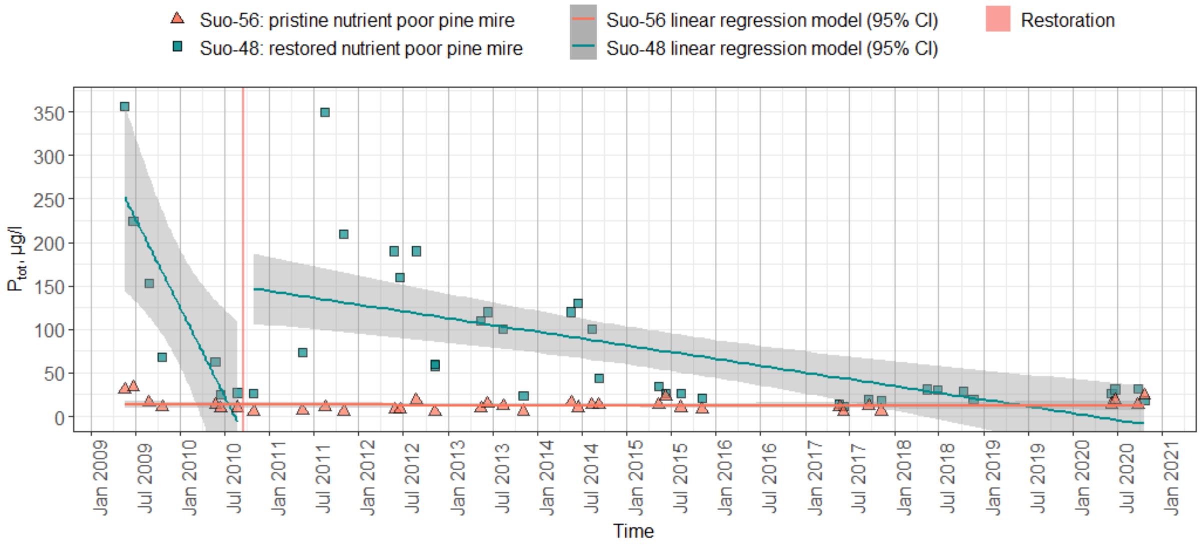
Jul 2020
Jan 2021
Time



Suo-56: pristine nutrient poor pine mire
Suo-48: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-48 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
50
100
150
200
250
300
350
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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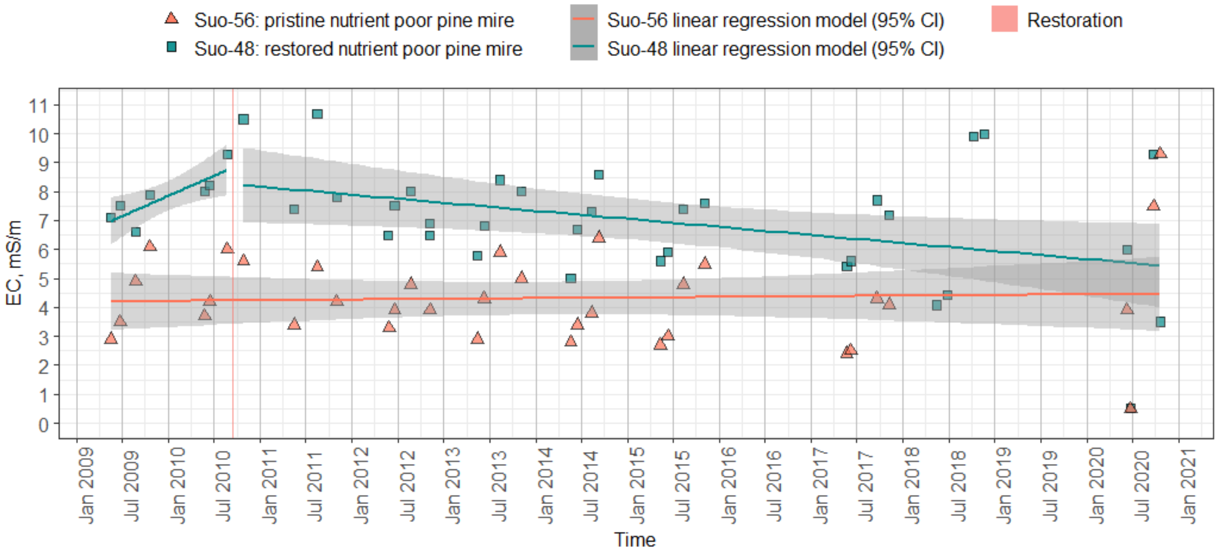
Jul 2020
Jan 2021
Time



Suo-56: pristine nutrient poor pine mire
Suo-48: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-48 linear regression model (95% CI)
Restoration
EC, mS/m
0
1
2
3
4
5
6
7
8
9
10
11
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
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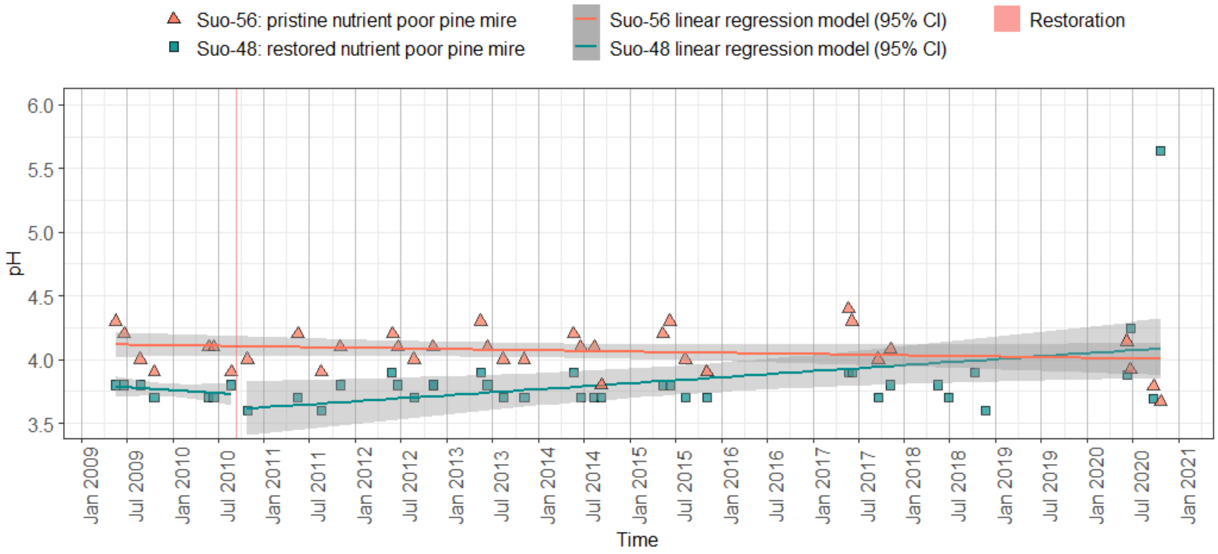
Jul 2020
Jan 2021
Time



Suo-56: pristine nutrient poor pine mire
Suo-48: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-48 linear regression model (95% CI)
Restoration
pH
3.5
4.0
4.5
5.0
5.5
6.0
Jan 2009
Jul 2009
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Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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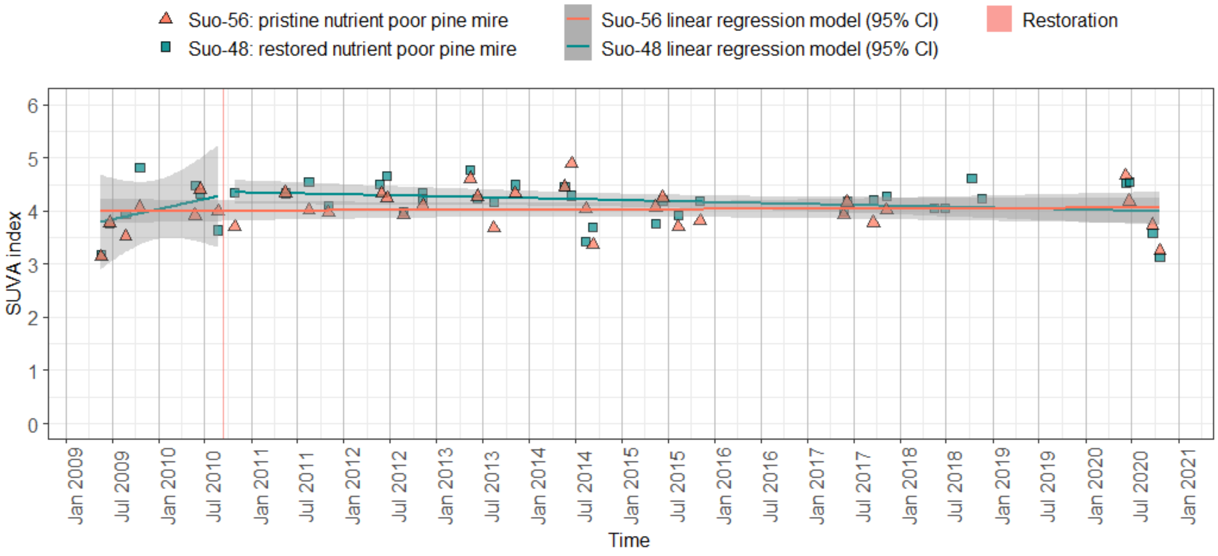
Time



Suo-56: pristine nutrient poor pine mire
Suo-48: restored nutrient poor pine mire
Suo-56 linear regression model (95% CI)
Suo-48 linear regression model (95% CI)
Restoration
SUVA index
0
1
2
3
4
5
6
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
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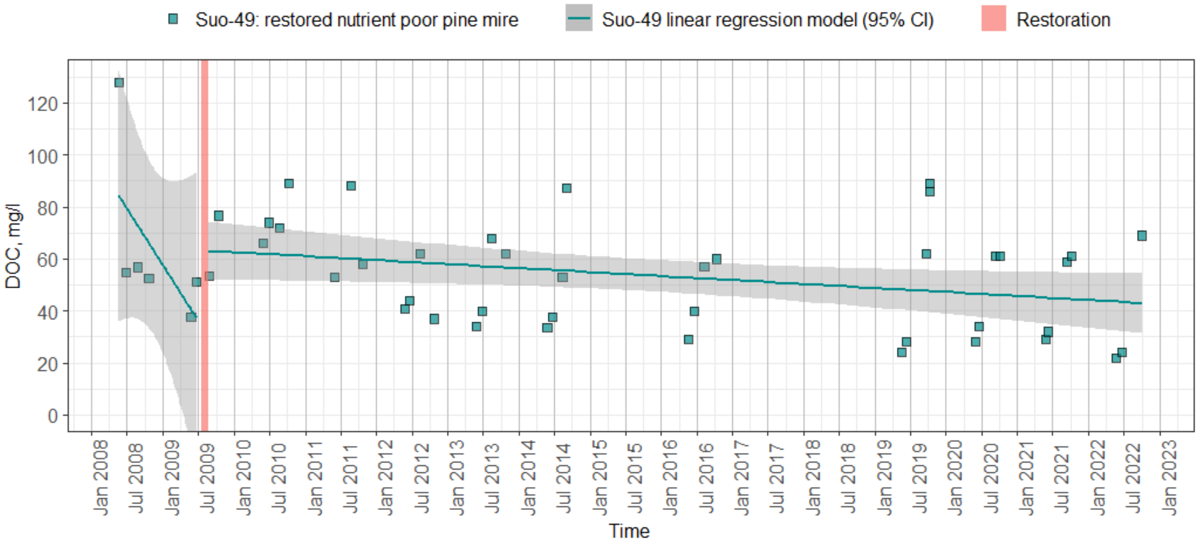
Time



Suo-49: restored nutrient poor pine mire
Suo-49 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
120
Jan 2008
Jul 2008
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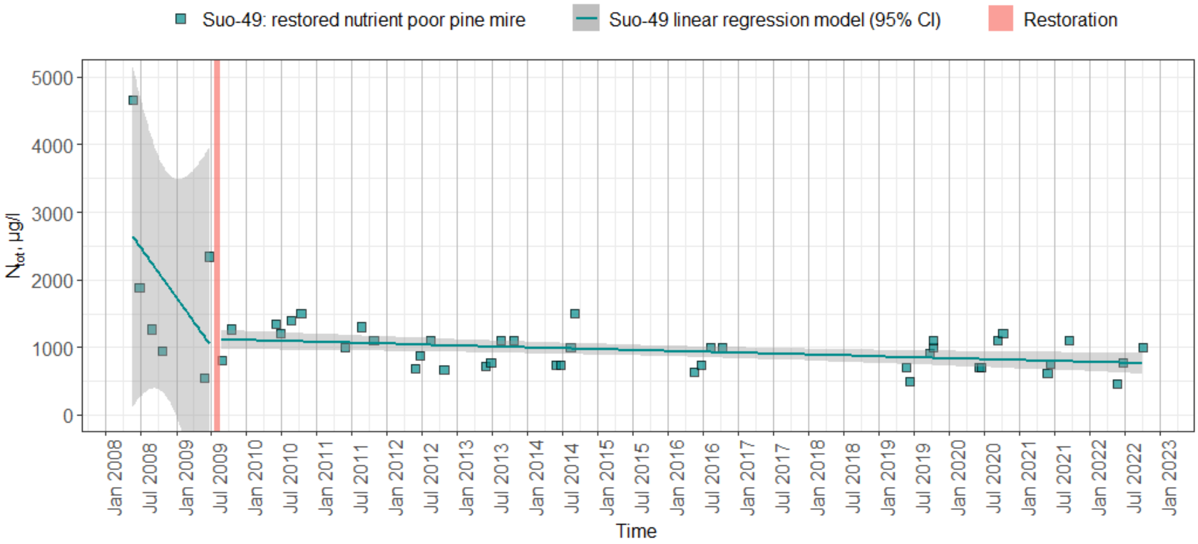
Time



Suo-49: restored nutrient poor pine mire
Suo-49 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
1000
2000
3000
4000
5000
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
Jul 2010
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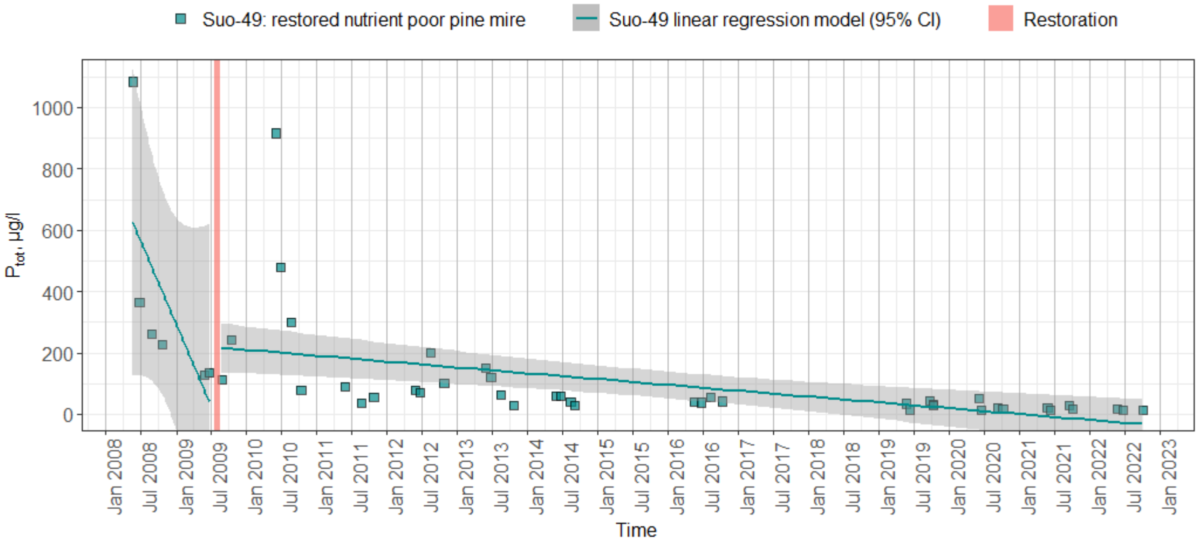
Jan 2023
Time



Suo-49: restored nutrient poor pine mire
Suo-49 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
200
400
600
800
1000
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
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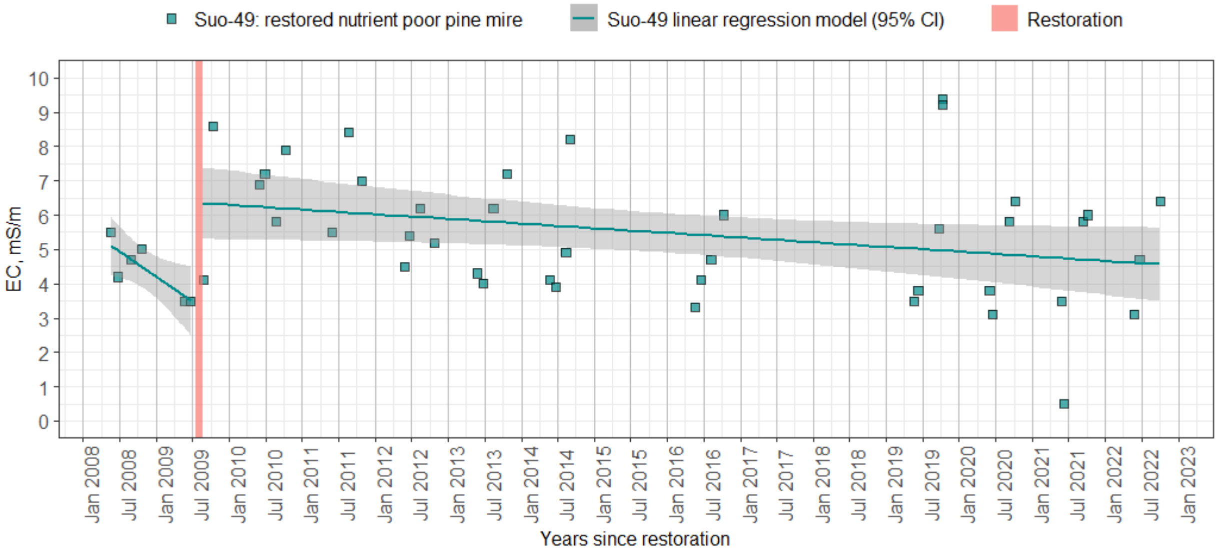
Time


Suo-49: restored nutrient poor pine mire
Suo-49 linear regression model (95% CI)
Restoration
EC, mS/m
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Jan 2008
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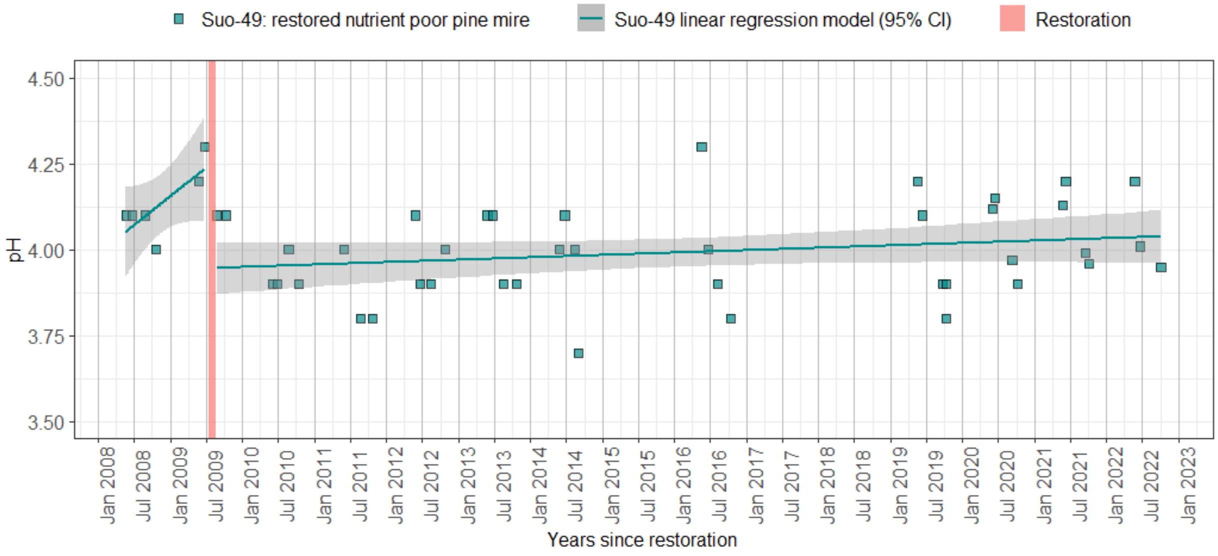
Jan 2023
Years since restoration


Suo-49: restored nutrient poor pine mire
Suo-49 linear regression model (95% CI)
Restoration
pH
3.50
3.75
4.00
4.25
4.50
Jan 2008
Jul 2008
Jan 2009
Jul 2009
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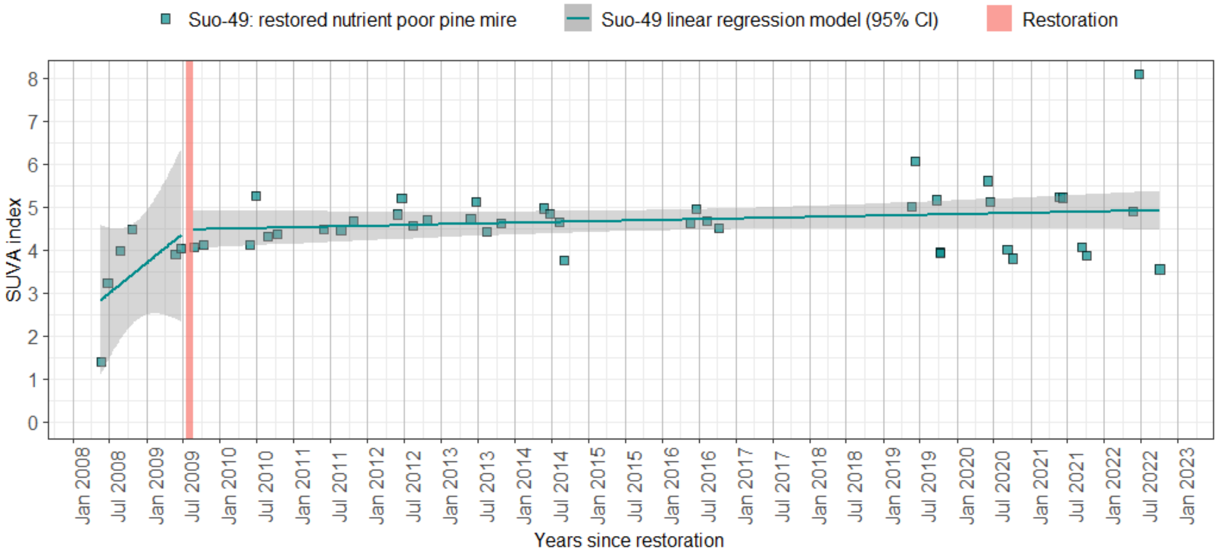
Jan 2023
Years since restoration


