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Rewetting of drained Ombrotrophic Bogs in Norway: Short-term Effects on Vegetation

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Master of Science in Natural Resource Management

Norwegian title:
Blautlegging av drenerte nedbørsmyrer i Norge: Korttidseffekter på vegetasjon

Preface

This thesis is written as the finale of my MSc in Natural resource management at the Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences (NMBU). Miljødirektoratet [The Norwegian Environmental Agency] contributed with funding of transport and field equipment; kindly acknowledged as it enabled an extensive data collection.

A group of four master's students have been studying the effects of mire rewetting, part of the national Wetland Restoration Plan by Miljødirektoratet. My work is one of four individual theses: Eirik Walle studying hydrology, Hanna Utseth entomology, Aase Johansen and myself studying vegetation. The selection of locations, planning and execution of the fieldwork were done as a team. Johansen and I developed the methodology for field work, data compilation, and analysis together for the vegetation survey. We assessed vegetation at two different resolutions, and it was natural to split our reports accordingly. I would like to thank all three, and especially Johansen, for the joint fieldwork, discussions and for supporting each other.

Many thanks to my supervisor Jan Vermaat for help and guidance, coordinating our team and taking time to join us in the first days of fieldwork. I would also like to thank my co supervisors Jonathan Colman and Marte Fandrem (Department of Natural History Faculty of Natural Sciences, NTNU University Museum) for all advice, and feedback on text. Special thanks to Fandrem for help with data management and statistical analysis. Thanks also to Hilde Vinje for statistical advice, and Maren Aunet for feedback on language. I would also like to acknowledge my gratitude towards the community of the R Project for Statistical Computing. A community who maintain free access to advanced statistical tools, and provide endless pages with examples, guides and Q&As on various forums – rarely cited, but much appreciated.

I would also like to thank Miljødirektoratet and Statens Naturoppsyn [Norwegian Nature Inspectorate]: Thanks to Liv Byrkjeland for providing information on the developing monitoring strategies and suggesting this study in the first place. Thanks to Pål Martin Eid for sharing information from of the rewetting project, describing locations, and bringing us along to observe rewetting in action.

Finally, a token of gratitude to my wife and newly arrived son, who both have endured the completion of this thesis during a pandemic lockdown, and received their share of my fascination for the many wonders of the world of mires.

Ås, Mai 31st 2021

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Abstract

The restoration of degraded mires is considered an important part of mitigating climate change and biodiversity loss. Mires are wetland ecosystems where organic matter is submerged and preserved as peat layers. Bogs are mires fed by rainwater, being nutrient poor and having a low pH, they are able to form deep layers of peat with high carbon storage. Draining bogs affected both the living surface vegetation and the peat. Drainage from ditches lowers the water table, allows air into the peat layers, and release carbon into the atmosphere. When the capacity of bogs to retain water is altered, the surface becomes dryer, changing environmental conditions, and thereby altering the composition of species. A quarter of Norwegian bogs are today lost or drained by ditches and other human land use changes. Ongoing restoration aims to reverse drainage by filling ditches, building dams, and removing trees (rewetting).

This study examined the early effects (1-5 years) on vegetation, following rewetting of drained bogs in South-eastern Norway. Line transects were used to obtain abundance of species and surface structures. The vegetation in drained, rewetted, and “pristine” bogs were surveyed and used to compare the effect of the three treatments, using generalized linear mixed models (GLMM).

The only significant changes found from drained to rewetted sites were increased pools, surface water and exposed peat, attributed to the disturbance of the terrain part of the rewetting activity. Drained sites differed from pristine having less *Sphagnum* spp. (Peat mosses), lawn structures and a higher proportion of other mosses, lichen and litter. The presence of forest and forest-affiliated species on earlier mire expanses were observe in drained bogs. The difference from drained to pristine sites differed less than expected, particularly in the field layer and surface structures. An explanation for the relatively small difference between the treatments is suggested to be too little time passed since rewetting, and possibly a lower ditching intensity than used in similar studies showing faster responses.

Oxycoccus (Cranberries) is proposed as a potential rapid colonizer in Norwegian bogs following rewetting. The intensity of ditching is suggested as an important variable to include both in the selection of restoration sites and future studies comparing them with drained and pristine reference sites. These results, along with Scandinavian studies, indicate that restoration is a slow attempt to reverse damage to bog systems, where long term studies are needed to measure the effects. This study underpins that the most effective way of gaining ecosystem services from peat accumulating *Sphagnum* layers, is to prevent initial drainage and degradation of existing bogs.