Suo-49: restored nutrient poor pine mire
Suo-49 linear regression model (95% CI)
Restoration
SUVA index
0
1
2
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7
8
Jan 2008
Jul 2008
Jan 2009
Jul 2009
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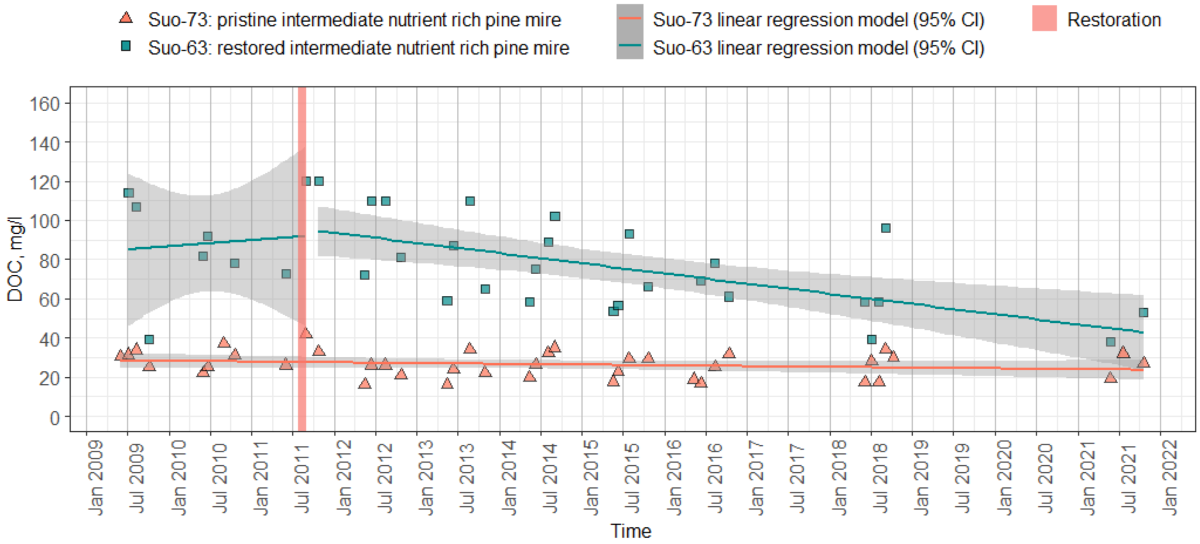
Jul 2022
Jan 2023
Years since restoration


Suo-73: pristine intermediate nutrient rich pine mire
Suo-63: restored intermediate nutrient rich pine mire
Suo-73 linear regression model (95% CI)
Suo-63 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
120
140
160
Jan 2009
Jul 2009
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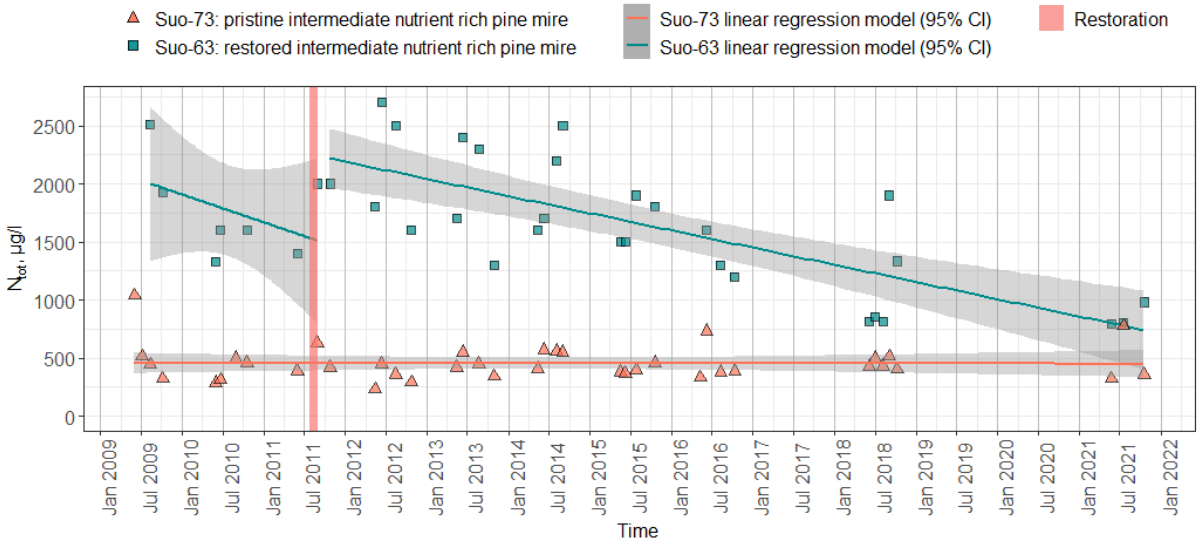
Jul 2021
Jan 2022
Time


Suo-73: pristine intermediate nutrient rich pine mire
Suo-63: restored intermediate nutrient rich pine mire
Suo-73 linear regression model (95% CI)
Suo-63 linear regression model (95% CI)
Restoration
N_tot, µg/l
0
500
1000
1500
2000
2500
Jan 2009
Jul 2009
Jan 2010
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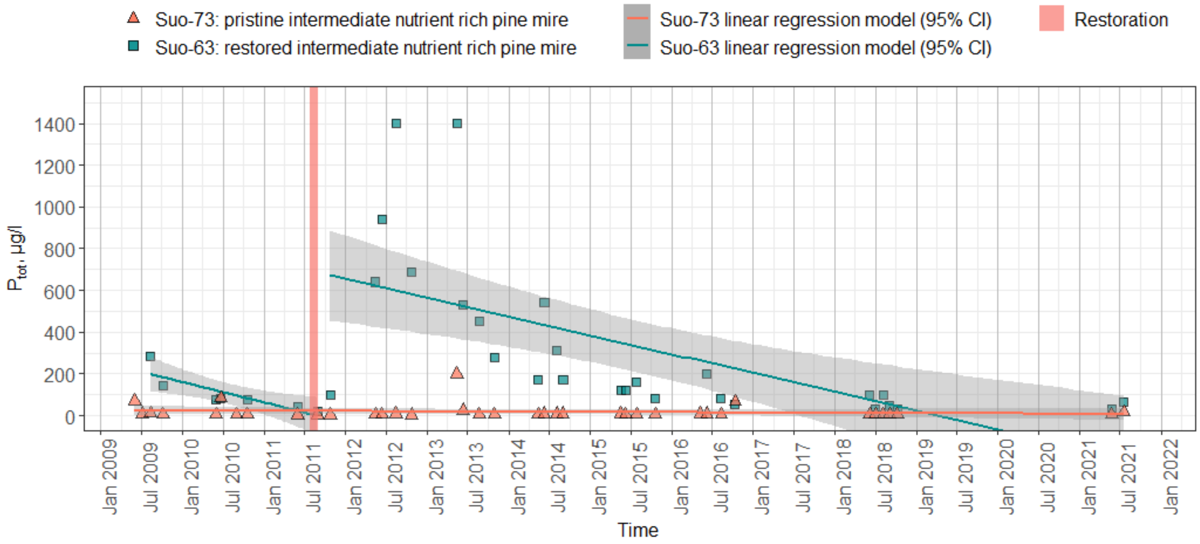
Time


Suo-73: pristine intermediate nutrient rich pine mire
Suo-63: restored intermediate nutrient rich pine mire
Suo-73 linear regression model (95% CI)
Suo-63 linear regression model (95% CI)
Restoration
P_tot, µg/l
0
200
400
600
800
1000
1200
1400
Jan 2009
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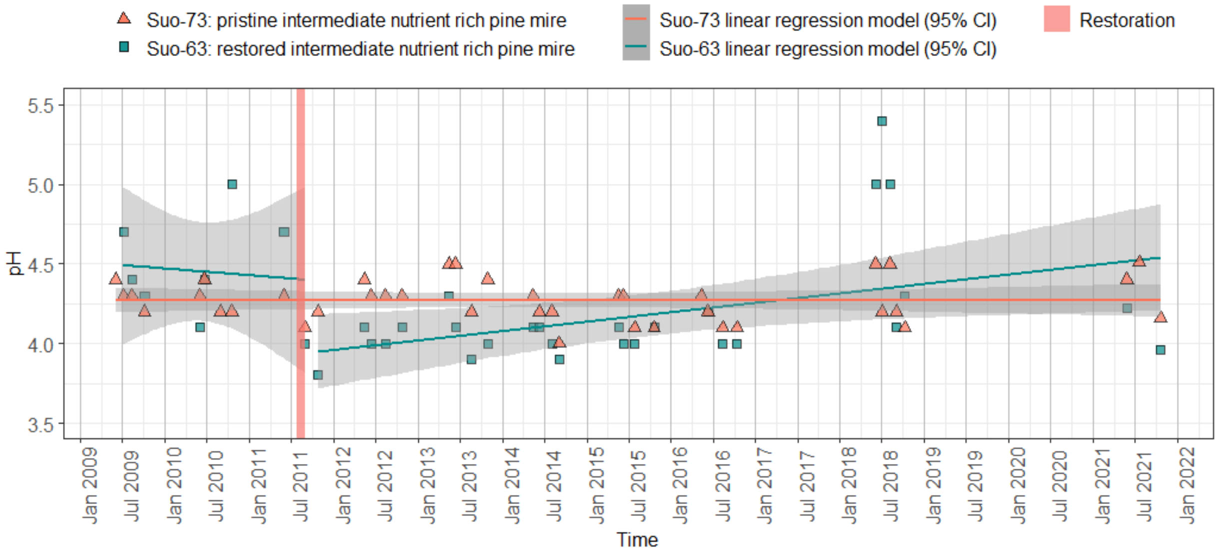
Suo-73: pristine intermediate nutrient rich pine mire
Suo-63: restored intermediate nutrient rich pine mire
Suo-73 linear regression model (95% CI)
Suo-63 linear regression model (95% CI)
Restoration
pH
5.5
5.0
4.5
4.0
3.5
Jan 2009
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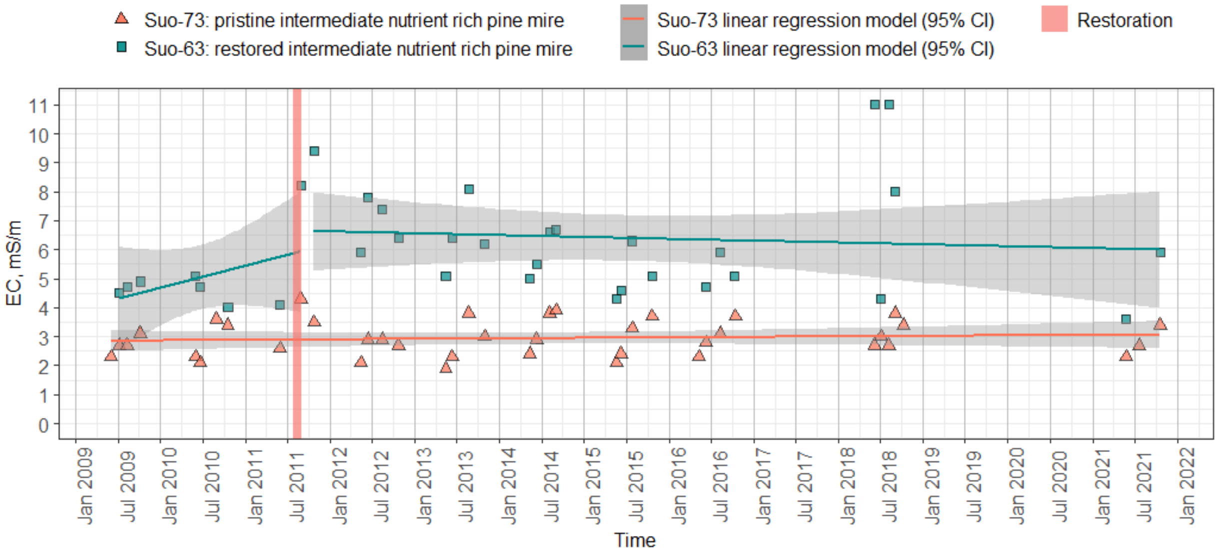
Suo-73: pristine intermediate nutrient rich pine mire
Suo-63: restored intermediate nutrient rich pine mire
Suo-73 linear regression model (95% CI)
Suo-63 linear regression model (95% CI)
Restoration
EC, mS/m
11
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Jan 2009
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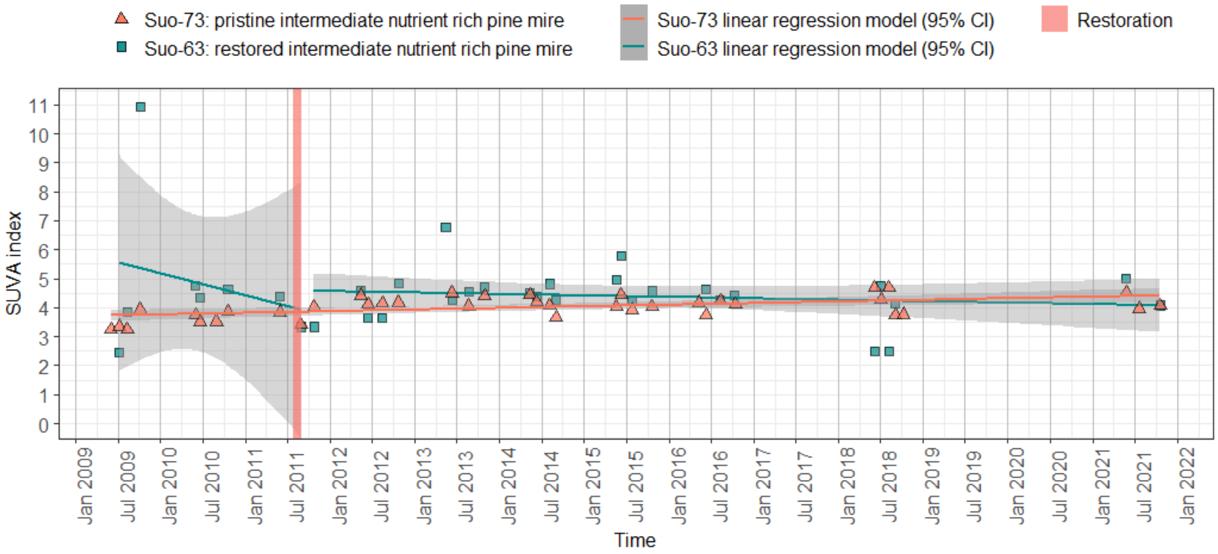
Suo-73: pristine intermediate nutrient rich pine mire
Suo-63: restored intermediate nutrient rich pine mire
Suo-73 linear regression model (95% CI)
Suo-63 linear regression model (95% CI)
Restoration
SUVA index
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Jan 2009
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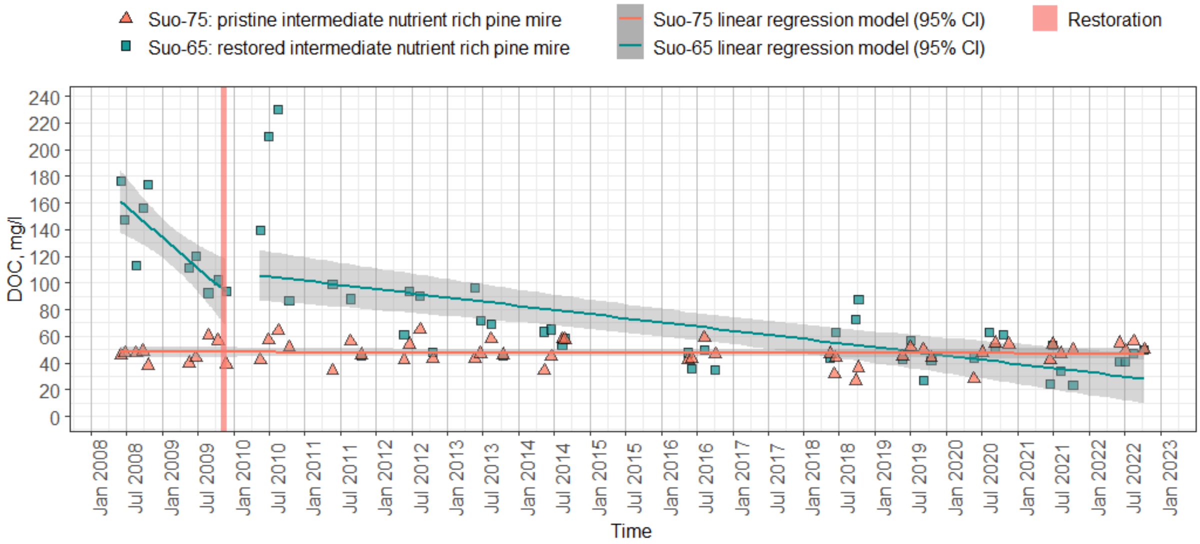
Suo-75: pristine intermediate nutrient rich pine mire
Suo-65: restored intermediate nutrient rich pine mire
Suo-75 linear regression model (95% CI)
Suo-65 linear regression model (95% CI)
Restoration
DOC, mg/l
0
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Jan 2008
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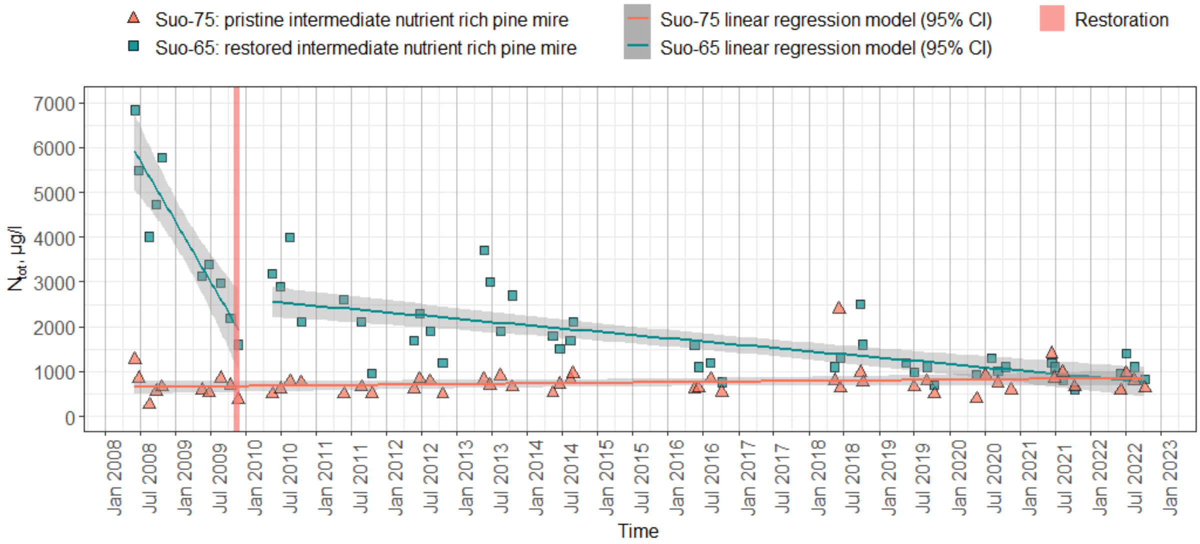
Suo-75: pristine intermediate nutrient rich pine mire
Suo-65: restored intermediate nutrient rich pine mire
Suo-75 linear regression model (95% CI)
Suo-65 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
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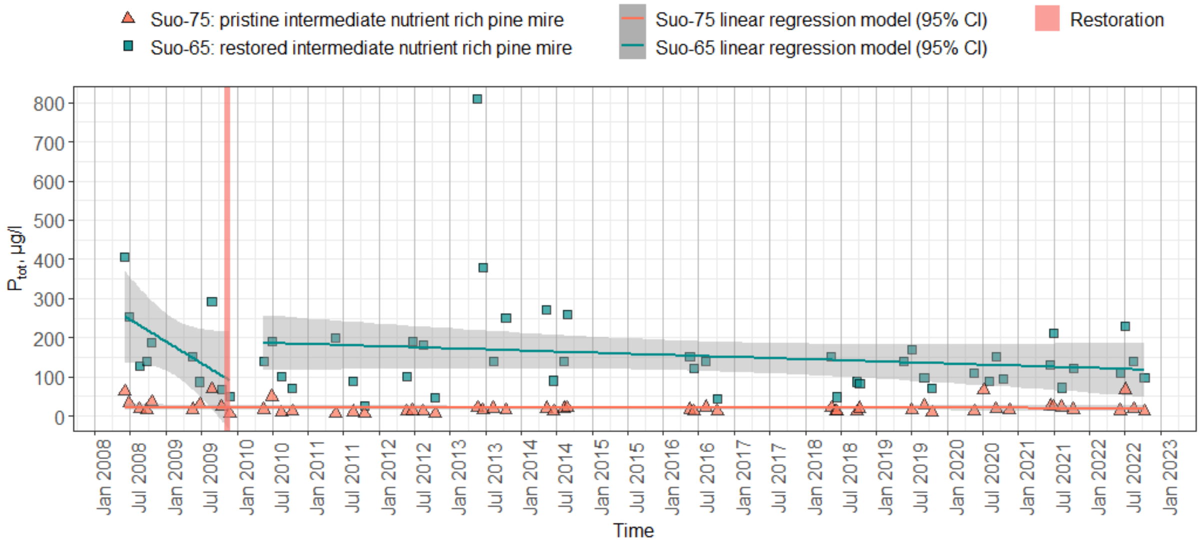
Suo-75: pristine intermediate nutrient rich pine mire
Suo-65: restored intermediate nutrient rich pine mire
Suo-75 linear regression model (95% CI)
Suo-65 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
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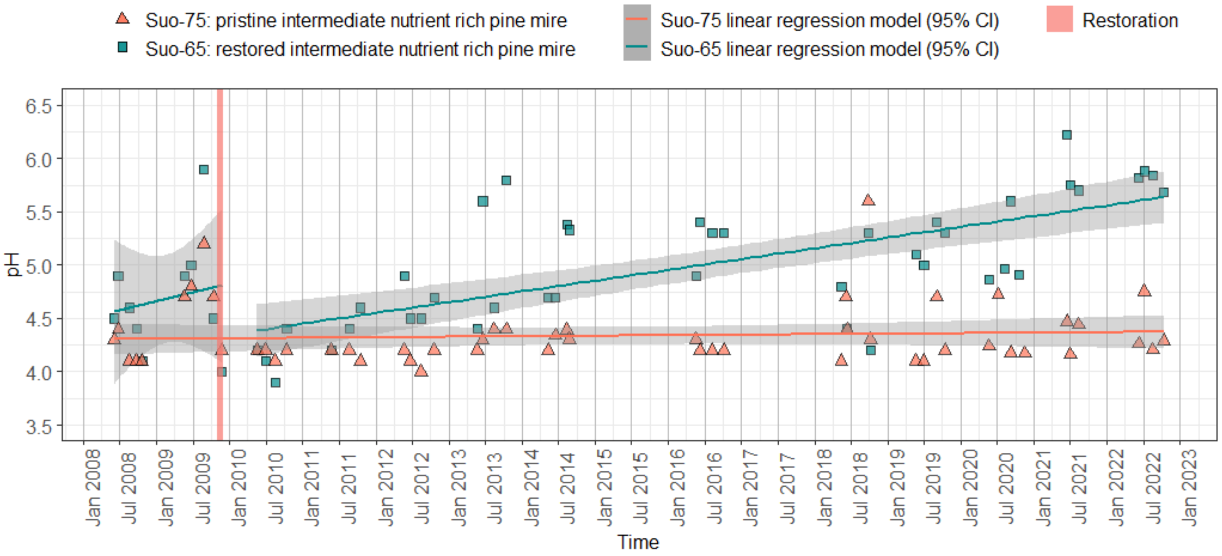