Sammendrag

Å restaurere drenerte myrer anses som en viktig del av å begrense klimaendringer og tap av naturmangfold. Myr er våtmarkssystemer der organisk materiale dekkes av vann og lagres som torv. Myrer som kun tilføres vann via nedbør kalles nedbørsmyrer. Nedbørsmyrer er næringsfattige, har lav pH og kan bygge opp tykke torvlag med store mengder bundet karbon. Drenering av nedbørsmyr påvirker både vegetasjonen på overflaten og torva. Med drenerende grøfter senkes vannivået, luft slipper til torva og karbon blir frigjort til atmosfæren. Når myra sin kapasitet til å holde på vann reduseres blir overflaten tørrere, miljøforhold forandres og dermed endres sammensetningen av plantearter. En fjerdedel av myrer i Norge er i dag tapt eller påvirket av grøfter og andre menneskelige arealbruksendringer. Pågående restaurering har som mål å reversere drenering ved å fylle igjen grøfter, bygge demninger og fjerne trær (blautlegging).

Denne studien undersøker de tidlige effektene (1-5 år) på vegetasjon ved blautlegging av drenerte nedbørsmyrer i Sørøst-Norge. Linjetransekter ble brukt til å måle mengden av arter og overflatestrukturer på myrene. Vegetasjonen i drenerte, blautlagte og "urørte" myrer ble undersøkt og brukt for å sammenligne effekten av de tre tilstandene. Effektene ble sammenlignet ved bruk av generaliserte, lineære, blandede modeller (GLMM).

Den eneste signifikante endringene fra drenerte til blautlagte myrer var en økning av dammer, overflatevann og blottlagt torv som forklares med forstyrrelser i terrenget av blautlegginginngrepene. Drenerte områder har mindre *Sphagnum* spp. (Torvmoser) og strukturen mykmatter, og høyere andel av andre moser, lav og strø, enn urørte områder. Både skog og arter tilknyttet skog var til stede i de drenerte områdene som tidligere har vært åpne myrflater. Forskjellen mellom drenerte og urørte myrer var allikevel mindre enn forventet, særlig i feltsjikt og overflatestrukturer. For lite tid siden blautlegging, og en mulig lavere grøfteintensitet foreslås som en forklaring på de relativt lave observert forskjellene mellom tilstandene, sammenlignet med tilsvarende studier.

Oxycoccus (Tranebær) ser ut til å raskt kunne kolonisere blautlagte nedbørsmyrer i Norge. Grøfteintensitet løftes som en viktig variabel å ta hensyn til både ved utvelgelse av lokaliteter for restaurering, men også framtidige studier som sammenligner dem med drenerte og urørte referanseområder. Resultatene i denne studien, sammen med skandinavisk forskning, indikerer at restaurering er saktevirkende forsøk på å reversere skader i myrøkosystemer. For å måle effekten av tiltakene vil det være nødvendig med gjenundersøkelser i lang tid. Denne studien underbygger at den mest effektive måten å få økosystemtjenester fra torvproduserende *Sphagnum* er å unngå at myrer dreneres og forringes i utgangspunktet.

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Introductory definitions

Restoration is defined by the Society for Ecological Restoration (SER) as "the process of assisting the recovery of an ecosystem that has been degraded (…) [and] to move [it] to a trajectory of recovery that allows adaptation to local and global changes, as well as persistence and evolution of its component species." (Gann et al., 2019). SER uses the term *recovery* for the desired goal of the restoration process, but acknowledges that it is common to use *restoration* for both the process and the outcome.

Rewetting is an activity applied to restore degraded mires that have been drained through re-establishing hydrological conditions conducive for a mire's existence. Rewetting is a part of the restoration process which in time might lead to the desired recovery of mires.

Names of plant species follow Artsdatabanken [Norwegian Biodiversity Information Centre] without author citation. Institutions are addressed using their Norwegian name. The Norwegian translation for terminology with well-established Norwegian terms, without and obvious English equivalent, is presented in square brackets.

Introduction

The restoration of degraded mires is considered to be an important part of mitigating climate change and biodiversity loss (Joosten et al., 2012; Miljødirektoratet, 2021). Mires are wetlands accumulating organic matter in peat, and is estimated to make up 3% of global land area (Rydin & Jeglum, 2006) and 10% of the Norwegian mainland (Moen et al., 2011; Tanneberger et al., 2017). These peat layers store twice as much carbon as all the world's forests (Joosten & Clarke, 2002 p. 35). Human disturbance, such as drainage, releases mire-bound carbon into the atmosphere. In Norway, such emissions are estimated to equal 5% (2-3,4 million carbon dioxide equivalents) of the annual national anthropogenic emissions of greenhouse gases (Miljødirektoratet og Landbruksdirektoratet, 2016; Moen et al., 2011). Not only reducing climate emissions, but also improving ecological conditions in waterways and halting the extinction of species desired goals of restoring mire ecosystems (Miljødirektoratet, 2021, chap. 1.1.3). Mires have thus appeared to become a favoured strategy to fulfil international agreements by preserving and restoring these ecosystems and their function. As restoring mires increase in priority, there is also an increasing need for knowledge of the effects from the restoration activities presently used in Norway.

Mires consist of vegetation growing close to the water table and they are broadly divided into two categories (Wheeler & Proctor, 2000). The partly submerged bottom layer consists of mosses, often *Sphagnum* spp. (Peatmosses) which can colonize open bodies of water (Moen, 1998). When such moss layers grow level with the water table, the mire surface is observed as a flat cover in landscape depressions. Such mires are generally categorized as fens and are in direct contact with groundwater (geogenous mires) and the plants have access to dissolved minerals from mineral soil or bedrock (minerotrophic vegetation) (Flatberg, 2013). The other category of mires are bogs, where peat accumulation and continuous upward growth of *Sphagnum* raises the surface above the water table of the surrounding landscape (Moen et al., 2011). The elevated layer of the bog retains rainwater (ombrogenous mires) submerging the plants without being in direct contact with groundwater (ombrotrophic vegetation). Bogs are particularly nutrient poor with low pH, giving less variation in plant species than fens. The surface growth, combined with acidic and anoxic conditions below the water table, allows deep peat layers to form, with high carbon storages accumulated over centuries. Bogs are the dominating mire form of South-eastern Norway (Fandrem et al., 2018; Moen, 1998). Ombrotrophic bogs are the focus of this study.

Variation along two environmental gradients account for most of the natural variation in bogs, as described in the EcoSyst framework and "Nature in Norway" (NiN) (Halvorsen et al., 2020). The *dry-wet gradient* describes the range from dry hummocks to floating mats of mosses. This gradient is created by the distance from the water table to the surface, and is in Scandinavian literature divided into categories representing different surface structures; hummock, lower hummock, lawn, hollow and pools (Flatberg, 2013, p. 29-34). The other gradient is the *mire expanse - mire margin gradient* [No. Myrflate - Myrkant] encompassing the many changes from the open tree less bog centre to the forested margins and surrounding forest on non-wetland ground [No. fastmark]. These two gradients explain the spatial distribution of species and is used to define bog habitat types in Norway (Halvorsen, 2015). Different *Sphagnum* species and the relatively few vascular plants occupying different niches within these gradients in Norwegian bogs, as described in Halvorsen et al. (2016) and summarized in Appendix: Table A1. Examples of such niche adaptations are *Sphagnum* spp.

generally tolerating wetter conditions than other non-wetland generalist mosses occurring in bogs, such as *Hylocomium splendens* (glittering woodmoss). *Rhynchospora alba* (white beak-sedge) is a specialist found in wet parts of the mire expanse while *Vaccinium vitis-idaea* (lingonberry) prefer dry hummocks in margins and non-wetland forest. This kind of adaptations and gradients can be used to predict vegetation changes when the environmental conditions of "pristine" bogs are altered by, for example, drainage.

Drainage reduced the ability of bogs to retain water. Ditches lower the water table and affects both the living vegetation and the peat. Depending on the intensity of ditching, bogs can be transformed into dry land [No. fastmark] supporting agriculture and forestry. Significant drainage of mires in Norway started around the 1700's for agricultural purposes, while the main reason during the last century has been forestry (Moen et al., 2011). According to Moen et al. (2011) human land use change is estimated to have caused the drainage or loss of a quarter of Norway's historic mire area. While ditching mires to establish new forestry was banned in 2007, maintenance of existing diches is still allowed (Miljødirektoratet og Landbruksdirektoratet, 2016, chap. 1.2.2). Recent legislative changes in regulations of land use change reduced the possibility to convert mires into farmland by imposing a general ban, with some exceptions (Endr. i forskrift om nydyrking, 2020). The increased focus by policymakers on reducing mire degradation has been accompanied by a national Wetland Restoration Plan (Miljødirektoratet, 2021).

Norwegian environmental authorities use the method of rewetting to restore drained and damaged mires. The rewetting method focuses on raising the water table by stopping the draining effect of ditches. Dams are constructed across ditches using local peat. Excavators are used and although dams are plastered with living vegetation, there is an unavoidable disturbance of the existing vegetation cover[1]. The dams are wide enough to hinder the waterflow both along the ditch itself, and the subsided area extending from the ditch due to decomposition of peat. With an average of one dam per 20 cm altitude change, water is retained and guided out from the ditch to surrounding bog surface (Miljødirektoratet, 2021, chap. 3.1.2). The first national project was initiated in 2015, starting with 18 locations within nature reserves (Miljødirektoratet, 2015). This pilot project has been extended to a large number of mires across Norway, mainly on state and municipality owned land (Miljødirektoratet, 2021, chap. 5.2). The rewetting method is well established and Similä et al. (2014) have compiled more than 25 years of experience with the method in Finland.

Several studies report changes in vegetation following rewetting, but the effect depends on the type of mire and time since rewetting. The response in bogs is slower than that of more nutrient rich fens following both rewetting (Jukaine et al., 1995; Komulainen et al., 1999) and drainage (Hedberg et al., 2012; Laine et al., 2011). Nevertheless, effects of drainage common for all mire types are increased occurrence of non-wetland forest species and decrease of mire specialists (Jukaine et al., 1995; Vasander, 1982). Rewetting rapidly raises the water table and can reverse the succession towards forest vegetation already within the first three years (Komulainen et al., 1999; Punttila et al., 2016). These effects of rewetting is found to continue in long-term studies such as Haapalehto et al. (2011) without reaching pristine conditions even after ten years. There are few comparable mire restoration projects in Norway prior to 2015, and thus, studies monitoring these effects are rare. One such is the monitoring of

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[1] As confirmed by P. M. Eid (personal communication, 15.04.21) during field visit near Oslo.

vegetation by Nordbakken and Økland (2004) 6 and 16 years after rewetting of a raised bog in 1982. These authors did find the expected increase in *Sphagnum* cover.