Suo-75: pristine intermediate nutrient rich pine mire
Suo-65: restored intermediate nutrient rich pine mire
Suo-75 linear regression model (95% CI)
Suo-65 linear regression model (95% CI)
Restoration
pH
6.5
6.0
5.5
5.0
4.5
4.0
3.5
Jan 2008
Jul 2008
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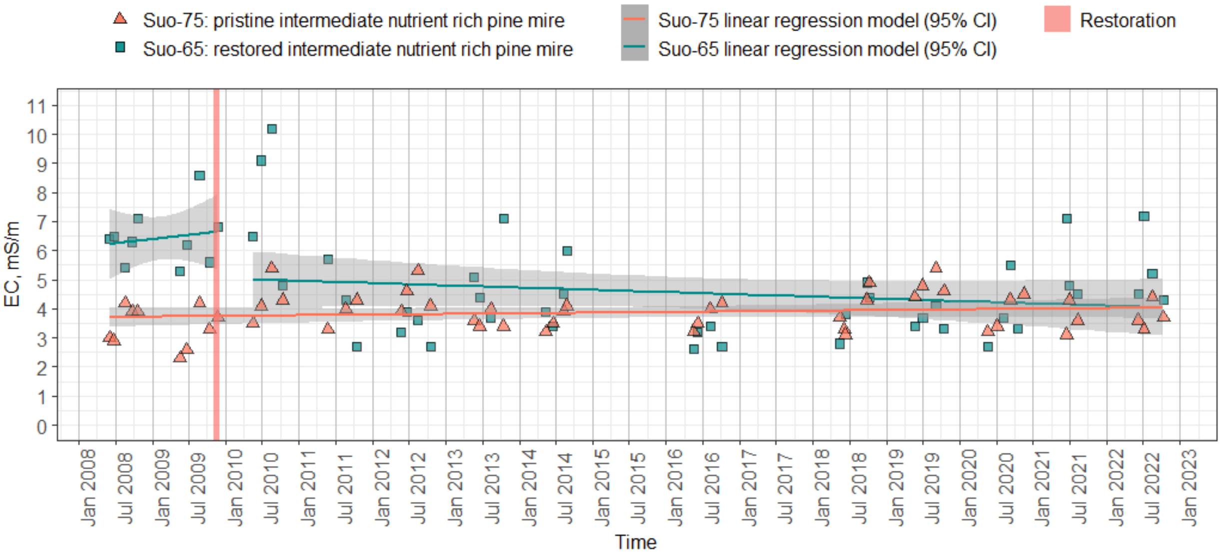

Suo-75: pristine intermediate nutrient rich pine mire
Suo-65: restored intermediate nutrient rich pine mire
Suo-75 linear regression model (95% CI)
Suo-65 linear regression model (95% CI)
Restoration
EC, mS/m
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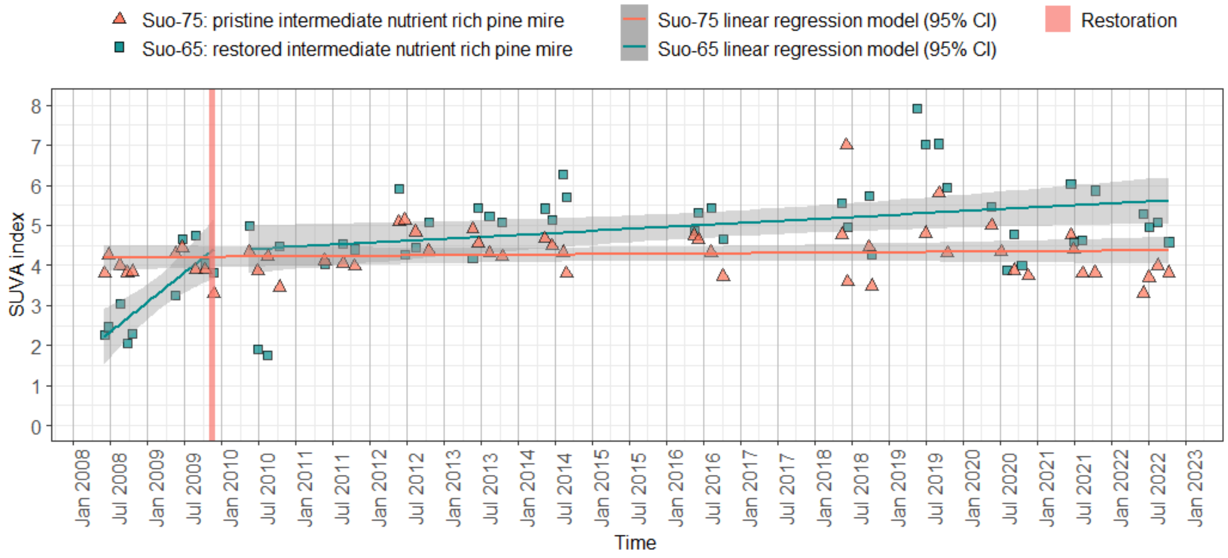

Suo-75: pristine intermediate nutrient rich pine mire
Suo-65: restored intermediate nutrient rich pine mire
Suo-75 linear regression model (95% CI)
Suo-65 linear regression model (95% CI)
Restoration
SUVA index
8
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Jan 2008
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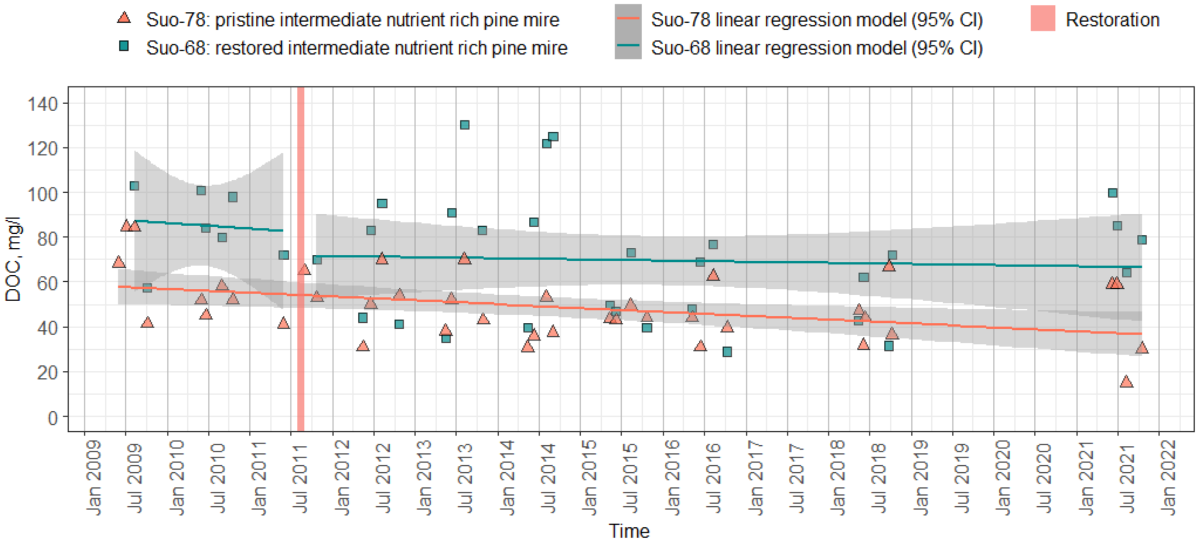
Suo-78: pristine intermediate nutrient rich pine mire
Suo-68: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-68 linear regression model (95% CI)
Restoration
DOC, mg/l
0
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Jan 2009
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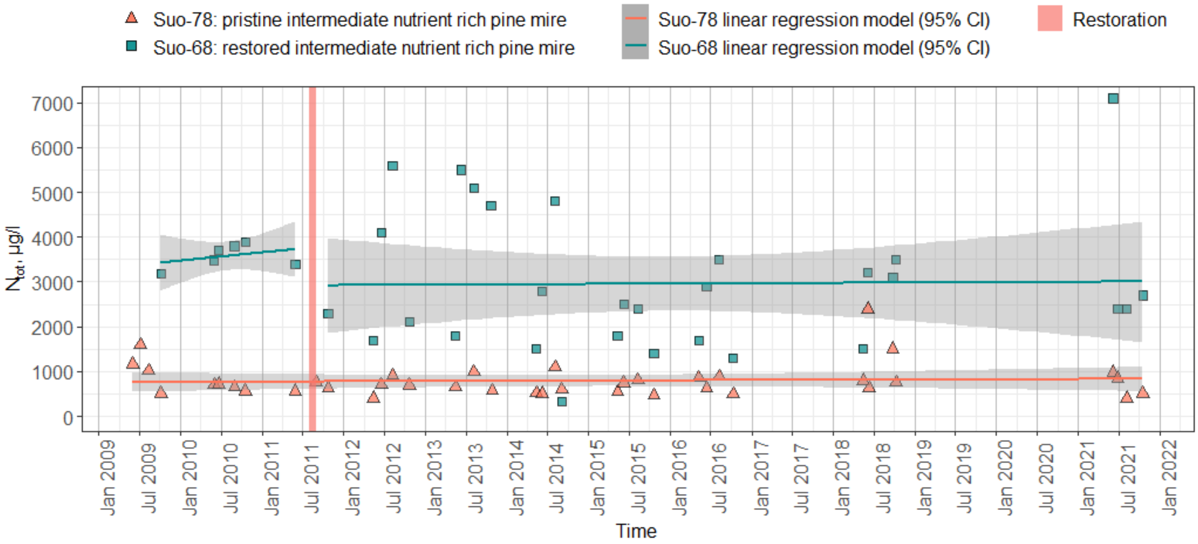
Suo-78: pristine intermediate nutrient rich pine mire
Suo-68: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-68 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
1000
2000
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4000
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7000
Jan 2009
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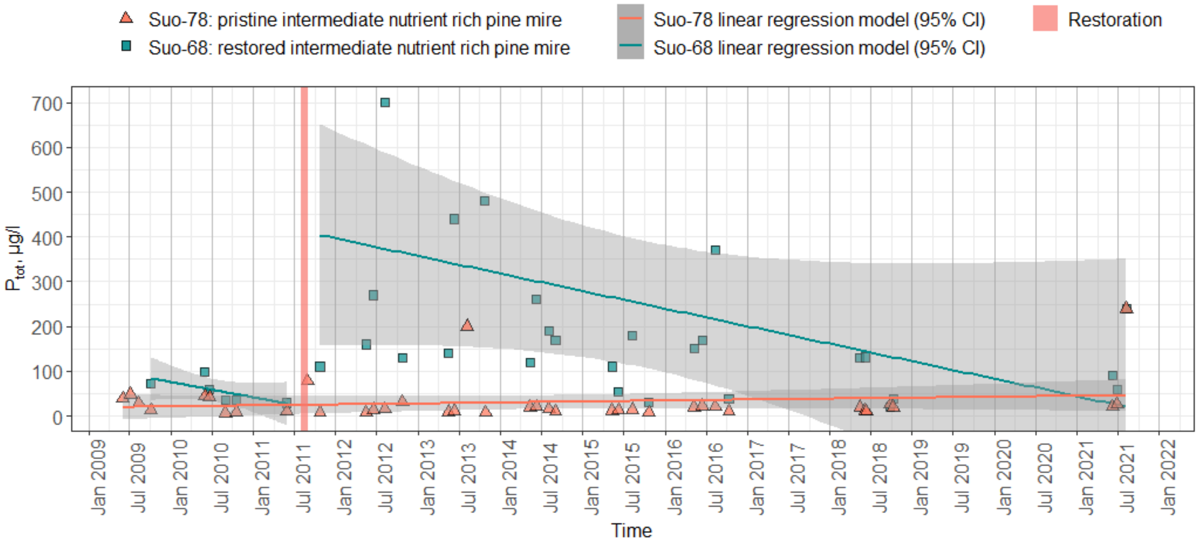
Suo-78: pristine intermediate nutrient rich pine mire
Suo-68: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-68 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
100
200
300
400
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700
Jan 2009
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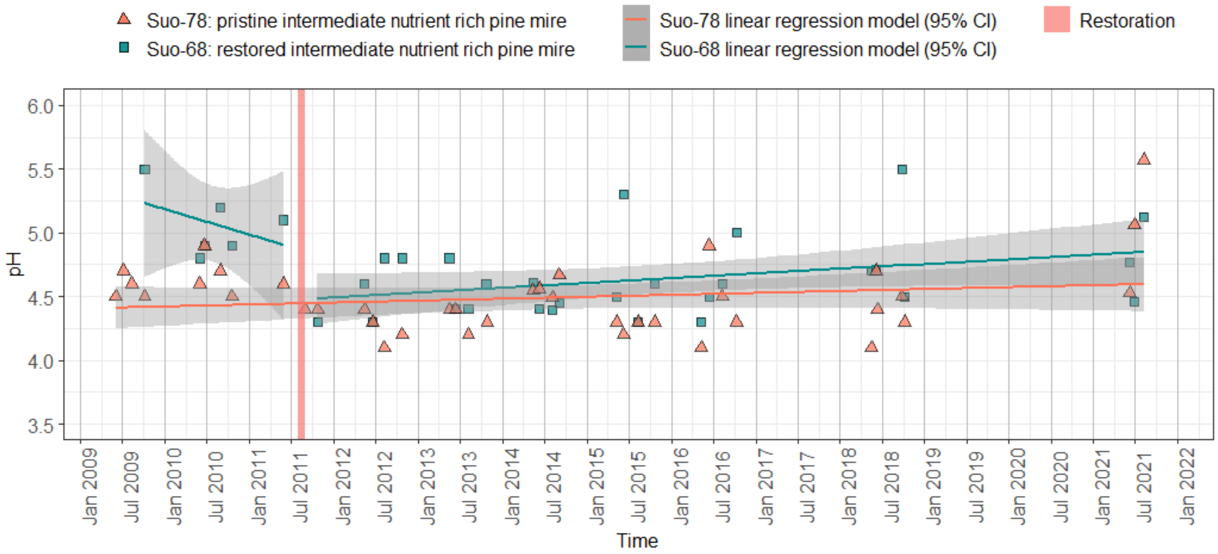
Suo-78: pristine intermediate nutrient rich pine mire
Suo-68: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-68 linear regression model (95% CI)
Restoration
pH
6.0
5.5
5.0
4.5
4.0
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Jan 2009
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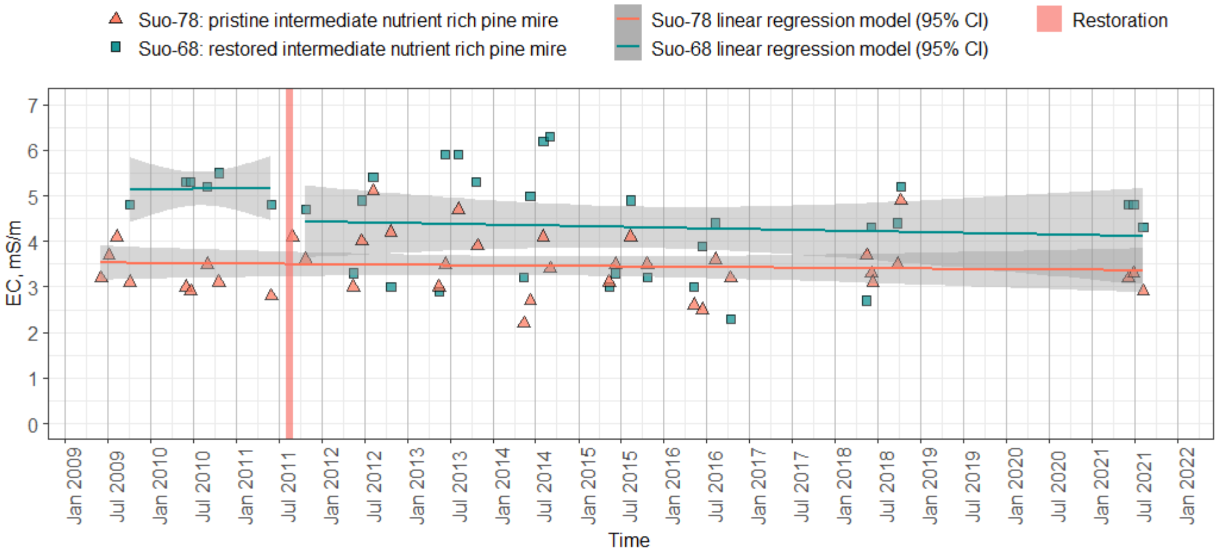
Suo-78: pristine intermediate nutrient rich pine mire
Suo-68: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-68 linear regression model (95% CI)
Restoration
EC, mS/m
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Jan 2009
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Time


Suo-78: pristine intermediate nutrient rich pine mire
Suo-68: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-68 linear regression model (95% CI)
Restoration
SUVA index
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Jan 2009
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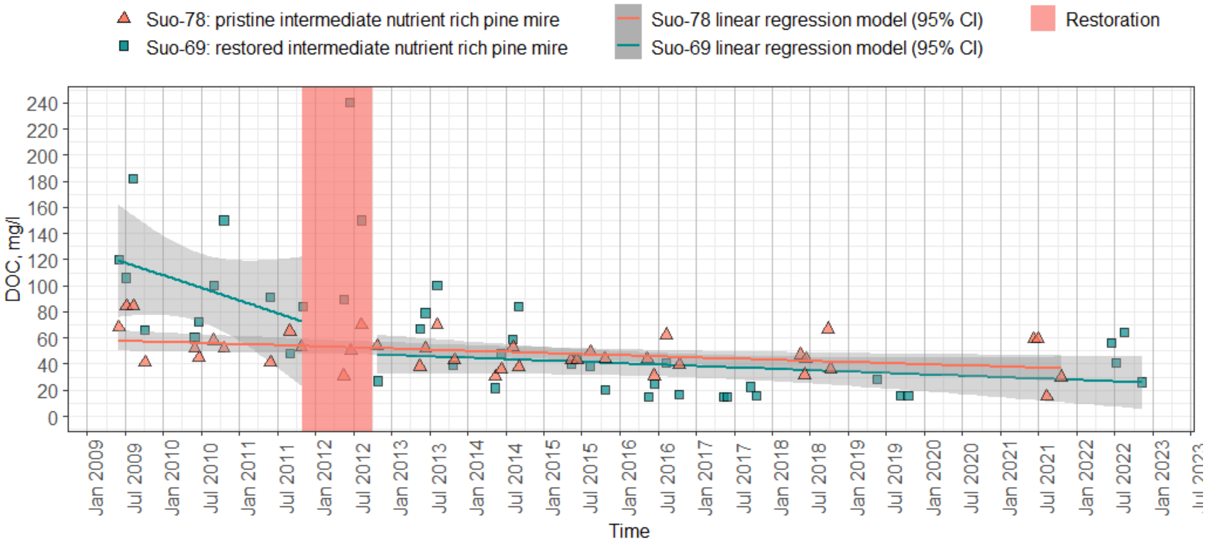
Suo-78: pristine intermediate nutrient rich pine mire
Suo-69: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-69 linear regression model (95% CI)
Restoration
DOC, mg/l
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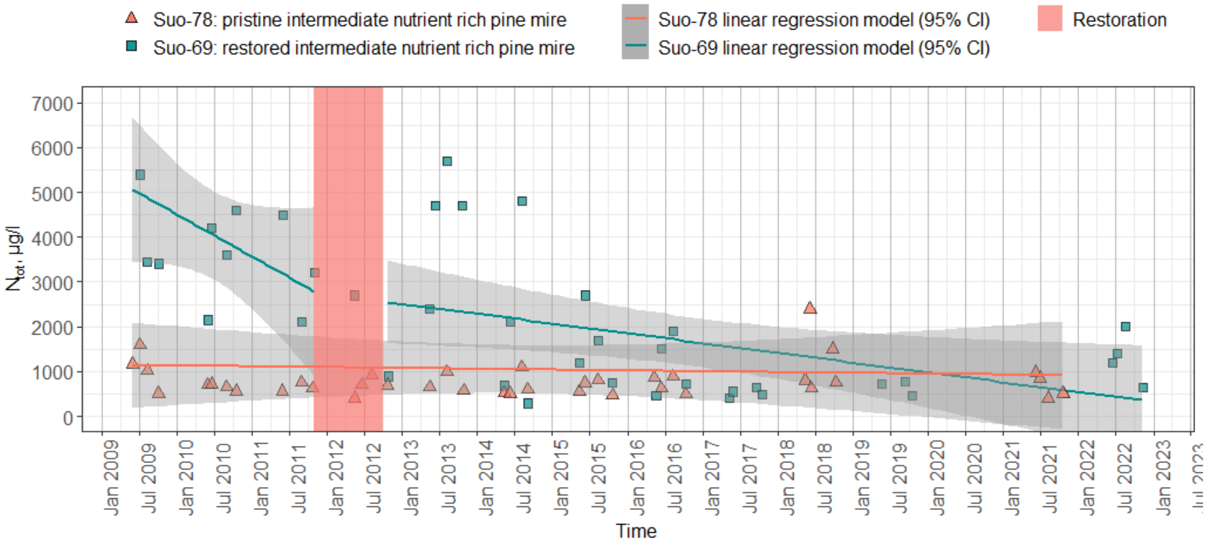
Time


Suo-78: pristine intermediate nutrient rich pine mire
Suo-69: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-69 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
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2000
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Jan 2009
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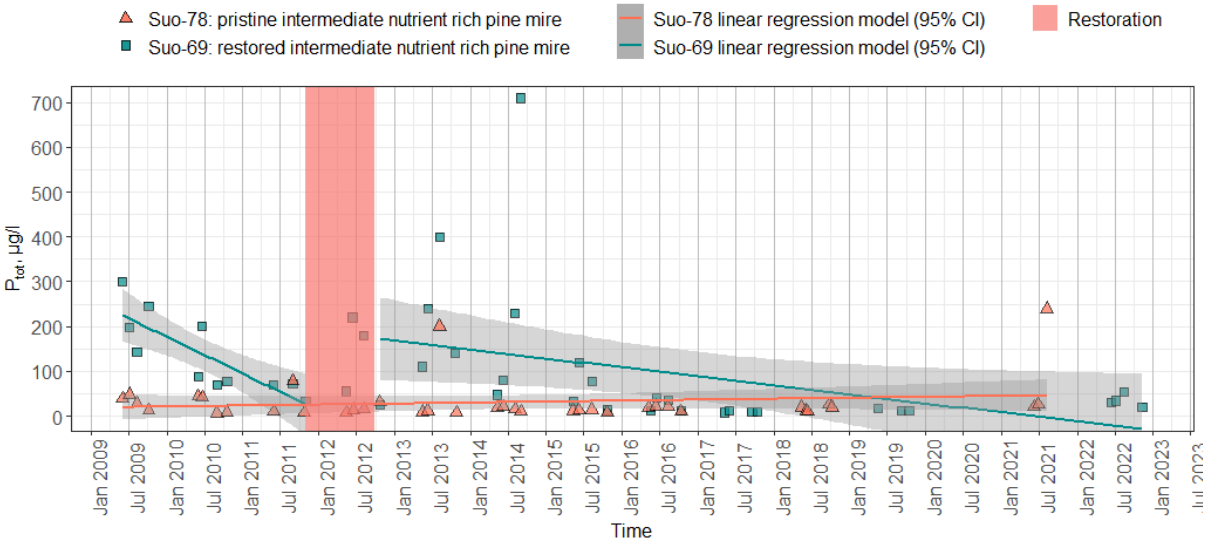
Time


Suo-78: pristine intermediate nutrient rich pine mire
Suo-69: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-69 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
100
200
300
400
500
600
700
Jan 2009
Jul 2009
Jan 2010
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Jan 2011
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Jan 2021
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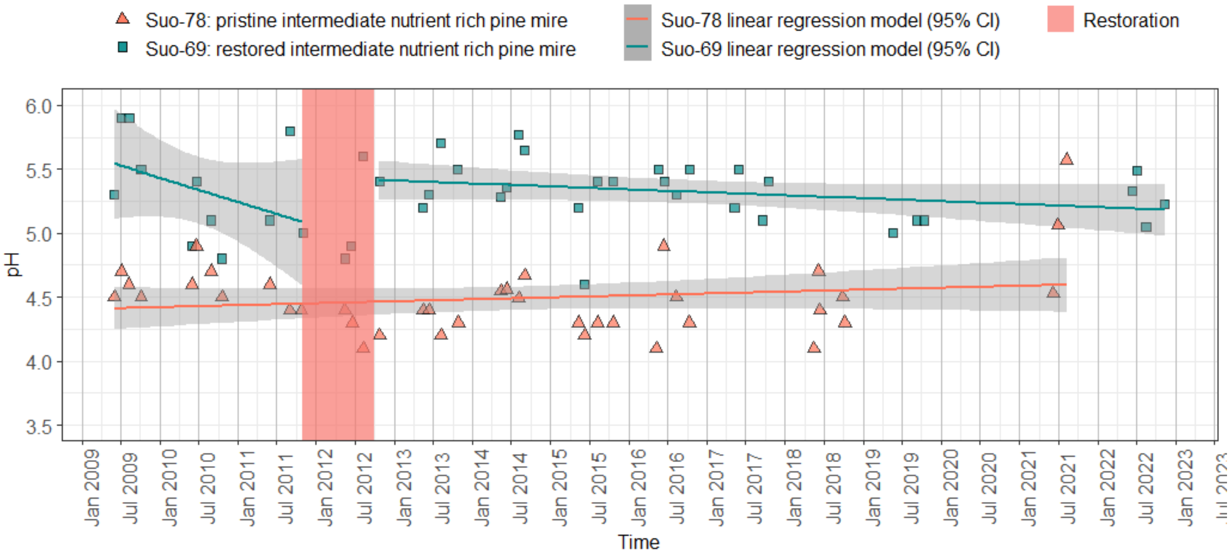
Jan 2022
Jul 2022
Jan 2023
Time