The effects of the current Norwegian restoration program have yet to be tested. Miljødirektoratet [En. The Norwegian Environmental Agency (NEA)] is compiling two bodies of information on vegetation conditions pre and post rewetting: an "extensive" and an "intensive" survey. The extensive survey is a simple monitoring of *Sphagnum* presence carried out by Statens Naturoppsyn [En. Norwegian Nature Inspectorate] at all restoration projects prior to rewetting. Standardizing methodology, resurveying after rewetting, publishing and analysing this body of information is still work in progress (Miljødirektoratet, 2021, chap. 4.4.1)[2]. The intensive survey is developed by Norsk institutt for naturforskning [En. The Norwegian Institute for Nature Research] (NINA) (Hagen et al., 2015). It is a comprehensive survey method, used for a few selected locations. Only preliminary reports from two locations exist with before/after surveys using this method (Kyrkjeeide et al., 2018). There is a need to analyse the early effect of the ongoing rewetting, and to monitor whether the Norwegian restoration attempts are effective.

This study examined the early effects (1-5 years) on vegetation following rewetting of drained bogs in South-eastern Norway. The vegetation in drained, rewetted, and pristine bogs were surveyed and compared. Line transects were used to obtain abundance of species and surface structures. A comparison of the effects of treatments using generalized linear mixed models was used to answer 1) Whether the vegetation composition differed among drained, rewetted and pristine bogs, 2) Whether the occurrence of species and surface structures differed? and 3) What are the implications of these findings for the management, monitoring and planning of rewetting programs?

I hypothesise that the effect of drainage and rewetting causes opposite changes to the two environmental gradients of pristine bogs: *Dry-wet* and *mire margin-expanse*. These changes are for drained bogs increased mire margins and dry surface structures at the expense of open mire expanse and wet surface structures. I suppose the opposite to be valid for rewetted bogs. Based on the affinity of species and surface structures along these two gradients I predict whether vegetation will be favoured by drainage or rewetting. I expect that generalist species common in non-wetland forest, mire margins and the driest surface structures will be favoured by drainage. Similarly, I expect rewetting to favour specialists of mire expanses and the wettest surface structures.

I also hypothesise that a third gradient, *short-term human disturbance*, will differ across drained, rewetted, and pristine bogs. I expect the recent rewetting measures will cause mechanical disturbances of the terrain, increasing dead vegetation litter, exposed peat, and new pools. This disturbance effect is expected to occur over a short-term period in rewetted bogs. Any similar short-term disturbance from the drainage measures in the in the drained sites is expected to have been reversed and recolonized as the time since drainage is on the scale of decades[3]. These predictions are summarized in Table 1.

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[2] As elaborated by L. Byrkjeland (personal communication, 11.03.21) by email.

[3] As confirmed on publicly available aerial photos, available at e.g., https://www.norgeibilder.no/ (29.05.21). Most sites were drained >42-84 years ago, two sites had been (re)drained prior to 2005 (>16 years).

Table 1. Effects in drained, rewetted, and pristine bogs by environmental gradients and vegetation variables studied. Gradients 1 and 2 are described by Flatberg (2013) and Halvorsen (2016, chap. B), and 3 is mechanical disturbances of terrain by human activity of drainage or rewetting. The overall effects expected in drained and rewetted bogs are presented per gradient, compared to the reference of pristine bogs assumed to have an “normal” state. Predictions, based on Halvorsen et al. (2016), as summarized in Appendix Table A1, are presented per vegetation variable. Numbers in brackets refer to the gradient(s) the predictions are based on. Vegetation variables are defined in Table 3, in the method section.

		Drained	**Rewetted**	**Pristine**	
Gradients					
1. Dry-wet		Dryer	Wetter	Normal	
2. Mire margin-mire expanse		More margin	More expanse	Normal	
3. Short-term human disturbance		No (Minimal)	High	No	
Predictions per vegetation variable					
Surface structure	Pool	Decrease	Increase	Normal	(1+3)
	Hollow	Decrease	Increase	Normal	(1)
	Lawn	Decrease	Increase	Normal	(1)
	Lower hummock	Decrease	Increase	Normal	(1)
	Hummock	Increase	Decrease	Normal	(1)
	Bog margin	Increase	Decrease	Normal	(1+2)
	Forest	Increase	Decrease	Normal	(1+2)
	Ditch verge	Increase	Decrease	Normal	(1+3)
Bottom layer	*Sphagnum*	Decrease	Increase	Normal	(1+2)
	Other mosses	Increase	Decrease	Normal	(1+2)
	Lichen	Increase	Decrease	Normal	(1+2)
	Litter	Increase	Increase	Normal	(1+2+3)
Field layer	*Eriophorum*	Decrease	Increase	Normal	(1+2)
	Other Cyperaceae	Decrease	Increase	Normal	(1+2)
	Trichophorum cespitosum	Decrease	Increase	Normal	(1+2)
	Andromeda polifolia	Decrease	Increase	Normal	(1+2)
	Oxycoccus	Decrease	Increase	Normal	(1+2)
	Caluna vulgaris	Increase	Decrease	Normal	(1+2)
	Other herbs	Increase	Decrease	Normal	(1+2)
	Empetrum nigrum	Increase	Decrease	Normal	(1+2)
	Vaccinium vitis-idaea	Increase	Decrease	Normal	(1+2)
	Vaccinium myrtillus	Increase	Decrease	Normal	(1+2)
	Vaccinium uliginosum	Increase	Decrease	Normal	(1+2)
Other	Exposed peat	Normal	Increase	Normal	(3)
	Surface water	Decrease	Increase	Normal	(1+3)