Suo-78: pristine intermediate nutrient rich pine mire
Suo-69: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-69 linear regression model (95% CI)
Restoration
pH
6.0
5.5
5.0
4.5
4.0
3.5
Jan 2009
Jul 2009
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Jul 2020
Jan 2021
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time

Suo-78: pristine intermediate nutrient rich pine mire
Suo-69: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-69 linear regression model (95% CI)
Restoration
EC, mS/m
10
9
8
7
6
5
4
3
2
1
0
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
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Jul 2020
Jan 2021
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time

Suo-78: pristine intermediate nutrient rich pine mire
Suo-69: restored intermediate nutrient rich pine mire
Suo-78 linear regression model (95% CI)
Suo-69 linear regression model (95% CI)
Restoration
SUVA index
8
7
6
5
4
3
2
1
0
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
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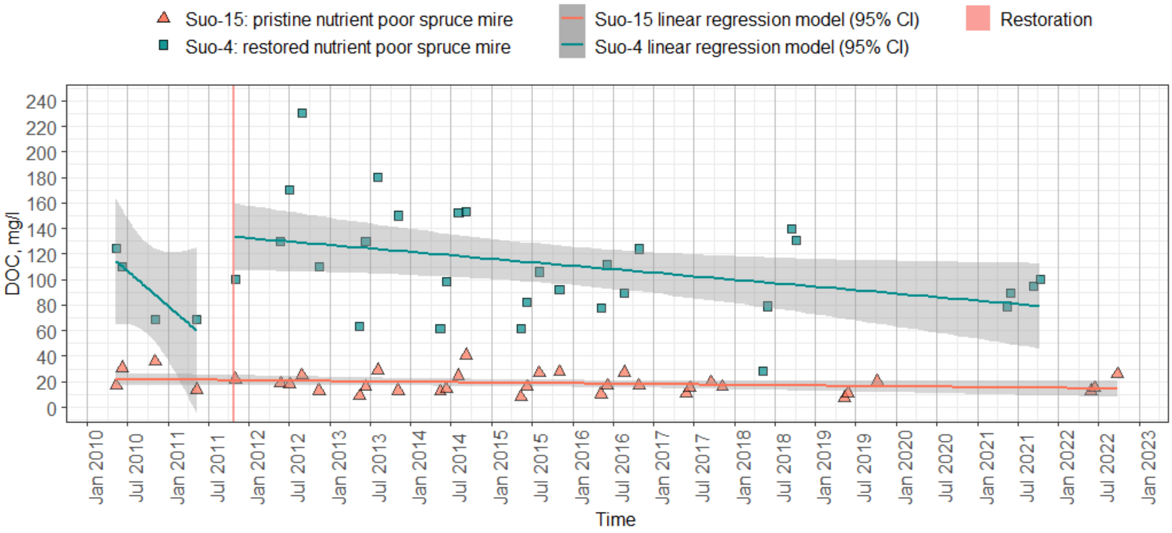
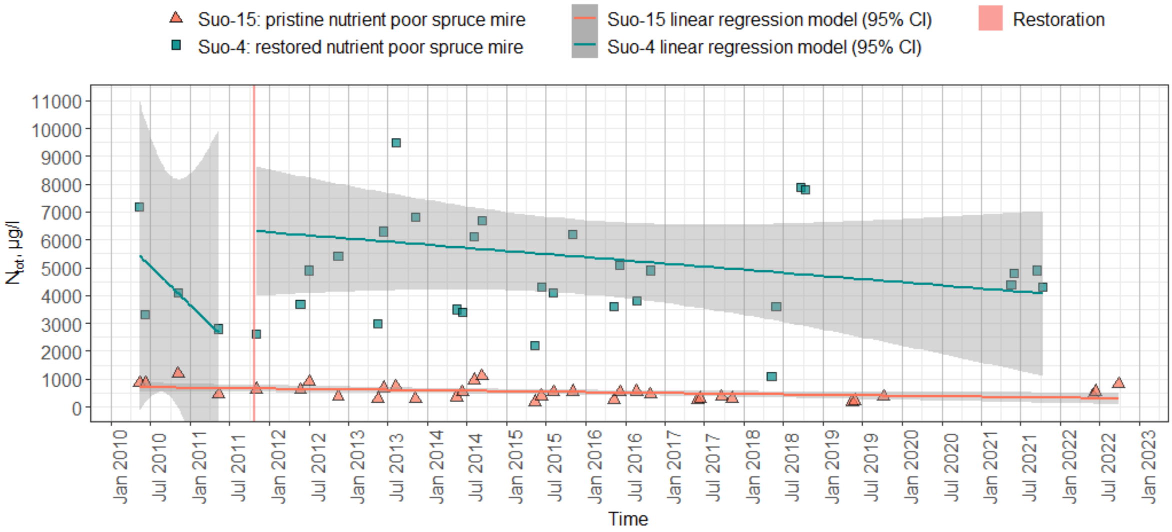
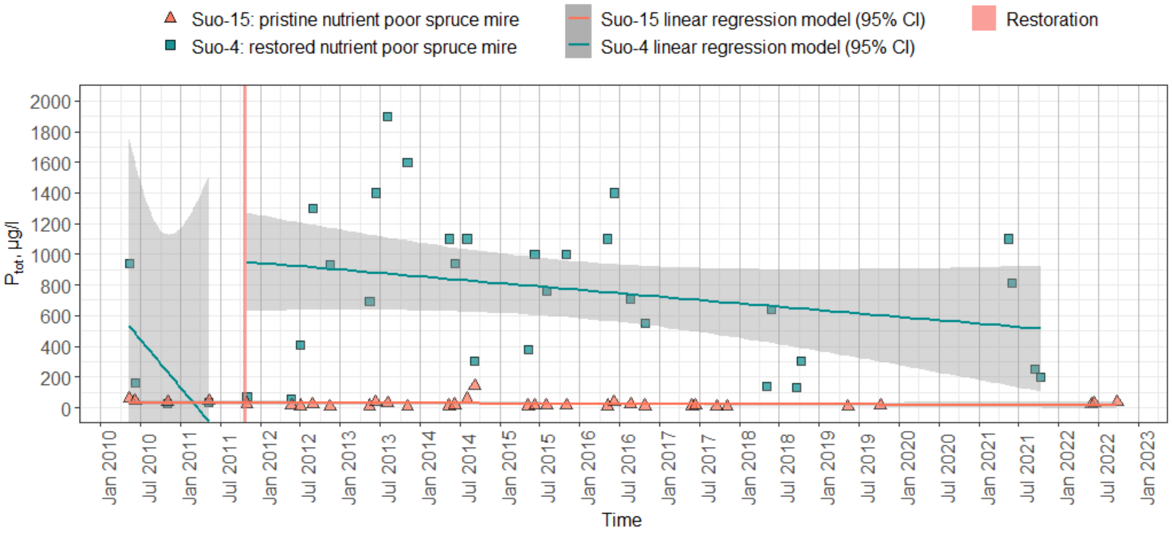
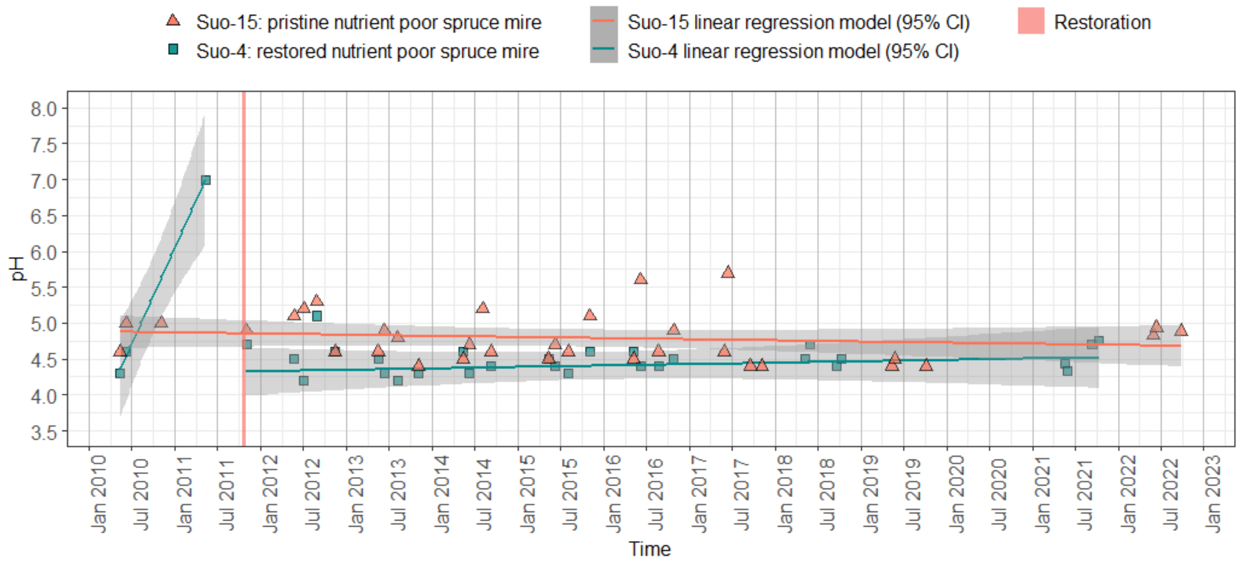
Jan 2021
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time

Appendix 2C. 10-year water quality observations in the peatland monitoring network – Spruce mires









Suo-15: pristine nutrient poor spruce mire
Suo-4: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-4 linear regression model (95% CI)
Restoration
pH
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
Jan 2010
Jul 2010
Jan 2011
Jul 2011
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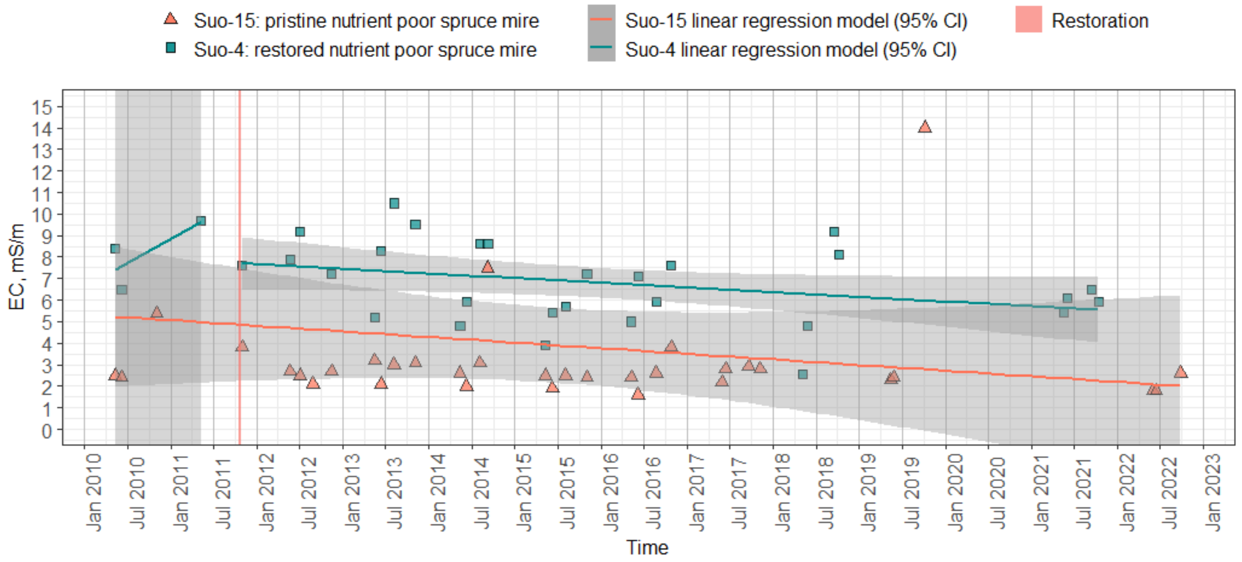
Jan 2021
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time



Suo-15: pristine nutrient poor spruce mire
Suo-4: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-4 linear regression model (95% CI)
Restoration
EC, mS/m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Jan 2010
Jul 2010
Jan 2011
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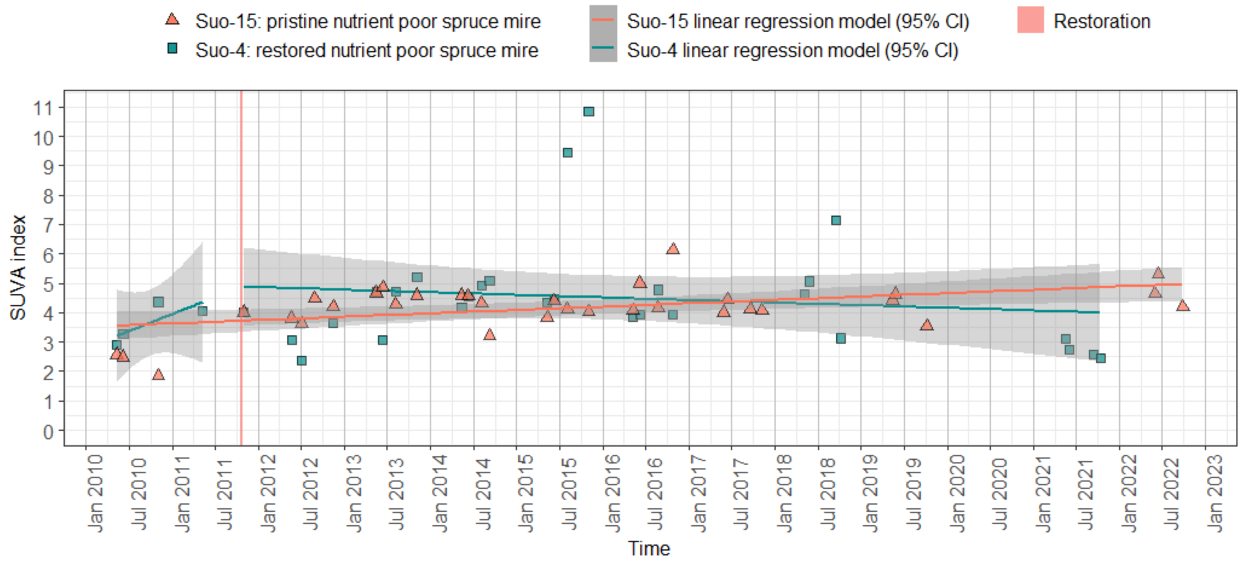
Jul 2022
Jan 2023
Time



Suo-15: pristine nutrient poor spruce mire
Suo-4: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-4 linear regression model (95% CI)
Restoration
SUVA index
11
10
9
8
7
6
5
4
3
2
1
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Jan 2010
Jul 2010
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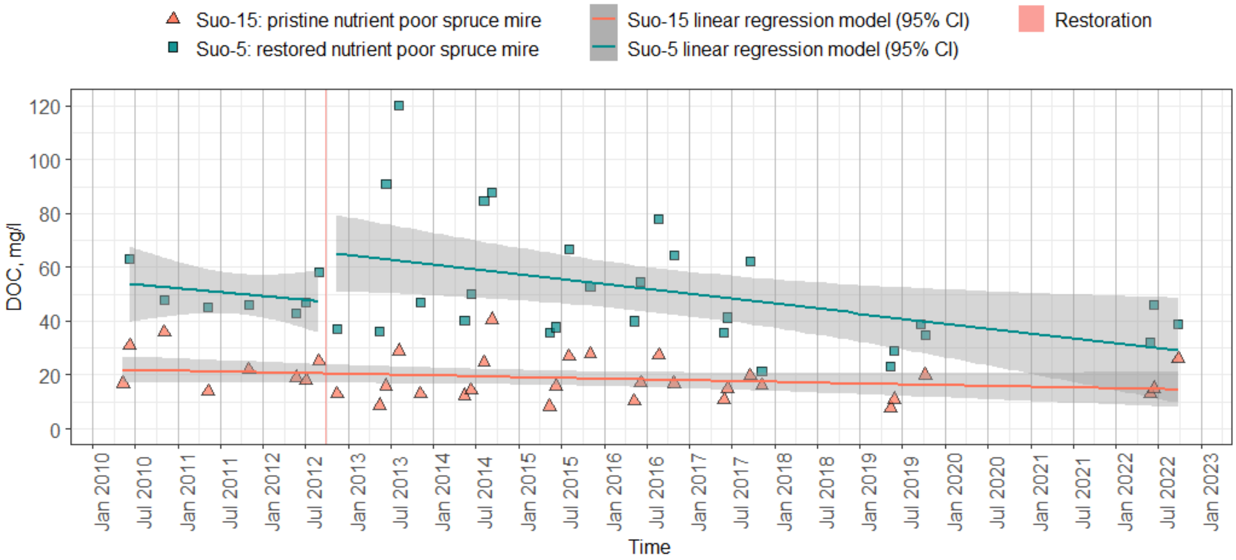
Jan 2022
Jul 2022
Jan 2023
Time


Suo-15: pristine nutrient poor spruce mire
Suo-5: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-5 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
120
Jan 2010
Jul 2010
Jan 2011
Jul 2011
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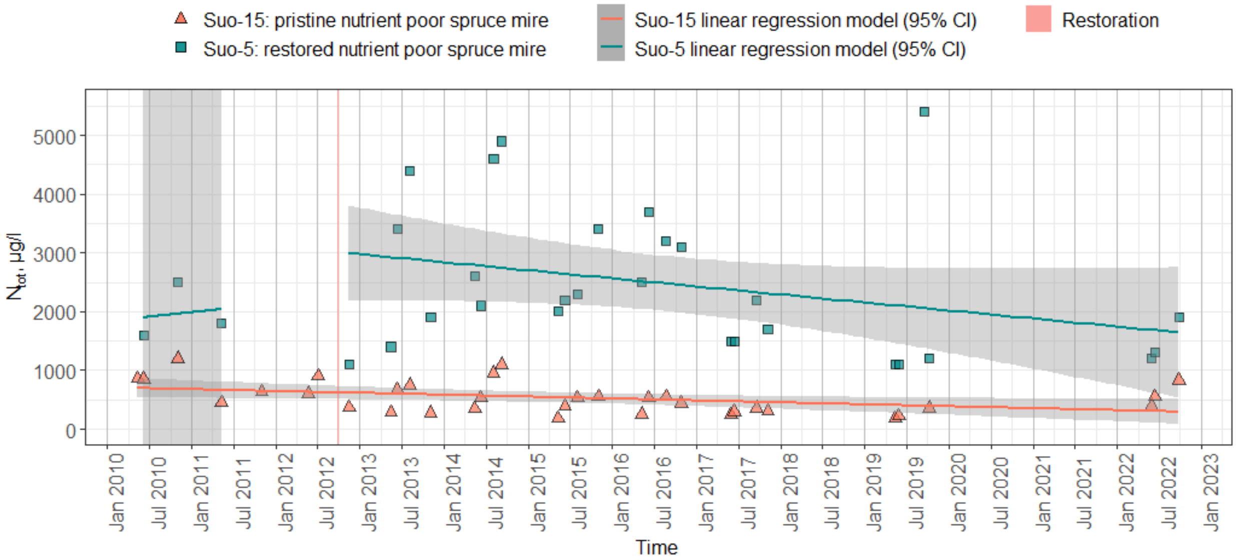
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time


Suo-15: pristine nutrient poor spruce mire
Suo-5: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-5 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
1000
2000
3000
4000
5000
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
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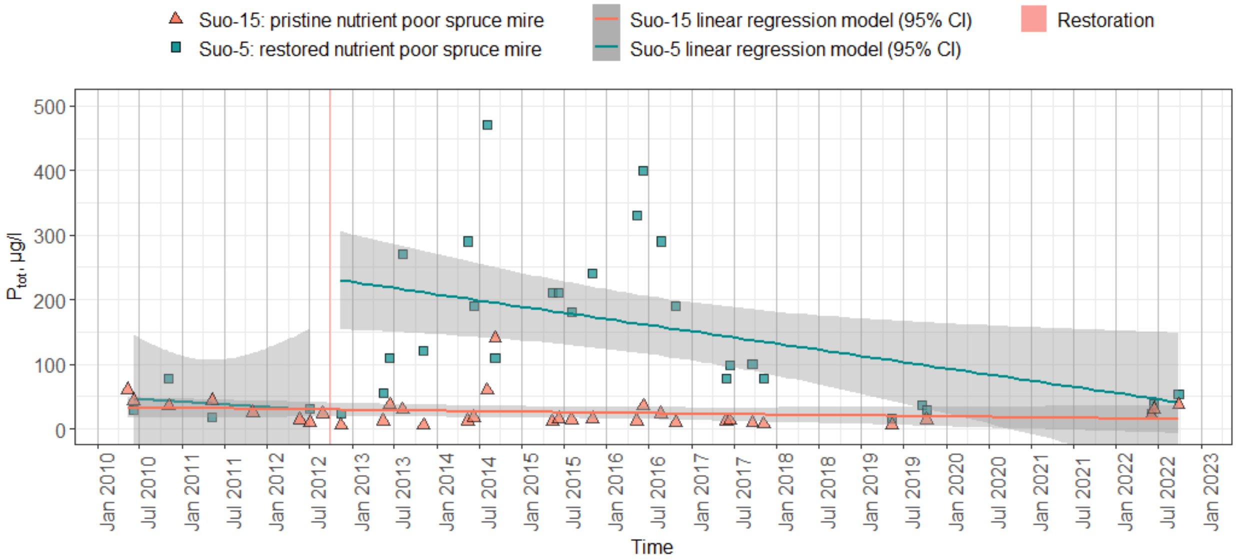
Jan 2022
Jul 2022
Jan 2023
Time


Suo-15: pristine nutrient poor spruce mire
Suo-5: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-5 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
100
200
300
400
500
Jan 2010
Jul 2010
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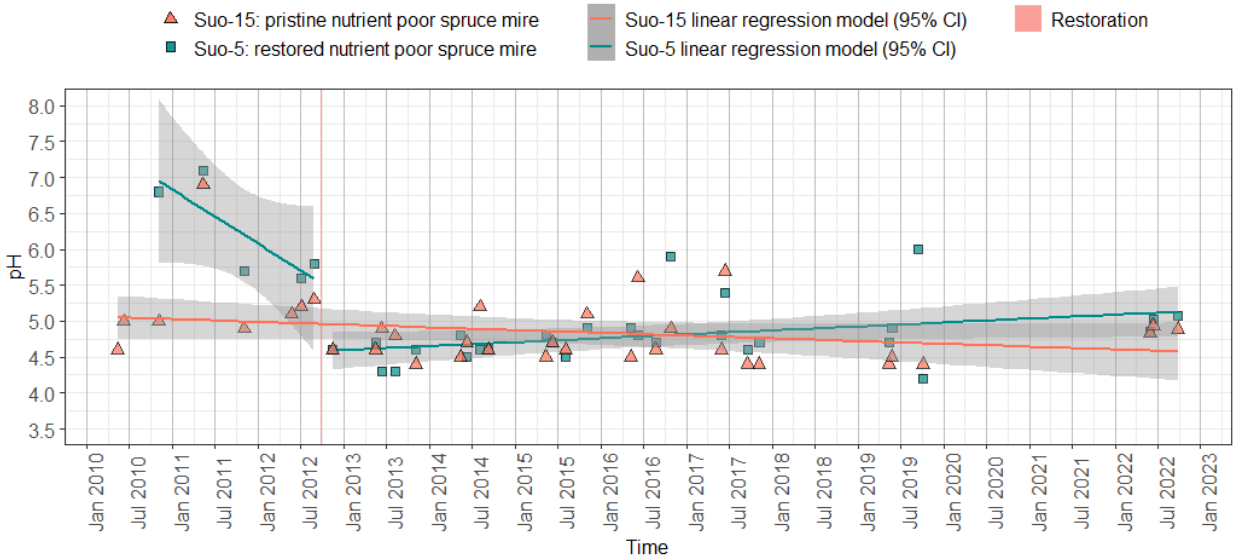
Jan 2022
Jul 2022
Jan 2023
Time


Suo-15: pristine nutrient poor spruce mire
Suo-5: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-5 linear regression model (95% CI)
Restoration
pH
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
Jan 2010
Jul 2010
Jan 2011
Jul 2011
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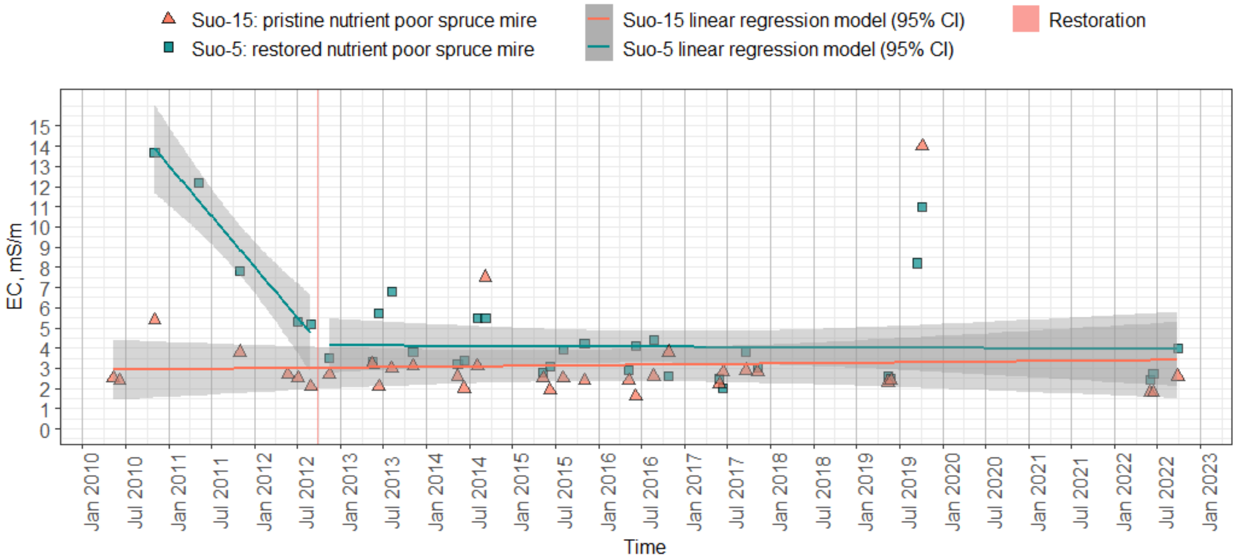
Jan 2023
Time


Suo-15: pristine nutrient poor spruce mire
Suo-5: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-5 linear regression model (95% CI)
Restoration
EC, mS/m
15
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Jan 2010
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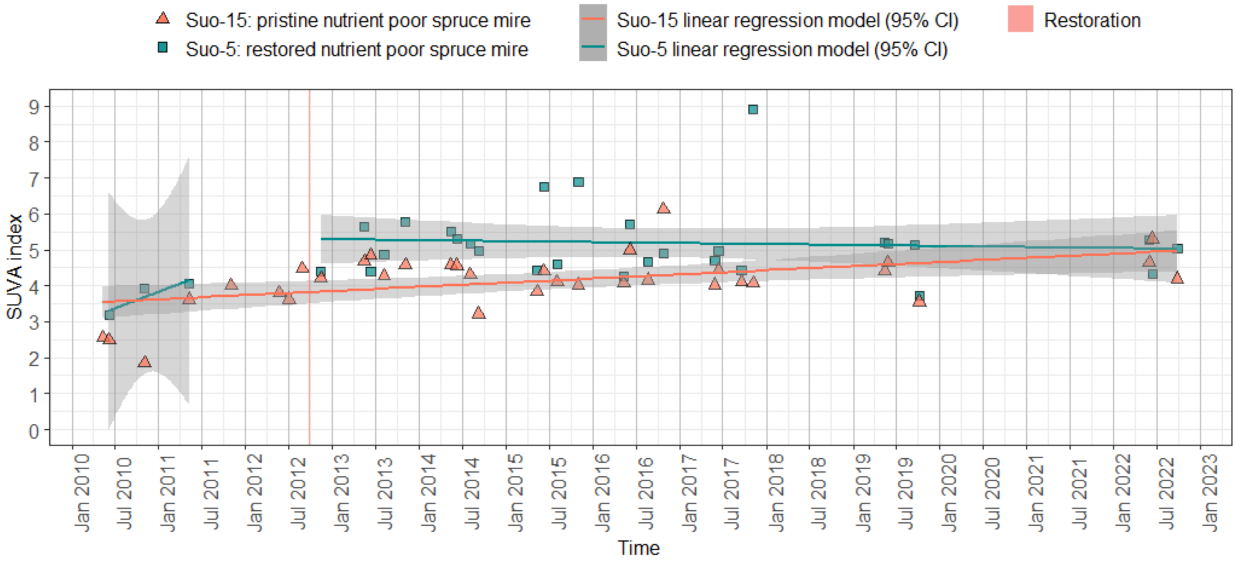
Time


Suo-15: pristine nutrient poor spruce mire
Suo-5: restored nutrient poor spruce mire
Suo-15 linear regression model (95% CI)
Suo-5 linear regression model (95% CI)
Restoration
SUVA index
9
8
7
6
5
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Jan 2010
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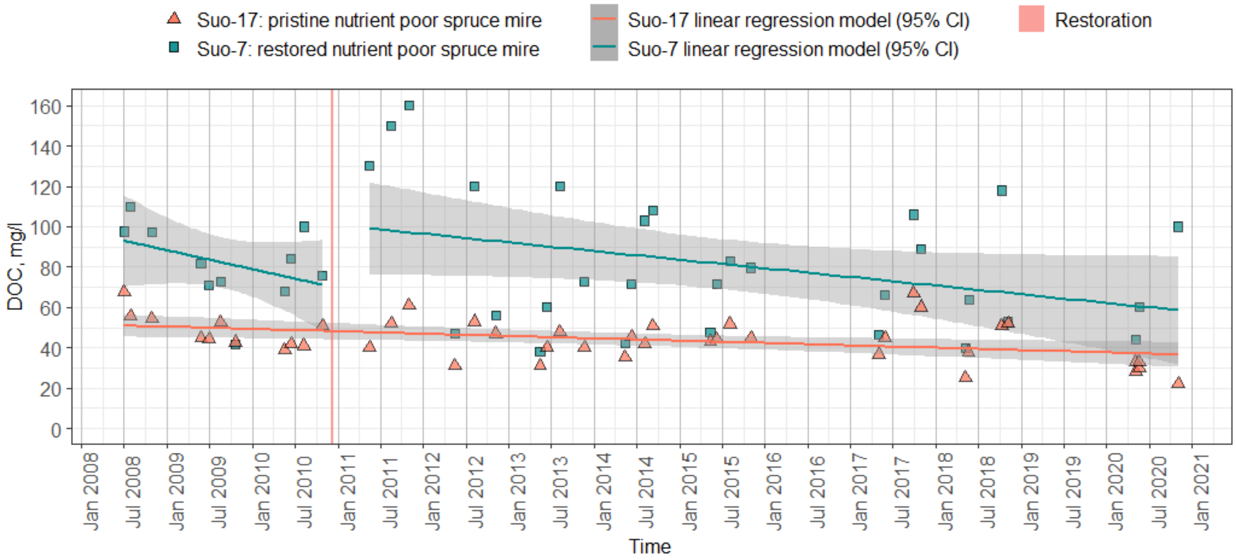
Time


Suo-17: pristine nutrient poor spruce mire
Suo-7: restored nutrient poor spruce mire
Suo-17 linear regression model (95% CI)
Suo-7 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
120
140
160
Jan 2008
Jul 2008
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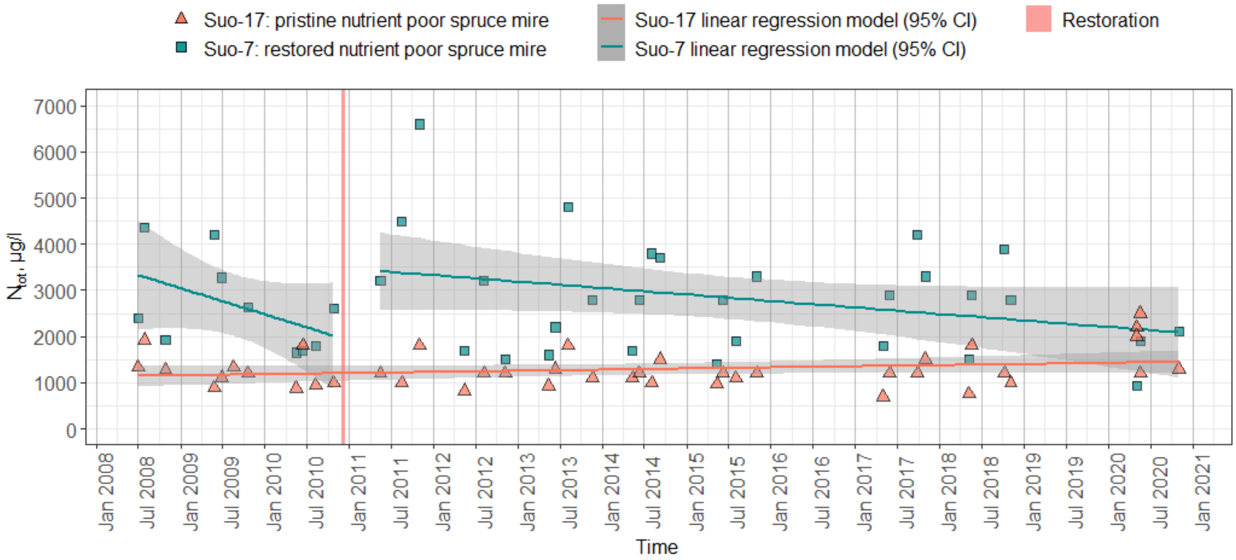
Jul 2020
Jan 2021
Time


Suo-17: pristine nutrient poor spruce mire
Suo-7: restored nutrient poor spruce mire
Suo-17 linear regression model (95% CI)
Suo-7 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
0
1000
2000
3000
4000
5000
6000
7000
Jan 2008
Jul 2008
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Jan 2011
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Jan 2020
Jul 2020
Jan 2021
Time


Suo-17: pristine nutrient poor spruce mire
Suo-7: restored nutrient poor spruce mire
Suo-17 linear regression model (95% CI)
Suo-7 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
0
200
400
600
800
1000
1200
1400
1600
Jan 2008
Jul 2008
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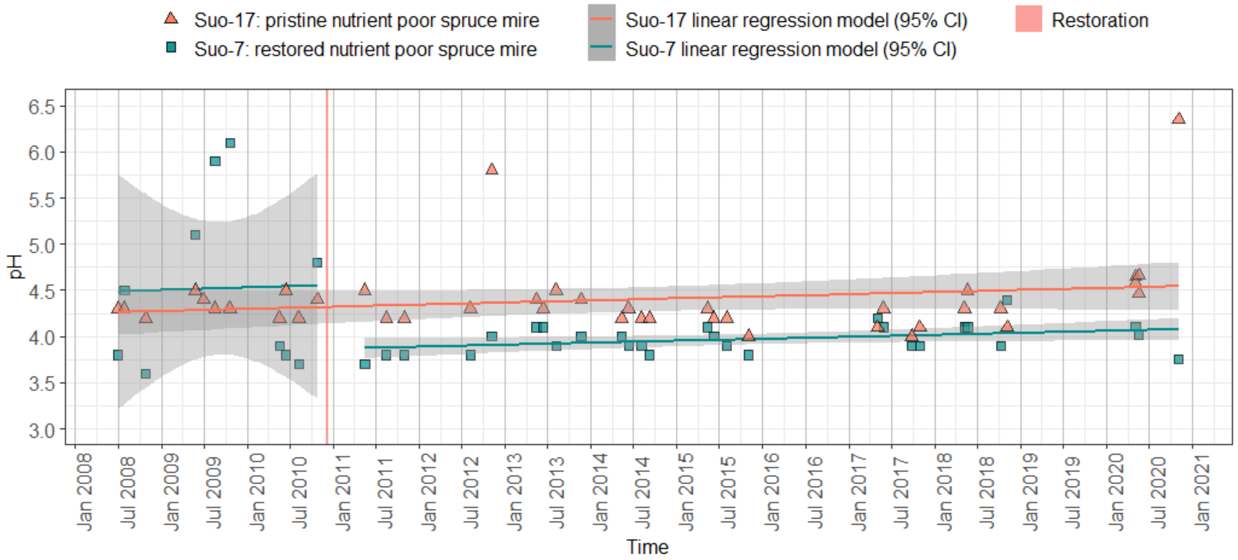
Time


Suo-17: pristine nutrient poor spruce mire
Suo-7: restored nutrient poor spruce mire
Suo-17 linear regression model (95% CI)
Suo-7 linear regression model (95% CI)
Restoration
pH
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
Jan 2008
Jul 2008
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Jul 2020
Jan 2021
Time


Suo-17: pristine nutrient poor spruce mire
Suo-7: restored nutrient poor spruce mire
Suo-17 linear regression model (95% CI)
Suo-7 linear regression model (95% CI)
Restoration
EC, mS/m
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Jan 2008
Jul 2008
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Jul 2020
Jan 2021
Time


Suo-17: pristine nutrient poor spruce mire
Suo-7: restored nutrient poor spruce mire
Suo-17 linear regression model (95% CI)
Suo-7 linear regression model (95% CI)
Restoration
SUVA index
9
8
7
6
5
4
3
2
1
0
Jan 2008
Jul 2008
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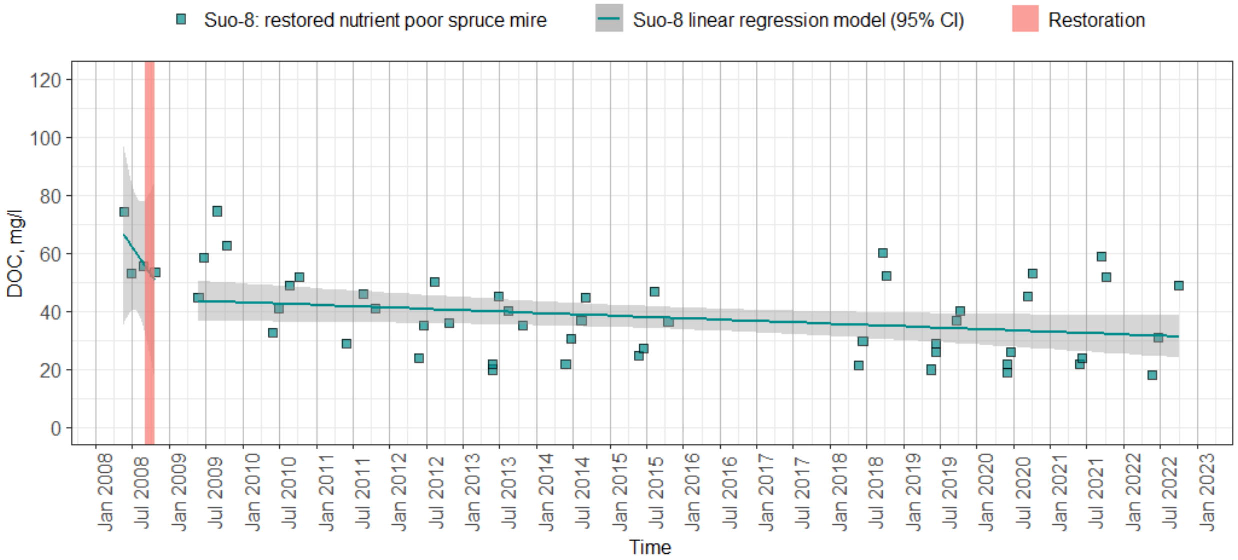
Jul 2020
Jan 2021
Time


Suo-8: restored nutrient poor spruce mire
Suo-8 linear regression model (95% CI)
Restoration
DOC, mg/l
120
100
80
60
40
20
0
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
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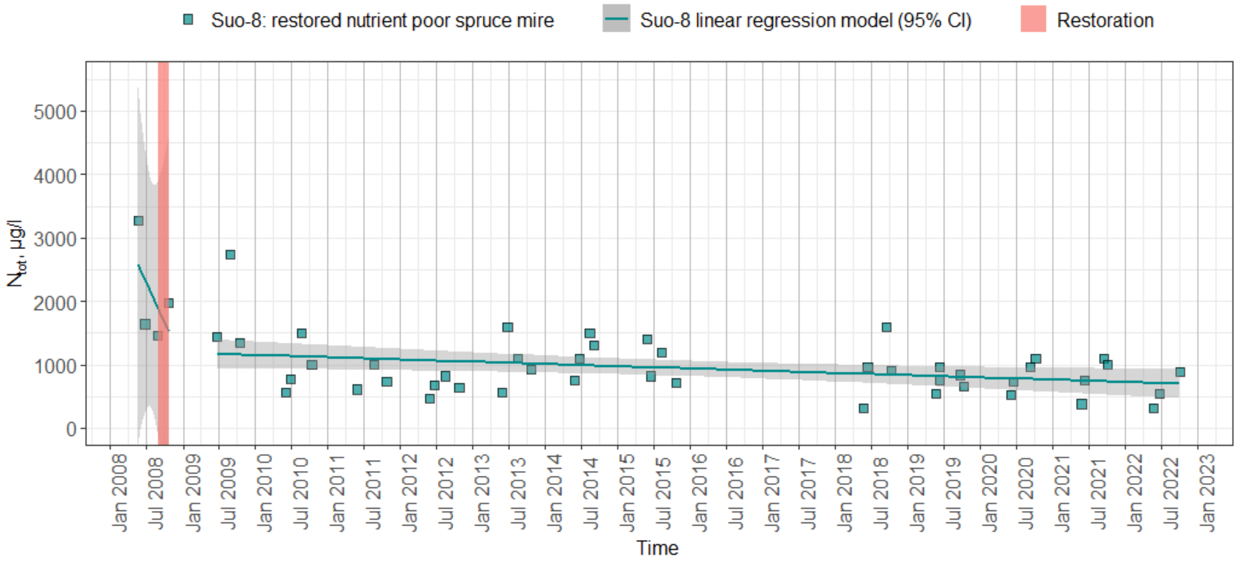
Jul 2022
Jan 2023
Time


Suo-8: restored nutrient poor spruce mire
Suo-8 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
5000
4000
3000
2000
1000
0
Jan 2008
Jul 2008
Jan 2009
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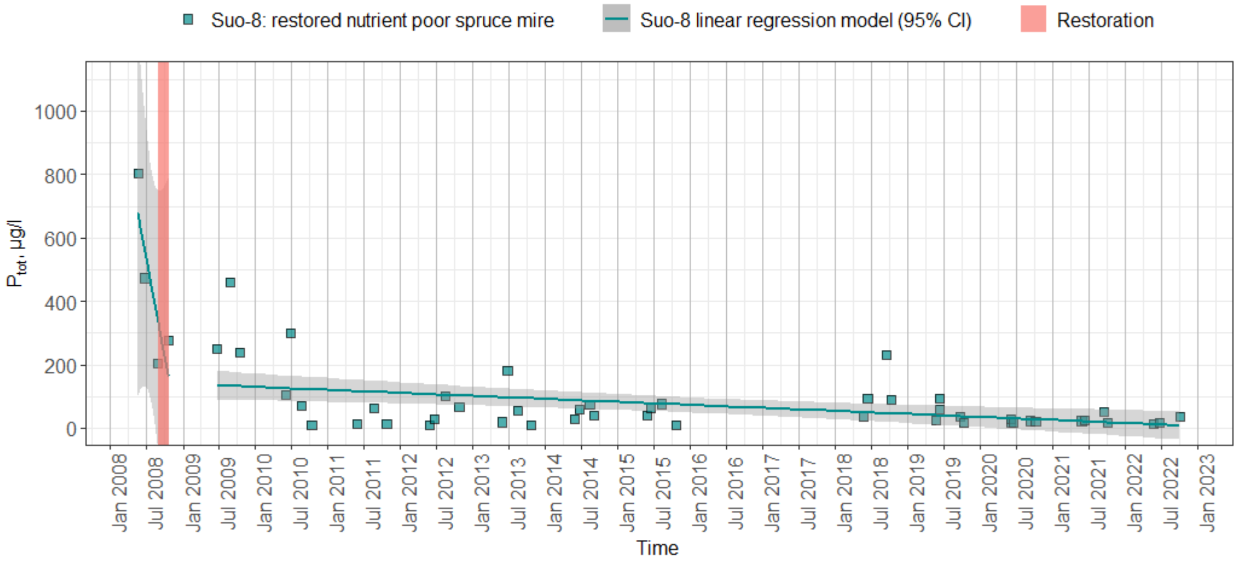
Jan 2022
Jul 2022
Jan 2023
Time


Suo-8: restored nutrient poor spruce mire
Suo-8 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
1000
800
600
400
200
0
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
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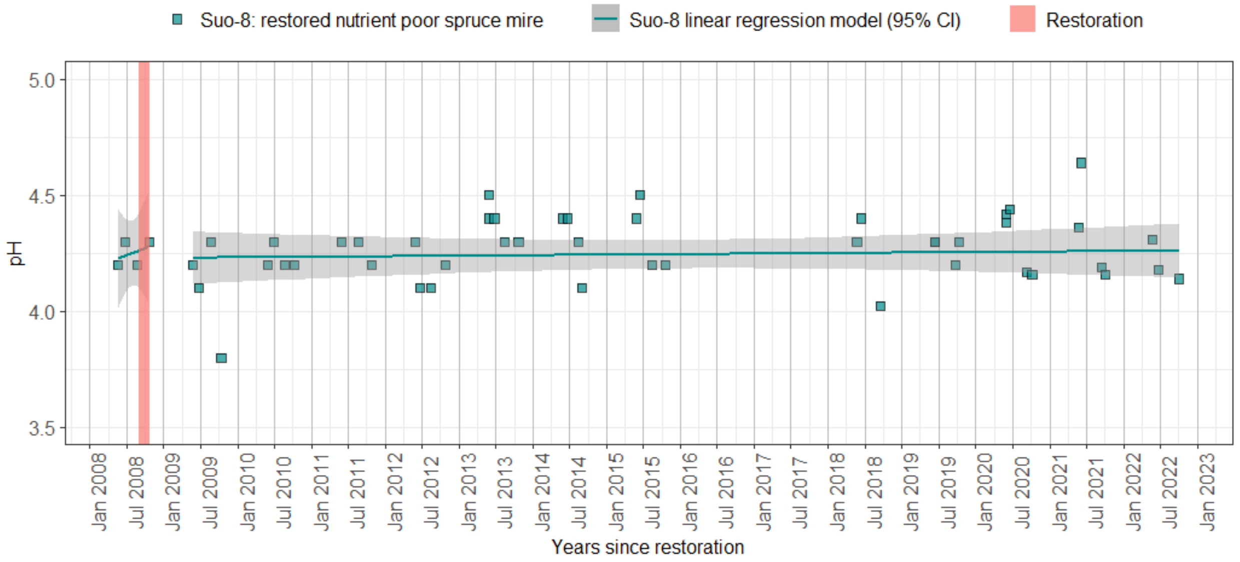
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Time