Method

Study area

The study area was located in the northern boreal forest vegetation zone [No. boreonemoral], South-eastern Norway (Fig. 1). All sampling locations were centred around the Oslo fjord, an area with a weak oceanic influence [No. svakt oseanisk], dominated by raised bogs (Moen, 1998).

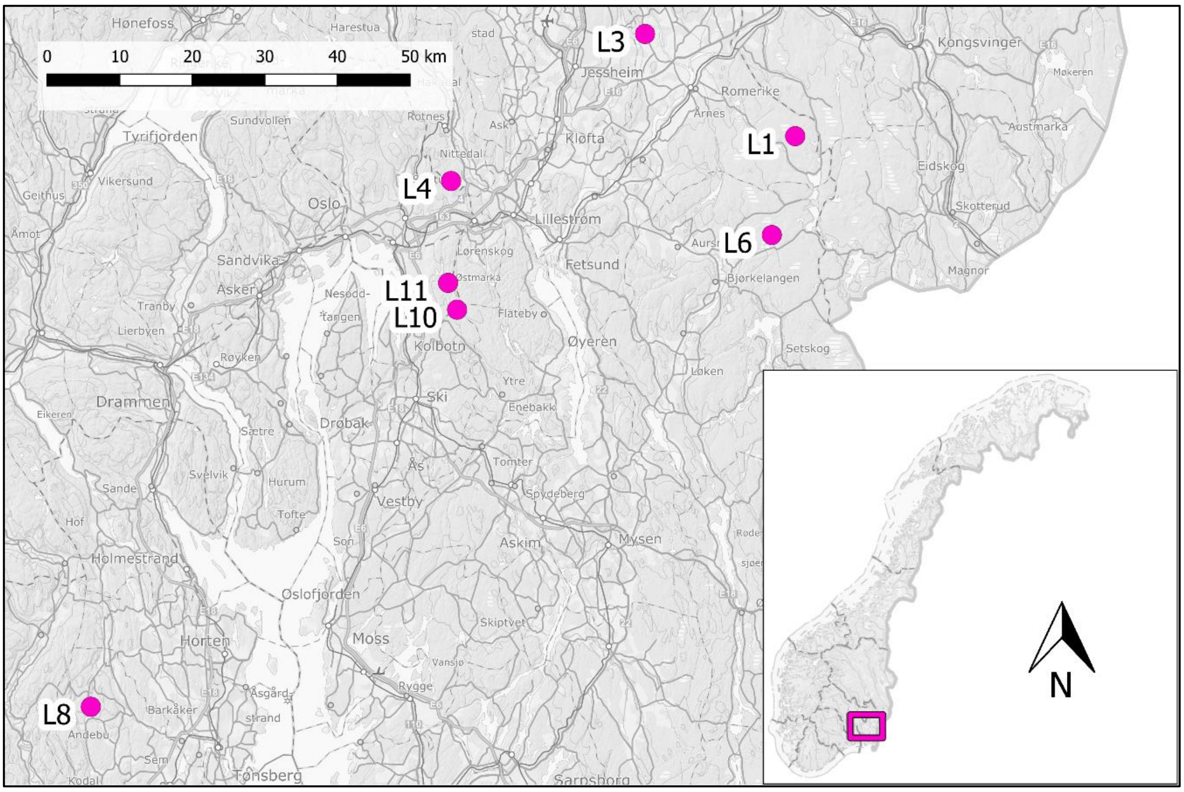

Fig.1. Map of all eight locations in South-eastern Norway. Location L10 and L10B consist of bog sites in the same area. Reference system ETRS89 / UTM 33N. Background map is *Topografisk norgeskart 4 gråtone,* Statens kartverk 2007.