Suo-8: restored nutrient poor spruce mire
Suo-8 linear regression model (95% CI)
Restoration
pH
5.0
4.5
4.0
3.5
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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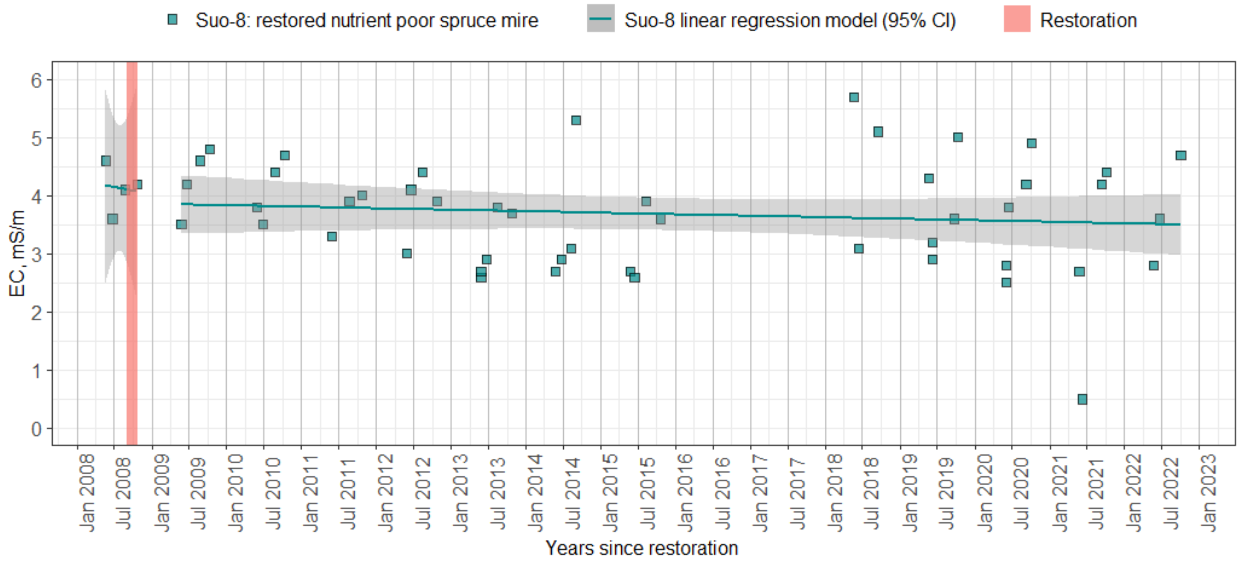
Jan 2022
Jul 2022
Jan 2023
Years since restoration


Suo-8: restored nutrient poor spruce mire
Suo-8 linear regression model (95% CI)
Restoration
EC, mS/m
6
5
4
3
2
1
0
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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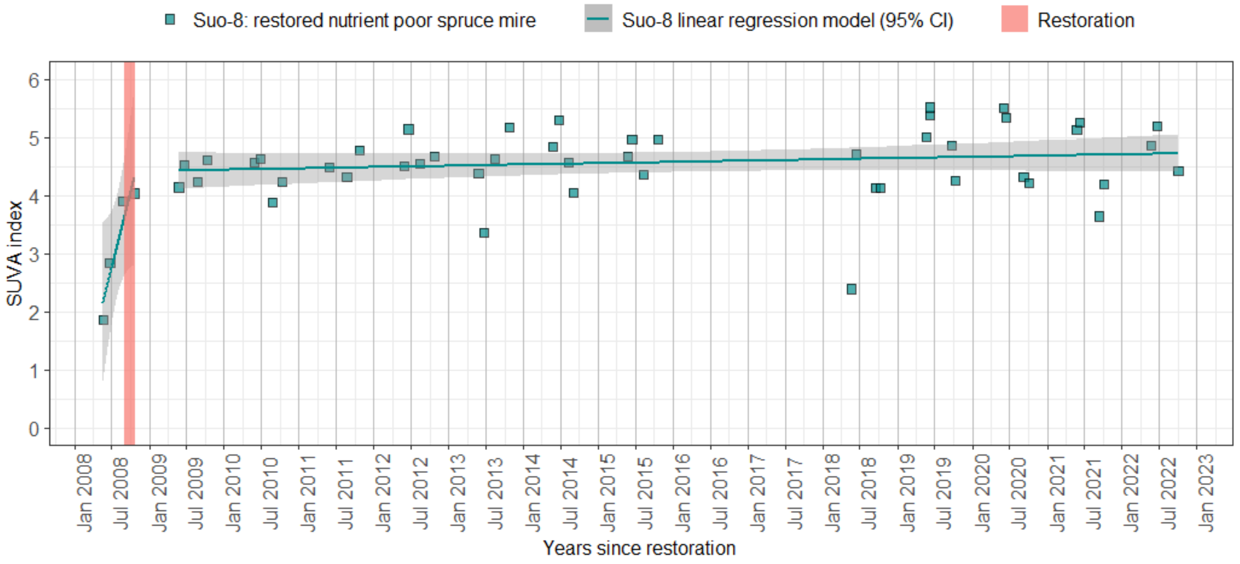
Jan 2022
Jul 2022
Jan 2023
Years since restoration


Suo-8: restored nutrient poor spruce mire
Suo-8 linear regression model (95% CI)
Restoration
SUVA index
6
5
4
3
2
1
0
Jan 2008
Jul 2008
Jan 2009
Jul 2009
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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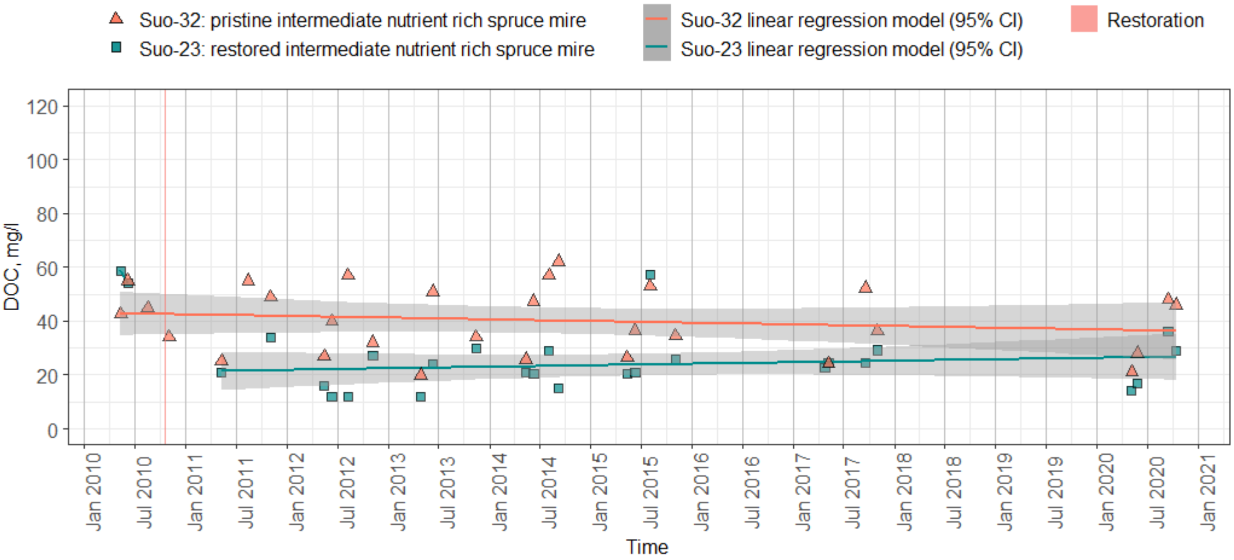
Jul 2021
Jan 2022
Jul 2022
Jan 2023
Years since restoration


Suo-32: pristine intermediate nutrient rich spruce mire
Suo-23: restored intermediate nutrient rich spruce mire
Suo-32 linear regression model (95% CI)
Suo-23 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
40
60
80
100
120
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
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Jan 2014
Jul 2014
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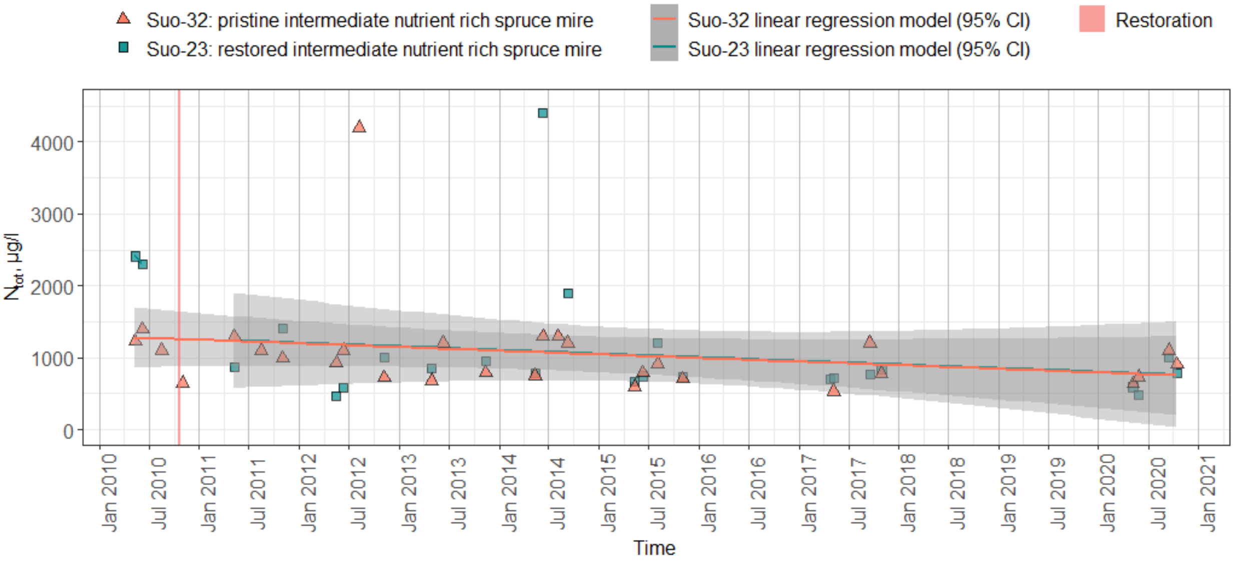
Jan 2020
Jul 2020
Jan 2021
Time