This study is limited to the mire type ombrotrophic bogs and is based on eight locations. Rewetted bogs part of the restoration project by the Miljødirektoratet [En. The Norwegian Environmental Agency] were the starting point for choosing the locations (Table 2). The year of rewetting span from 2015 to 2019. The rewetting approach has varied somewhat during this period. Building dams and filling ditches was the common approach used to reverse the effects of draining for all locations. The earthworks were done by excavators using local peat and other on-site organic materials from each mire. Trees had been harvested to a varying degree or were used in the foundation material for dams and fillings. Eight rewetted ombrotrophic bogs were selected. Avoiding fens and minerotropic areas reduced expected variation by the differences in topography, nutrients, pH and species composition. The fieldwork was caried out June-September 2020.

Table 2. Overview of the eight locations with their corresponding site names and treatment. Length and number of transects given per site. Coordinates per site (°N, °E) given for reference system Euref89 UTM32.

Location	Site	Treatment	Transects length (m)	Rewetted	Coordinates
L1 Sakkhusmåsan	Villpostmåsan	drained	30, 40		60.067385, 11.736947
	Sakkhusmåsan	rewetted	40, 40	2015	60.069704, 11.732560
	Sakkhusmåsan	pristine	30, 40		60.069704, 11.732560
L10 Fjøsmåsan	Eiriksvannmåsan	rewetted	30, 30, 50		59.845864, 10.943277
	Fjøsmåsan	rewetted	30, 50	2019	59.832232, 10.922190
	S of Rulleåsene	pristine	30		59.844451, 10.913008
L10B Eiriksvannm.	Starrmåsan	drained	30, 50		59.823055, 10.932512
	Eiriksvannmåsan	rewetted	30, 30, 30	2018	59.832760, 10.928210
	Stormyr	pristine	50, 50		59.820382, 10.927771
L3 Aurstadmåsan	Flakstadmåsan	drained	40, 40		60.172084, 11.331314
	Aurstadmåsan S	rewetted	30, 50, 50	2016	60.184310, 11.345163
	Aurstadmåsan W	pristine	40, 40		60.187327, 11.338902
L4 Romsmåsan	W of Lomtjern	drained	30, 30, 31		59.995716, 10.878654
	Romsmåsan	rewetted	30, 50, 50	2016	59.985788, 10.884853
	S of Rudspytten	pristine	30, 40		60.002778, 10.866177
L11 Øgårdsmåsan	Skullerudmåsan W	drained	30, 40		59.861760, 10.859510
	Øgårdsmåsan	rewetted	30, 30, 35	2019	59.865237, 10.893689
	Skullerudmåsan S	pristine	30, 30		59.860759, 10.860219
L6 Midtfjellmåsan	Tjennshaugmåsan SW	drained	30, 30		59.943129, 11.666755
	E of Langtjern	rewetted	30, 35	2018	59.952038, 11.684221
	E of Vintertjern	pristine	30, 30, 40		59.954480, 11.693798
L8 Veggermyra	Strandemyra	drained	30, 40		59.312414, 10.076747
	Veggermyra S	rewetted	30, 30	2018	59.310722, 10.095210
	Veggermyra N	pristine	30, 30		59.312412, 10.094548

Study design

Each location consisted of three sites representing the different treatments: drained, rewetted, and pristine. Selection of the locations was initially based on the rewetted sites. The drained and pristine sites were subsequently selected based on proximity and similarity to the rewetted sites. Depending on size and availability of suitable nearby bogs, these drained and pristine sites were either located on the same bog or on neighbouring bogs (Fig. 2). Four of eight locations have two sites within the same bog (see sites with similar names in Table 2). These sites were positioned far enough from each other to ensure that drainage/rewetting had little or no expected effect.

Location selection was based on several sources of information. Miljødirektoratet had databases of ditches and restoration actions within rewetted sites[4]. Publicly available aerial photos and height data (Kartverket, 2020) were used to visually explore the surrounding

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[4] A portal with publicly accessible data and maps is available at http://bit.ly/myrkartet (21.05.21).

landscape and surface for bogs and ditches[5]. Locating suitable bogs and avoiding minerotrophic mires was guided by the public ecological database "Naturbase" (Miljødirektoratet, 2020) and fieldwork in the area by managers and researchers[6] (Moen, 1976). The a priori knowledge gave suggestions for drained, rewetted, and pristine sites that were finally decided in the field.

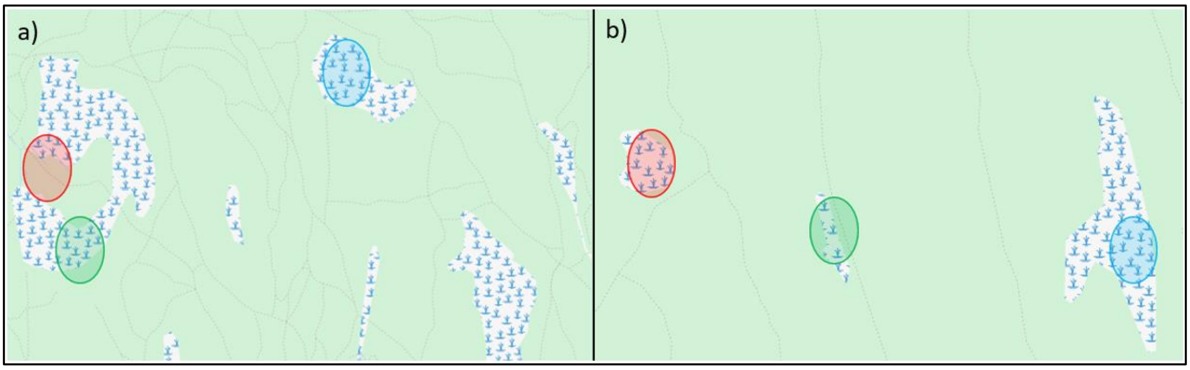

Fig.2 Illustration of the design; three sites per location: drained (red), rewetted (blue) and pristine (green). a) Location where the drained, and pristine site is located within the same bog while the rewetted site is on a neighbouring bog, b) location where all three sites are located in different bogs.

Data collection

Norsk institutt for naturforskning (NINA) has developed methods for surveying rewetted mires before and after restoration is initiated. Hagen et al. (2015) describes the method and surveyed drained mires planned for rewetting. A refinement is reported in Kyrkjeeide et al. (2018), who replicated the survey 1-2 years after restoration. The NINA-method consists of drone photography and terrain height (macroscale), nominal vegetation types (mesoscale) and species counts (microscale). This study is using an adapted version of the mesoscale methodology, whereas the parallel study by Johansen (2021) focused on the microscale.

Line transects were placed on all three treatment sites within each location. Transects were positioned in a manner that was representative for the site. The length and number of transects were site dependent and varied from one to three per site with a length of 30-50 m. In drained and rewetted sites, all transects crossed a minimum of one extant or filled ditch perpendicular to the direction of the ditch (Fig. 3). Transects were temporarily marked during the fieldwork and coordinates were obtained using mobile phone with embedded satellite navigation technology (Appendix Table A2).

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[5] digital surface model reveals ditches in the ground and digital elevation models reveal the amount of tree cover.

[6] Advice from recent years fieldwork from P. M. Eid and M. Fandrem (personal communication April - September 2020)

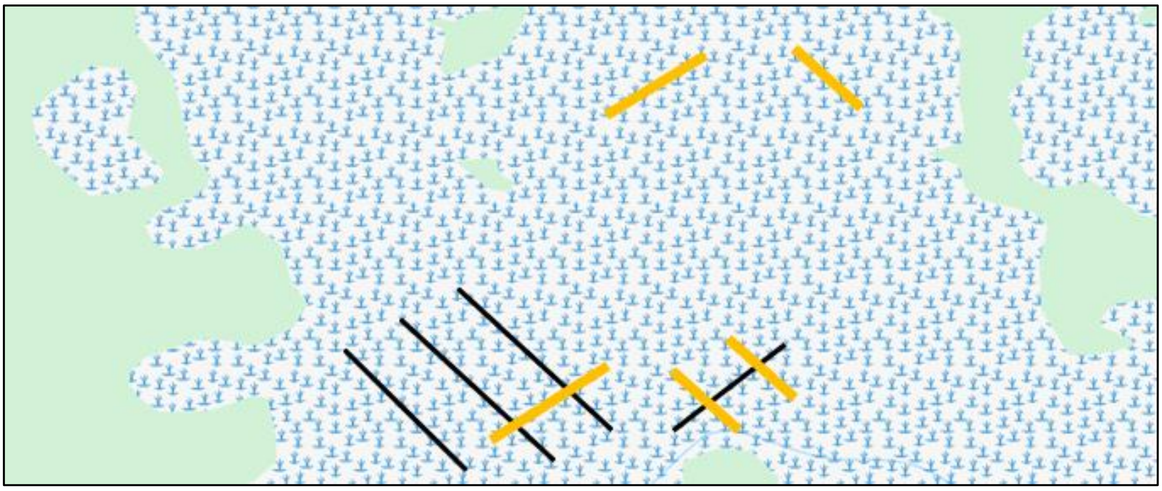

Fig. 3. Illustration of transects (orange) and ditches (black). Transects on drained and rewetted sites cross one or more ditches perpendicularly. For pristine sites, transects were placed on un-ditched area on the same bog or a neighbouring bog.

Each 0.5 m section along the transects was used as the unit of measurement. The area immediately beneath the transect and 5 cm extending on each side was examined. For each section, the dominating vegetation was recorded for three different layers (bottom-, field layer, and surface structures). In each of these layers several vegetation descriptors were assessed: including groups of species, single species, and small-scale topographic landforms. These descriptors are henceforth referred to as vegetation variables, as presented in Table 3**.** The main difference from Hagen et al. (2015) and (Kyrkjeeide et al., 2018) to this study is the use of single species of Ericaceae instead of pooling them into evergreen and deciduous Ericaceae.

The name and number of categories used for describing surface structures varies, even within the Scandinavian tradition, see for example Ohlson and Halvorsen Økland (1998) and Malmer & Wallén (1999). This study translates the categories of Hagen et al. (2015): “tue” to hummock; “fastmatte” - lower hummock; “mykmatte”- lawn; and “løsbunn[/matte]” - hollow. All categories for the different vegetation variables are defined in table 3.