Suo-32: pristine intermediate nutrient rich spruce mire
Suo-23: restored intermediate nutrient rich spruce mire
Suo-32 linear regression model (95% CI)
Suo-23 linear regression model (95% CI)
Restoration
N_tot, µg/l
0
1000
2000
3000
4000
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
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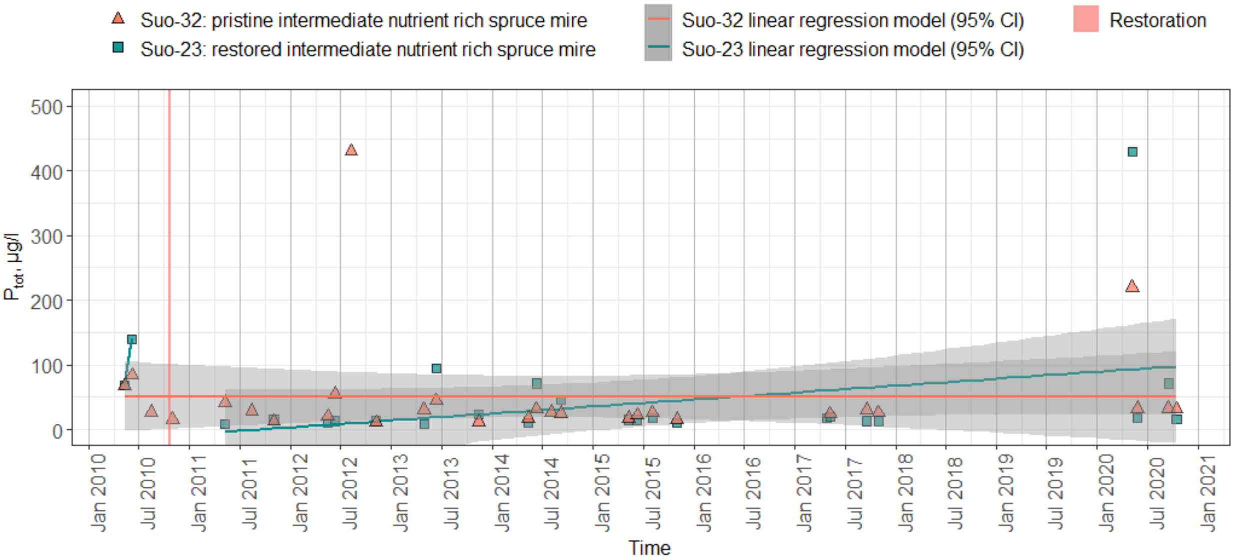
Suo-32: pristine intermediate nutrient rich spruce mire
Suo-23: restored intermediate nutrient rich spruce mire
Suo-32 linear regression model (95% CI)
Suo-23 linear regression model (95% CI)
Restoration
P_tot, µg/l
0
100
200
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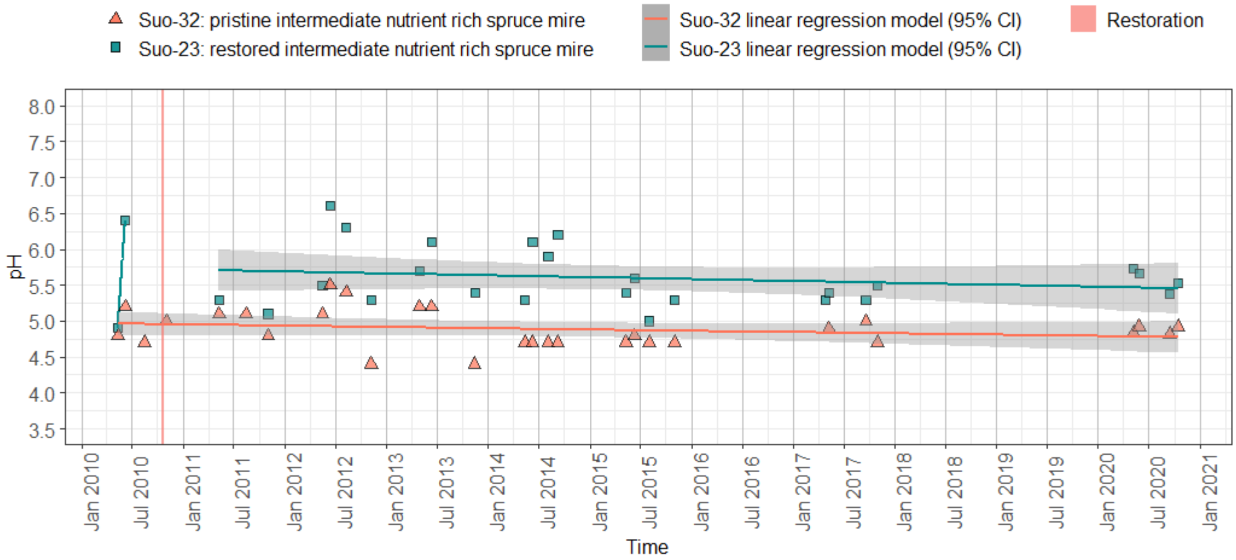
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Suo-23: restored intermediate nutrient rich spruce mire
Suo-32 linear regression model (95% CI)
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Restoration
pH
8.0
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Jan 2010
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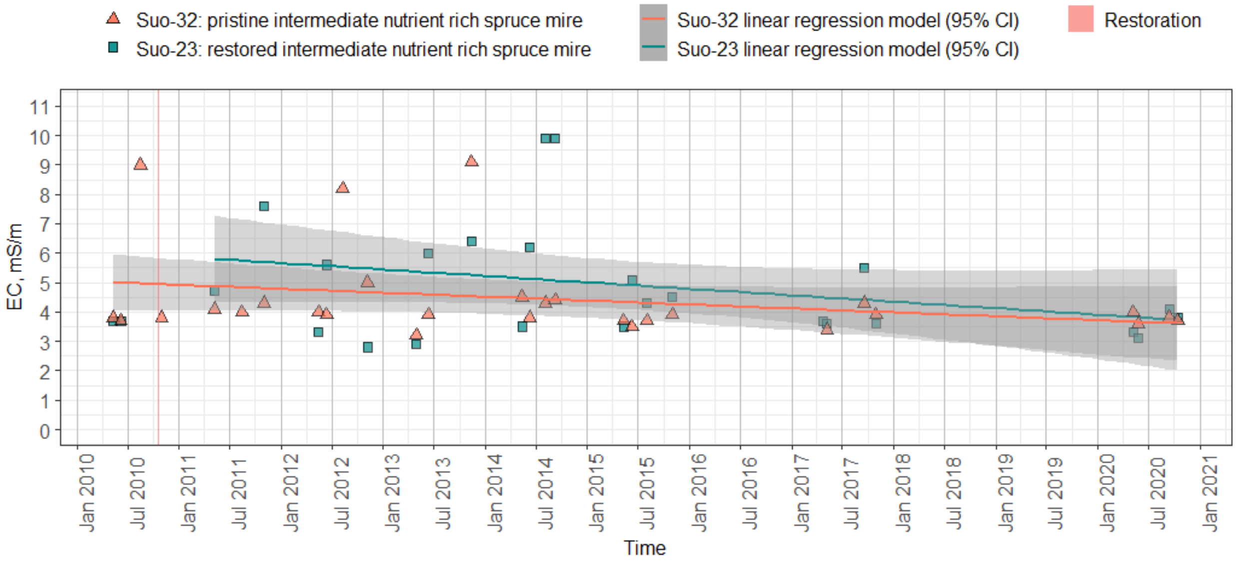
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Suo-23: restored intermediate nutrient rich spruce mire
Suo-32 linear regression model (95% CI)
Suo-23 linear regression model (95% CI)
Restoration
EC, mS/m
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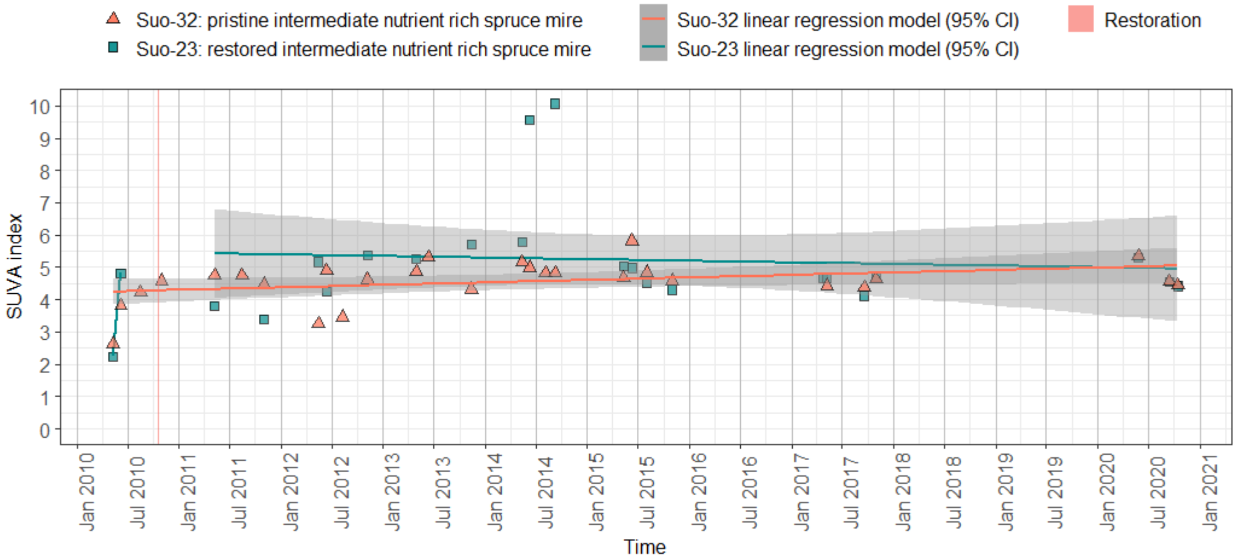
Suo-32: pristine intermediate nutrient rich spruce mire
Suo-23: restored intermediate nutrient rich spruce mire
Suo-32 linear regression model (95% CI)
Suo-23 linear regression model (95% CI)
Restoration
SUVA index
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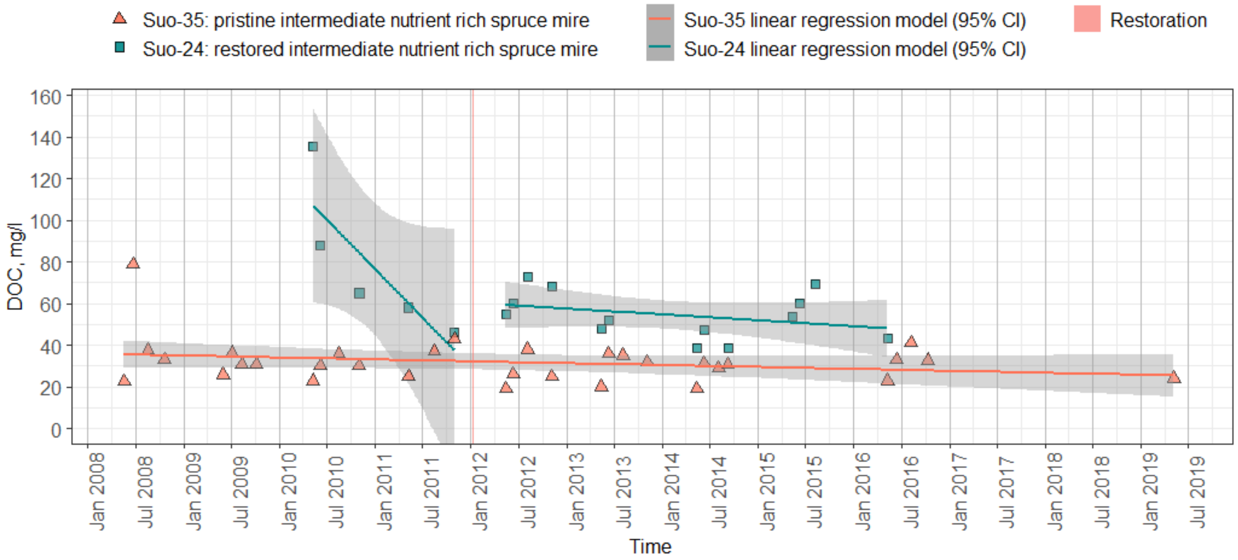
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Suo-24: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-24 linear regression model (95% CI)
Restoration
DOC, mg/l
160
140
120
100
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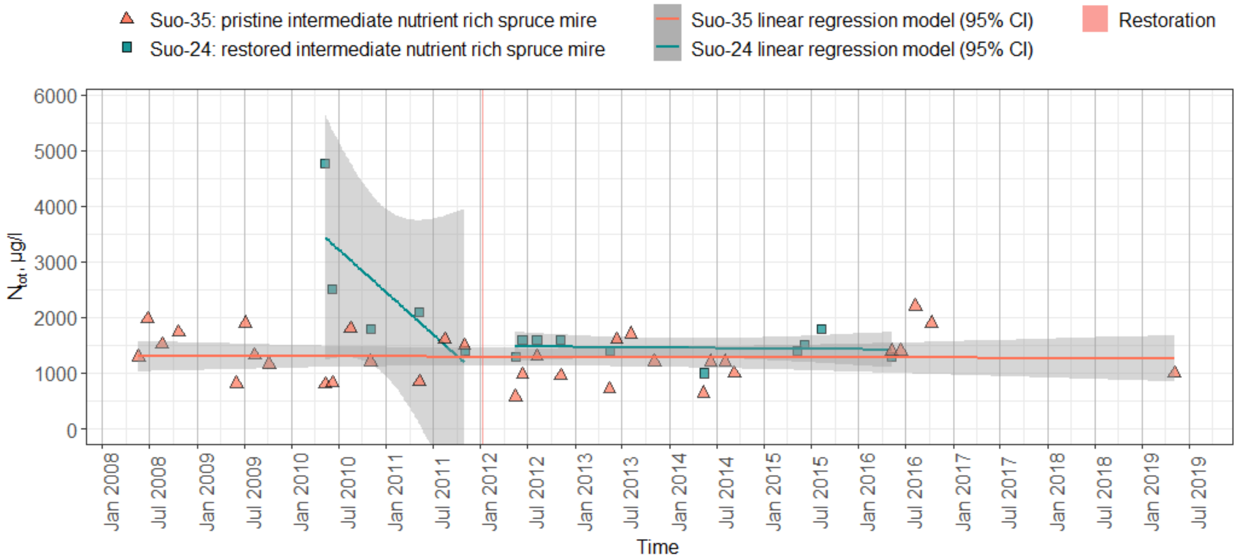
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Suo-24: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-24 linear regression model (95% CI)
Restoration
N_{tot}, µg/l
6000
5000
4000
3000
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0
Jan 2008
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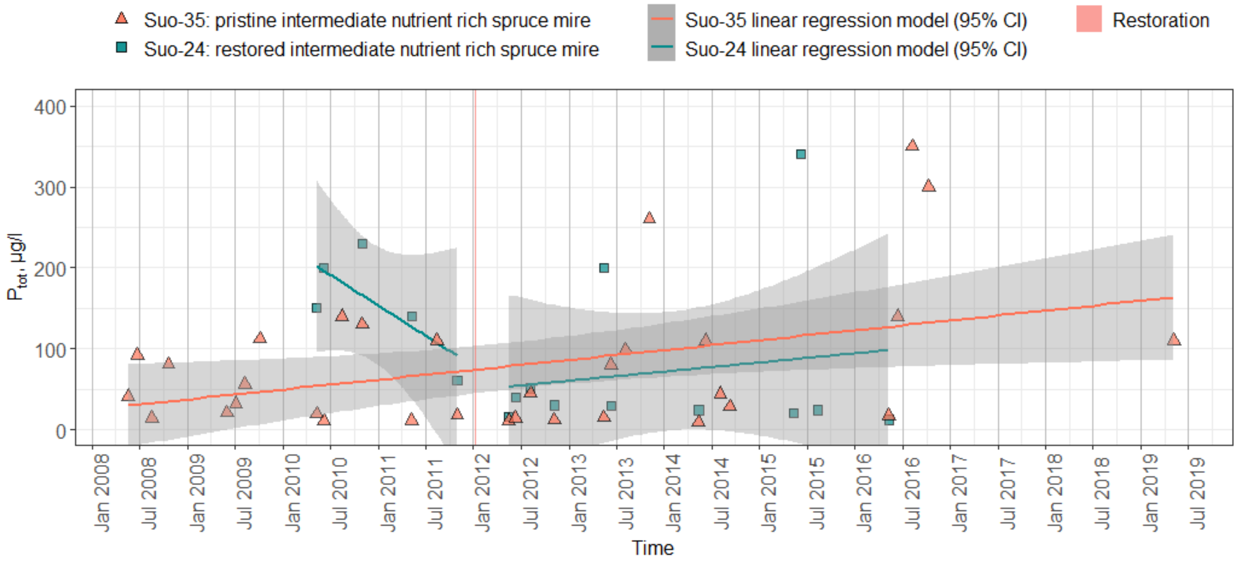
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Suo-24: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-24 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
400
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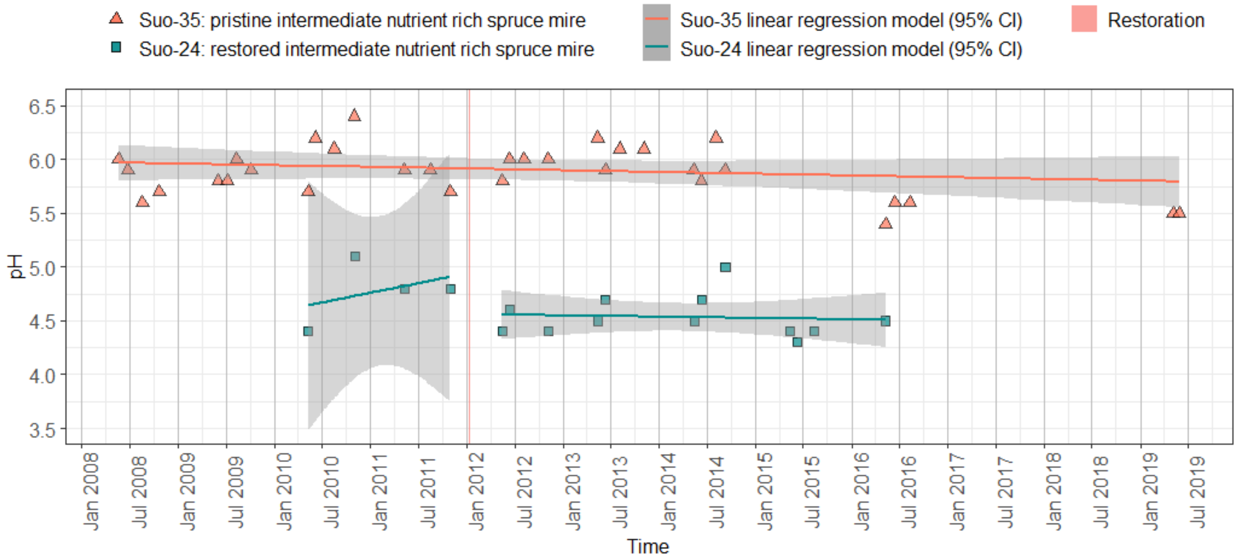
Suo-35: pristine intermediate nutrient rich spruce mire
Suo-24: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-24 linear regression model (95% CI)
Restoration
pH
6.5
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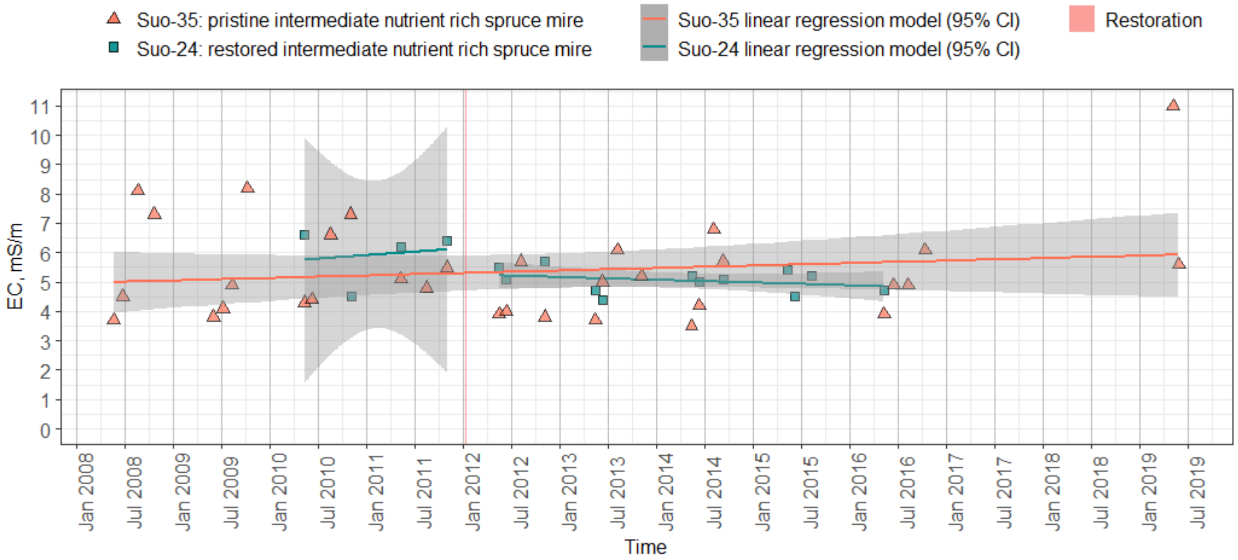
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Suo-24: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-24 linear regression model (95% CI)
Restoration
EC, mS/m
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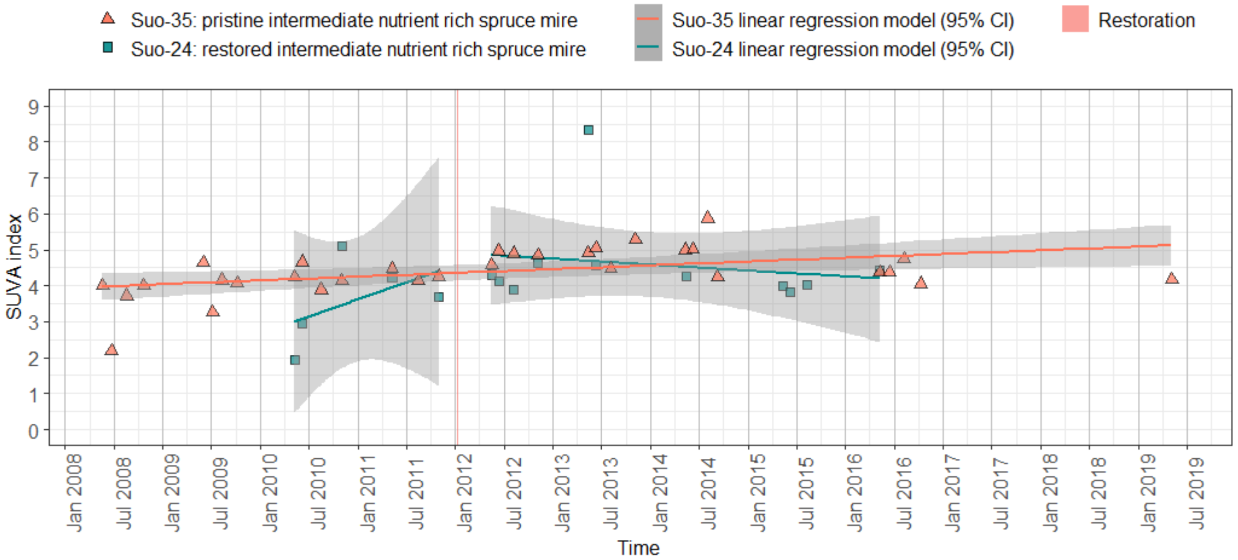
Suo-35: pristine intermediate nutrient rich spruce mire
Suo-24: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-24 linear regression model (95% CI)
Restoration
SUVA index
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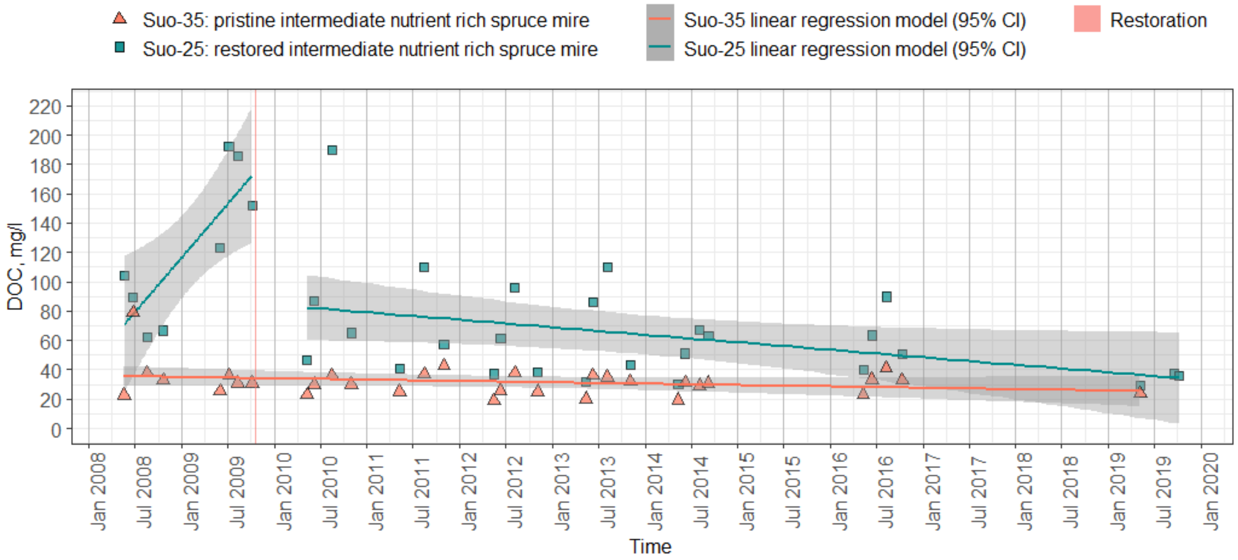
Suo-35: pristine intermediate nutrient rich spruce mire
Suo-25: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-25 linear regression model (95% CI)
Restoration
DOC, mg/l
0
20
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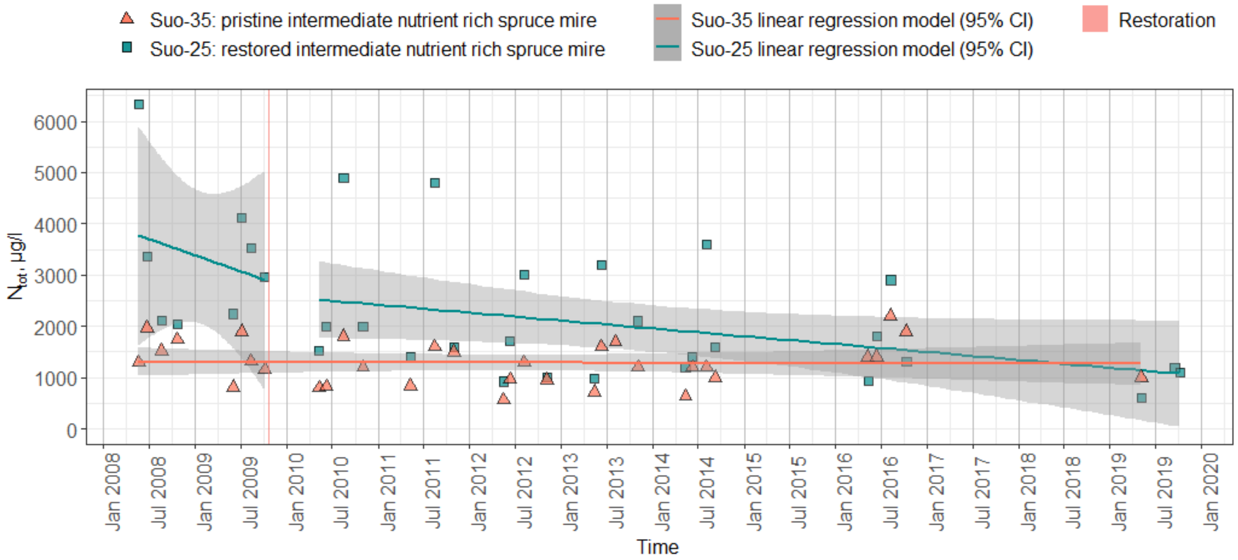
Suo-35: pristine intermediate nutrient rich spruce mire
Suo-25: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-25 linear regression model (95% CI)
Restoration
N$_{tot}$, µg/l
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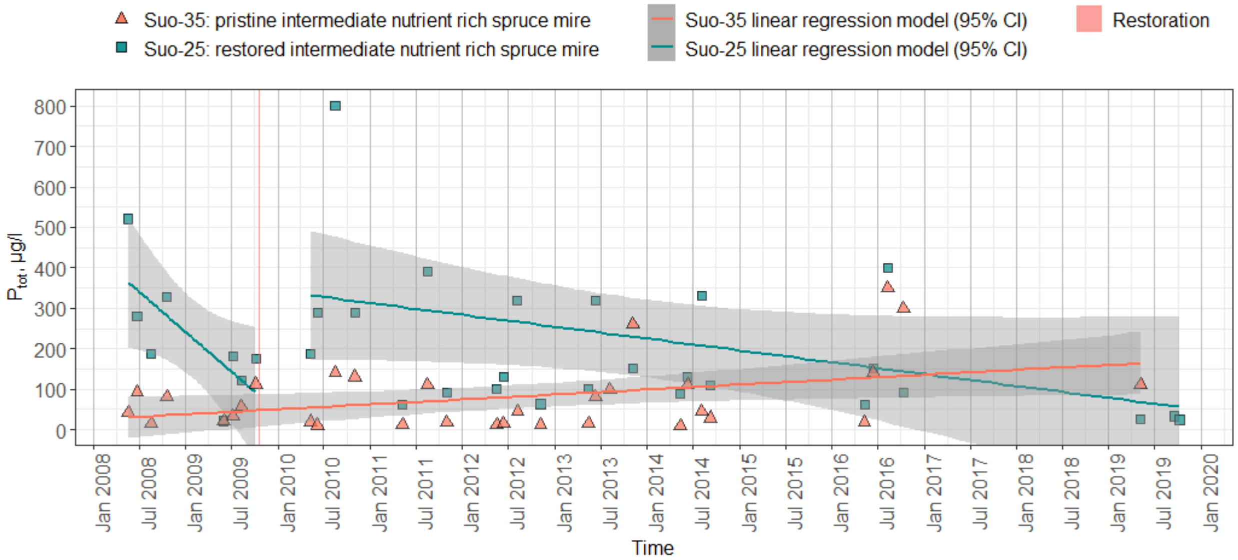
Suo-35: pristine intermediate nutrient rich spruce mire
Suo-25: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-25 linear regression model (95% CI)
Restoration
P$_{tot}$, µg/l
0
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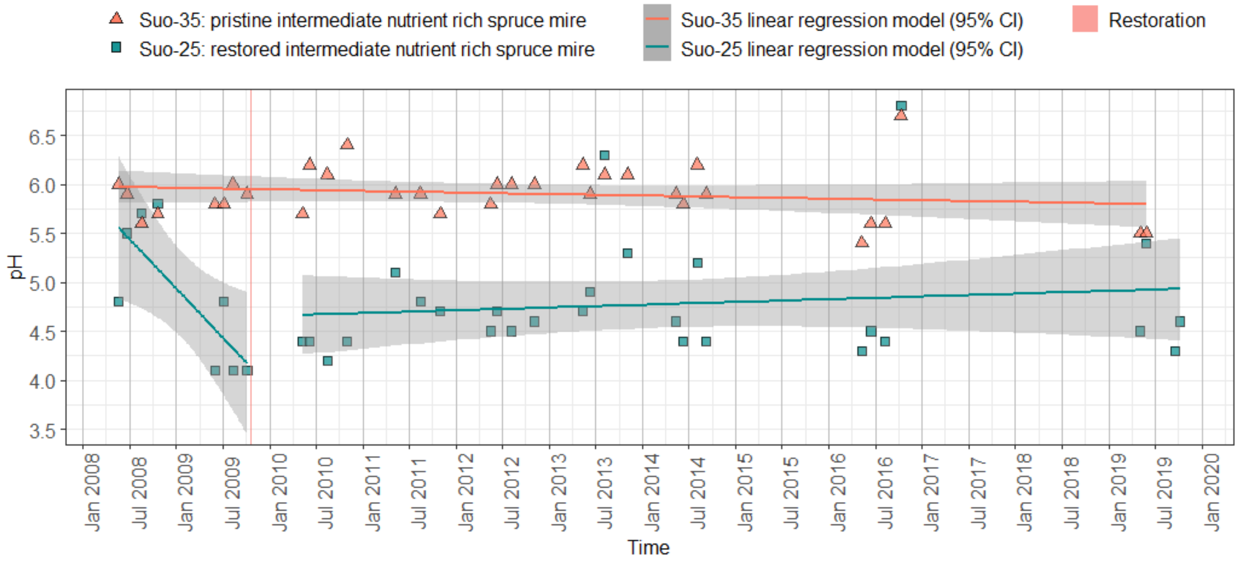
Suo-35: pristine intermediate nutrient rich spruce mire
Suo-25: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-25 linear regression model (95% CI)
Restoration
pH
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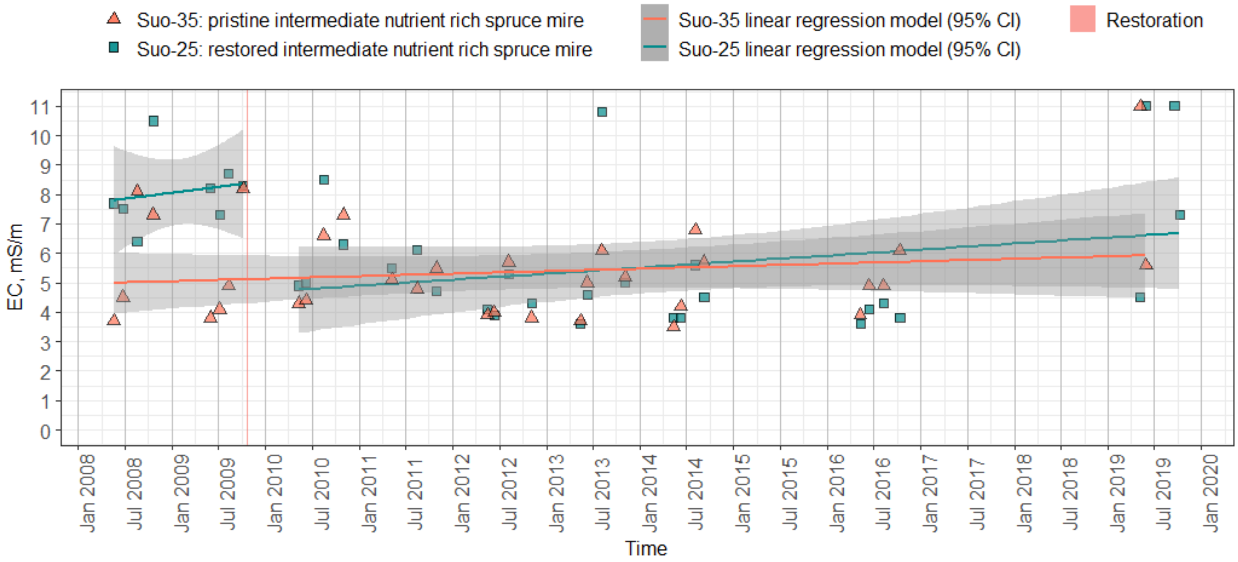
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Suo-25: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-25 linear regression model (95% CI)
Restoration
EC, mS/m
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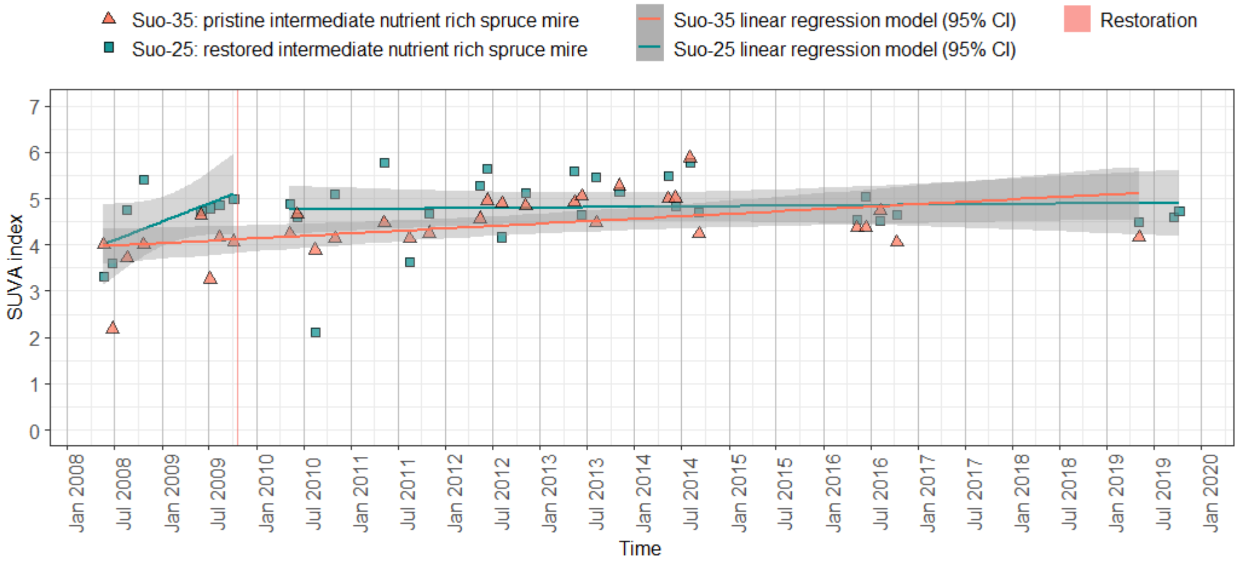
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Suo-25: restored intermediate nutrient rich spruce mire
Suo-35 linear regression model (95% CI)
Suo-25 linear regression model (95% CI)
Restoration
SUVA index
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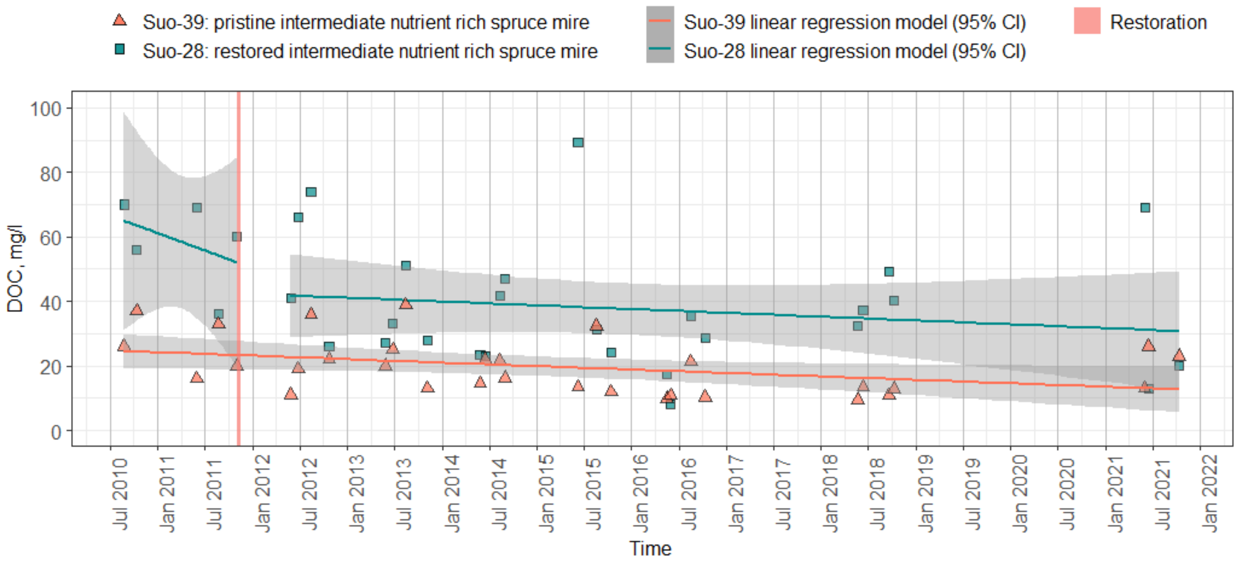
Suo-39: pristine intermediate nutrient rich spruce mire
Suo-28: restored intermediate nutrient rich spruce mire
Suo-39 linear regression model (95% CI)
Suo-28 linear regression model (95% CI)
Restoration
DOC, mg/l
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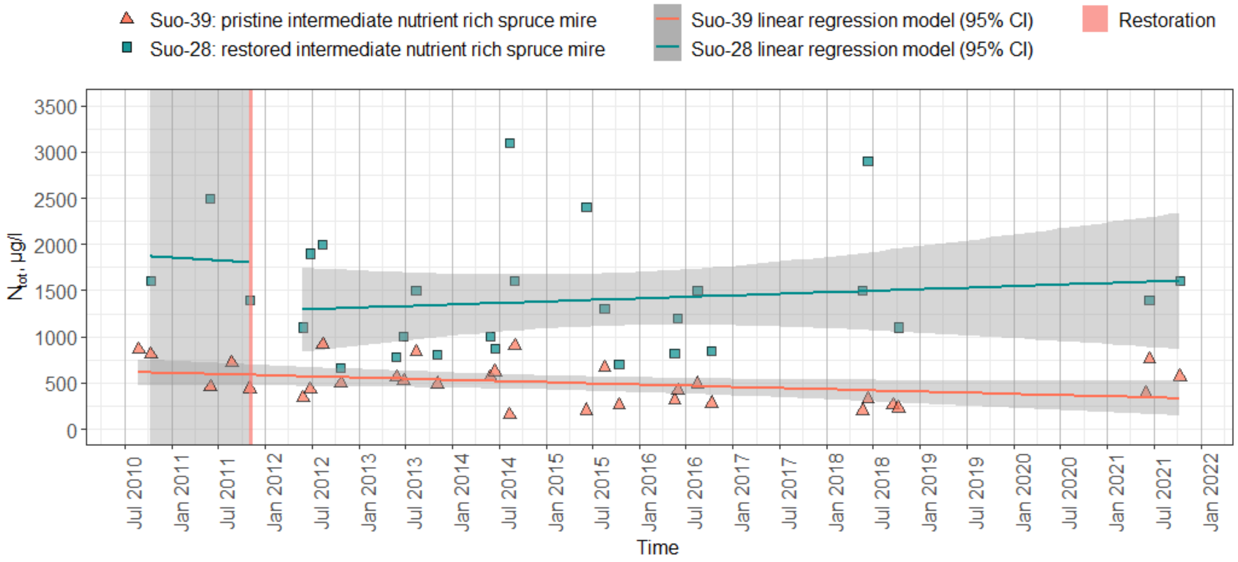
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Suo-39 linear regression model (95% CI)
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Restoration
N_{tot}, µg/l
3500
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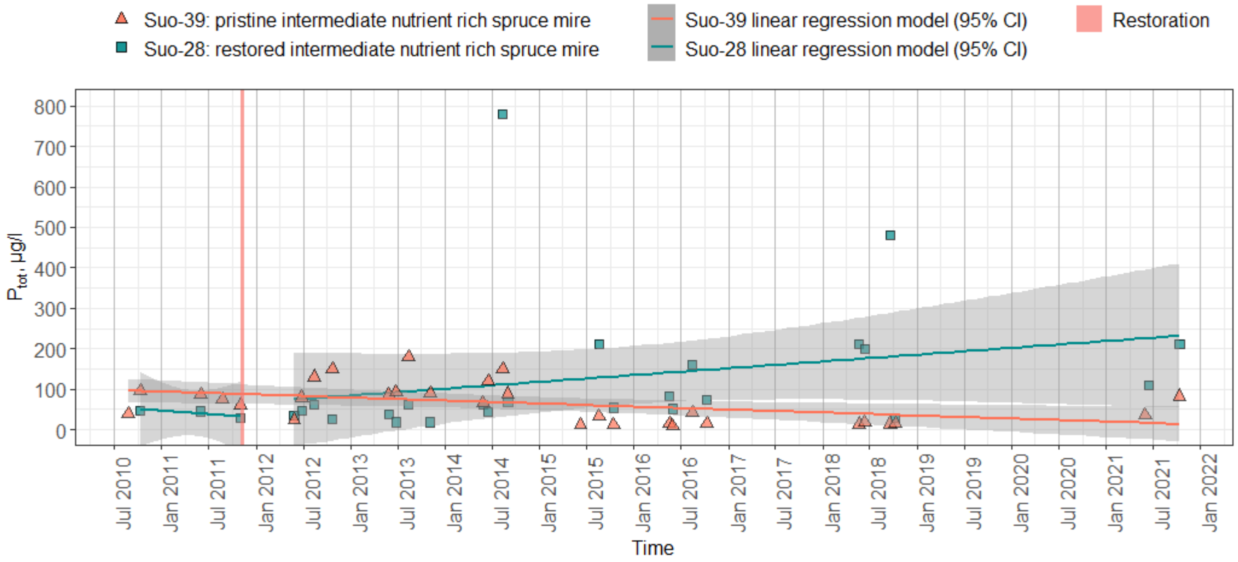
Suo-39: pristine intermediate nutrient rich spruce mire
Suo-28: restored intermediate nutrient rich spruce mire
Suo-39 linear regression model (95% CI)
Suo-28 linear regression model (95% CI)
Restoration
P_{tot}, µg/l
800
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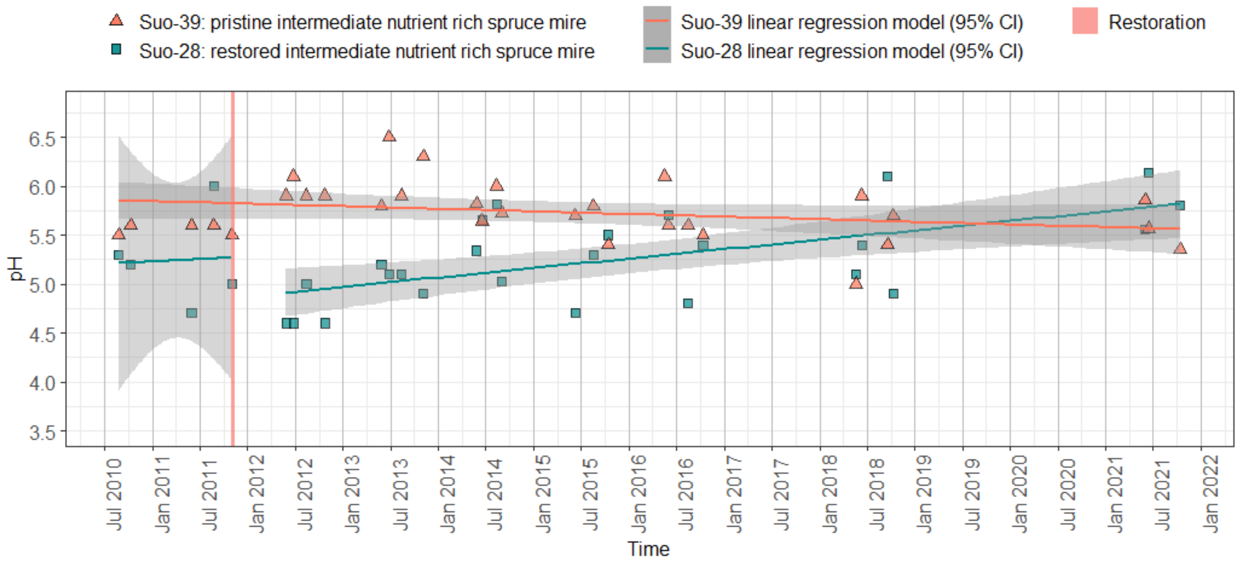
Suo-39: pristine intermediate nutrient rich spruce mire
Suo-28: restored intermediate nutrient rich spruce mire
Suo-39 linear regression model (95% CI)
Suo-28 linear regression model (95% CI)
Restoration
pH
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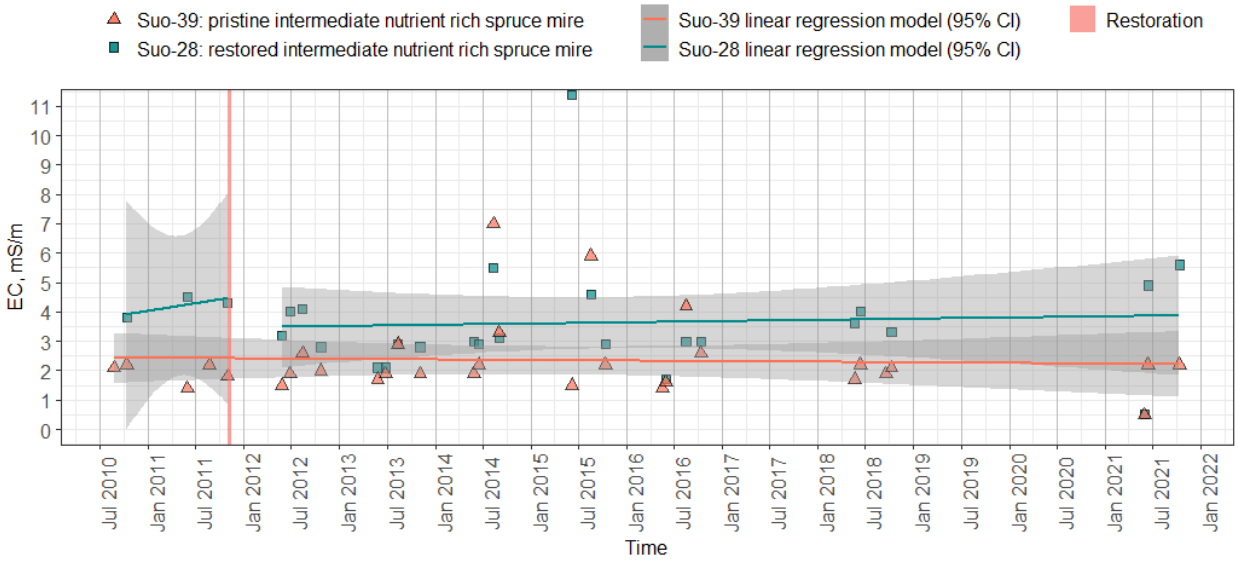
Suo-39: pristine intermediate nutrient rich spruce mire
Suo-28: restored intermediate nutrient rich spruce mire
Suo-39 linear regression model (95% CI)
Suo-28 linear regression model (95% CI)
Restoration
EC, mS/m
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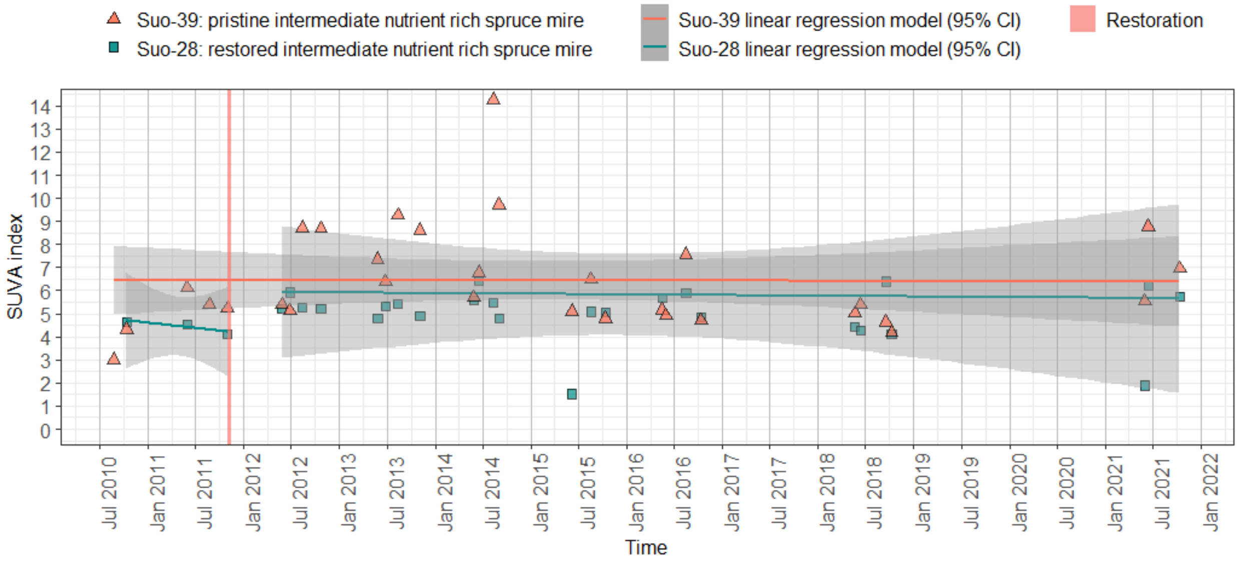
Suo-39: pristine intermediate nutrient rich spruce mire
Suo-28: restored intermediate nutrient rich spruce mire
Suo-39 linear regression model (95% CI)
Suo-28 linear regression model (95% CI)
Restoration
SUVA index
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Appendix 3. Correlations between peat, pore water and runoff water qualities

All sites surface peat and average pore and runoff water quality correlations with statistical significance ($p<0.05$)	Pearson correlation coefficient			Spearman correlation coefficient		
	r	N	p	ρ	N	p
Pore water avg P_{tot} (µg/l) and peat P (mg/kg dm)	0.294	16	0.270	0.698	16	0.003
Pore water avg N_{tot} (µg/l) and peat N (kg/t)	0.750	16	8.3E-4	0.492	16	0.053
Peat P (mg/kg dm) and peat Fe (mg/kg dm)	0.827	16	7.8E-5	0.823	16	9.2E-5
Peat P (mg/kg dm) and peat Al (mg/kg dm)	0.803	16	1.8E-4	0.811	16	1.4E-4
Pore water avg P_{tot} (µg/l) and peat Al (mg/kg dm)	0.527	16	0.036	0.583	16	0.018
Pore water pH and peat P (mg/kg dm)	0.578	16	0.019	0.653	16	0.006
Pore water pH and peat N (g/kg dm)	0.397	16	0.128	0.495	16	0.051
Pore water pH and peat Ca (mg/kg dm)	0.238	16	0.374	0.534	16	0.033
Pore water pH and peat Fe (mg/kg dm)	0.541	16	0.031	0.695	16	0.003
Pore water pH and peat Al (mg/kg dm)	0.621	16	0.010	0.758	16	6.7E-4
Runoff water NH_4-N (µg/l) and peat N (kg/t)	0.941	6	0.005	0.348	6	0.499

Table 1. Pearson r and Spearman's ρ correlation coefficient, number of observations (N), and p-value for all sites surface peat and average pore and ruinoff water qualities.

Restored sites surface peat and average pore and runoff water quality correlations with statistical significance ($p<0.05$)	Pearson correlation coefficient			Spearman correlation coefficient		
	r	N	p	ρ	N	p
Pore water avg N_{tot} (µg/l) and peat N ((kg/t)	0.799	10	0.006	0.818	10	0.004
Pore water avg N_{tot} (µg/l) and peat N (g/kg dm)	0.555	10	0.096	0.669	10	0.035
Peat P (mg/kg dm) and peat Fe (mg/kg dm)	0.872	10	9.9E-4	0.915	10	2E-4
Peat P (mg/kg dm) and peat Al (mg/kg dm)	0.836	10	0.003	0.891	10	5.4E-4
Pore water pH and peat P (mg/kg dm)	0.944	10	4E-5	0.879	10	8.1E-4
Pore water pH and peat Fe (mg/kg dm)	0.793	10	0.006	0.891	10	5.4E-4
Pore water pH and peat Al (mg/kg dm)	0.728	10	0.017	0.721	10	0.019
Runoff water NH_4-N (µg/l) and peat N (kg/t)	0.986	4	0.014	0.8	4	0.2

Table 2. Pearson r and Spearman's ρ correlation coefficient, number of observations (N), and p-value for restored sites surface peat and average pore and runoff water qualities.

Surface peat and average pore and runoff water quality correlations with statistical significance ($p<0.05$) for **pristine sites and restored sites data over 5 years after restoration**	Pearson correlation coefficient			Spearman correlation coefficient		
	r	N	p	ρ	N	p
Pore water avg P_{tot} (μg/l) and peat P (mg/kg dm)	0.294	16	0.270	0.698	16	0.003
Pore water avg N_{tot} (μg/l) and peat N (kg/t)	0.745	16	8.3E-4	0.492	16	0.053
Peat P (mg/kg dm) and peat Fe (mg/kg dm)	0.827	16	7.8E-5	0.823	16	9.2E-5
Peat P (mg/kg dm) and peat Al (mg/kg dm)	0.803	16	1.8E-4	0.811	16	1.4E-4
Pore water avg P_{tot} (μg/l) and peat Al (mg/kg dm)	0.527	16	0.036	0.582	16	0.0018
Pore water pH and peat P (mg/kg dm)	0.578	16	0.019	0.653	16	0.0061
Pore water pH and peat Ca (mg/kg dm)	0.234	16	0.374	0.534	16	0.033
Pore water pH and peat Fe (mg/kg dm)	0.541	16	0.031	0.695	16	0.003
Pore water pH and peat Al (mg/kg dm)	0.621	16	0.010	0.758	16	6.7E-4
Runoff water NH_4-N (μg/l) and peat N (kg/t)	0.911	6	0.011	0.493	6	0.320

Table 3. Pearson r and Spearman's ρ correlation coefficient, number of observations (N), and p-value for surface peat and average pore and runoff water qualities for pristine sites and restored sites data over 5 years after restoration.

Appendix 4. Drone flights

K = RGB-kartoitus / RGB mapping, M = Multispektrikartoitus / Multispectral mapping, L = Lämpökartoitus / Thermal mapping
V = Vapaita kuvia / Free images, I = Video, X = Laserkeilaus / Laser scanning

Kohde / Site	2018	2019	2020	2021	2022
Haikara-aapa					
Haikara-aapa		K V		K V	
Helvetinjärvi					
Löyttyjärvi				K K K	
Herankaira					
Herankaira		K V		K V	
Jäkäläkangas					
Kitsin paloalueen suo 1	K				
Kitsin paloalueen suo 2	K				
Kemihaaran suot					
Kemihaaran suot		K V			K V
Kesonsuo					
Mykränsuo		K		K	K V
Kinkerinsaarenneva					
Kinkerinsaarenneva		K			K I
Koitajoki					
Juurikkasuo I			K M		
Niemijärven pohjoispuolen suo			K M		
Koitajoen alue				K V I	K V

K = RGB-kartoitus / RGB mapping, M = Multispektrikartoitus / Multispectral mapping, L = Lämpökartoitus / Thermal mapping
V = Vapaita kuvia / Free images, I = Video, X = Laserkeilaus / Laser scanning

Kohde / Site	**2018**	**2019**	**2020**	**2021**	**2022**
Leivonmäki					
Haapasuo		K K			
Loukisen latvasoiden					
Kilpivuoma		K V			K V
Loukkuneva-Isoneva					
Loukkuneva		K V			K V I
Mujejärvi					
Jänissuo					V
Loukkusuo		K K M M M	K K K K K M M M L	K K M	K V I
Mustikkasuon lampi				K V	
Porrassuo	K M				
Tammalammen suo		K K M	K K K K K M M M L	K K V I	K V
Olvassuo					
Iso Leväniemi		K K K M L V I	K M L		
Kirkaslampi vanha		K M L			
Kirkaslampi kontrolli		K K M L V I	K M L		
Pikku Olvasjärvi vanha		K K M			
Pikku Olvasjärvi kontrolli		K			
Pisa-Kypäräinen					
Hoikanlampi		K K	K M		
Peuralamminneva					
Peuralamminneva		V K			

K = RGB-kartoitus / RGB mapping, M = Multispektrikartoitus / Multispectral mapping, L = Lämpökartoitus / Thermal mapping
V = Vapaita kuvia / Free images, I = Video, X = Laserkeilaus / Laser scanning

Kohde / Site	**2018**	**2019**	**2020**	**2021**	**2022**
Päätyeenlahti					
Päätyeenlahti		K K			V
Rimpijärvi-Uusijärvi					
Kauniinlamminaapa		K			K I
Ruunaa					
Ruunaan Palosärkät		K V		K V	
				K V	
Salamajärvi					
Ahvenlampi			K		
Tielampi	K K	V			
Kivipää			K K K X		
Saloneva	K K V				
Soikealamminneva	K K K K K V	K V	K K K K K	K	
Sarvisuo-Jerusaleminsuo					
Sarvisuo-Jerusaleminsuo					V I
Suolamminvaara-Tervasuo					
Salmilammen suo	K		K M	K V	
Tiilikkajärven kansallispuisto					
Sarvisuo-Jerusaleminsuo				K V I	I
Ukonsärkkä					
Haapahaasianvaaran suopelto	K				
Heinävaaran etelä-suo	K				

K = RGB-kartoitus / RGB mapping, M = Multispektrikartoitus / Multispectral mapping, L = Lämpökartoitus / Thermal mapping
V = Vapaita kuvia / Free images, I = Video, X = Laserkeilaus / Laser scanning

Kohde / Site	**2018**	**2019**	**2020**	**2021**	**2022**
Vahtisuo					
Vahtisuo	K V				K V
Veneneva-Pelso					
Temmesjoki Latvanneva			K		K I
Viiankiaapa					
Viiankiaapa			K V	K V K V	
Viitasuon P-puolella					
Koivuluhdansuo	K M V				

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