Table 3. Variables used to describe the dominating vegetation of 0.5 m sections along line transects withing the layers: surface structures, bottom-, and field layer. Adapted from Hagen et al. (2015) and Kyrkjeeide et al. (2018).

Layer	Variable	Definition
Surface structure		
	Pool	Pools of gyttja and/or water, regardless of origin.
	Hollow	Not safe to walk on without sinking in. Water table at surface. Sparse to no field layer.
	Lawn	Footprints remain, and safe to walk on. Water table close to or at surface. Sparse field layer with few to no Ericaceae species.
	Lower hummock	No or moderate footprints remain. Water table below surface. Continuous field layer.
	Hummock	Distinct elevations in microtopography. Field layer dominated by Ericaceae species.
	Bog margin	Tree layer with no or smaller trees. Occurrence of forest species in bottom and field layer.
	Forest	Tree layer dominated by full-grown trees, forest specialist species dominating in bottom and field layer.
	Ditch verge	Dry ground above water table, often with steep slopes. Originated from human digging in the terrain, ditching or rewetting.
Bottom layer	*Sphagnum* spp.	Category collective for all *Sphagnum* spp.
	Other mosses	Category of all species of mosses excluding *Sphagnum* spp.
	Lichen	Category collective for all lichen.
	Litter	Dead material from vegetation
Field layer	*Eriophorum* spp.	Category of all *Eriophorum* spp.
	Other Cyperaceae	Category of all specimens in the Cyperaceae family excluding *Eriophorum* spp. and *T. cespitosum*
	T. cespitosum	Single species [*Trichophorum*]
	Andromeda polifolia	Single species
	Oxycoccus spp.	Category collective for all Oxycoccus spp.
	Calluna vulgaris	Single species
	Other herbs	Category of all specimens of non-wooden flowering plants
	Empetrum nigrum	Single species
	Vaccinium vitis-idaea	Single species
	Vaccinium myrtillus	Single species
	Vaccinium uliginosum	Single species
Other		
	exposed peat present	Exposed peat at surface within 0.5 m section.
	Surface water present	Relatively permanent water at surface within 0.5 m section.

Statistical analysis

All analysis was done using RStudio in R version 4.0.5 (R Core Team, 2021). Plots were made using base R functions and the package ggplot2 (Wickham, 2016). A confidence interval of α = 0.05 were used for all statistical tests. Three groups of analyses were conducted.

Difference in vegetation composition by treatment

Chi squared tests of homogeneity were used to expose the effect of treatment on the composition of vegetation for surface structures, bottom- and field layer. Frequency tables pooled across all eight locations were used to test both overall and pair-wise comparison of the treatments drained, rewetted and pristine. The tests were conducted by the function chisqr.test using a continuity correction (“correct=T”).

Difference of individual vegetation variables by treatment

Generalized linear mixed models (GLMM), the function and package glmmTMB (Brooks et al., 2017) were used to create models for the 25 vegetation variables. The recorded abundance of vegetation variables in all three treatment groups were modelled to expose the effect of the sites condition being drained, rewetted or pristine. Comparing the effect of the treatment drained vs. pristine was done to determine any significant changes between drained and pristine bogs. Similarly, the effect of treatment rewetted were compared to pristine and drained to answer whether there was a significant difference between the three treatments.

Presence-absence data were aggregated to proportions per transect (n = 55) and modelled using a beta distribution. To handle the large amount of zero values the data were either squeezed (Y+0.00001 and values of “1” changed to 0.99) before modelling or a zero-inflation formula was added (ziformula=~1). Model diagnostics testing for over/under dispersion and zero-inflation were don using the package DHARMa (Harting & Lohse, 2021).

The study design is accounted for with a random factor nesting site within location (three sites per location, see Fig. 2). Five vegetation variables were unfit for modelling using GLMM (*V. vitis-idaea, V. myrtillus and V. uloginosum*, ditch verge, and forest). These data are presented visually without any statistical test of the treatment effect.

Difference of individual vegetation variables by year

Given the range of years since rewetting at the different sites it is possible to examine the short-term effect of time. The design of this study is not intended for such analyses as there are relatively few samples (n=21) and unbalanced as most locations were rewetted the year prior (2019) of our fieldwork (Table 4). Nevertheless, the vegetation variables from rewetted bogs were modelled to expose any effect of year since rewetting within this limited dataset. Presence-absence data were aggregated to proportions per transect and modelled using GLMM with a gaussian distribution using location as a random factor.

Table 4. Overview of year of rewetting for the drained sites per locations, and the corresponding transects.

Year of restoration	**2015**	**2016**	**2018**	**2019**	**Sum**
Number of locations	1	2	2	3	8
Number of transects	2	6	5	8	21

Results

Vegetation was distributed differently between all treatments in both the surface structures, bottom- and field layer (Fig. 4, Table 5). Modelling the effect of treatments revealed that there was no significant difference between rewetted and drained bogs except for increased cover of pools, presence of surface water and exposed peat (Fig. 6a-c).

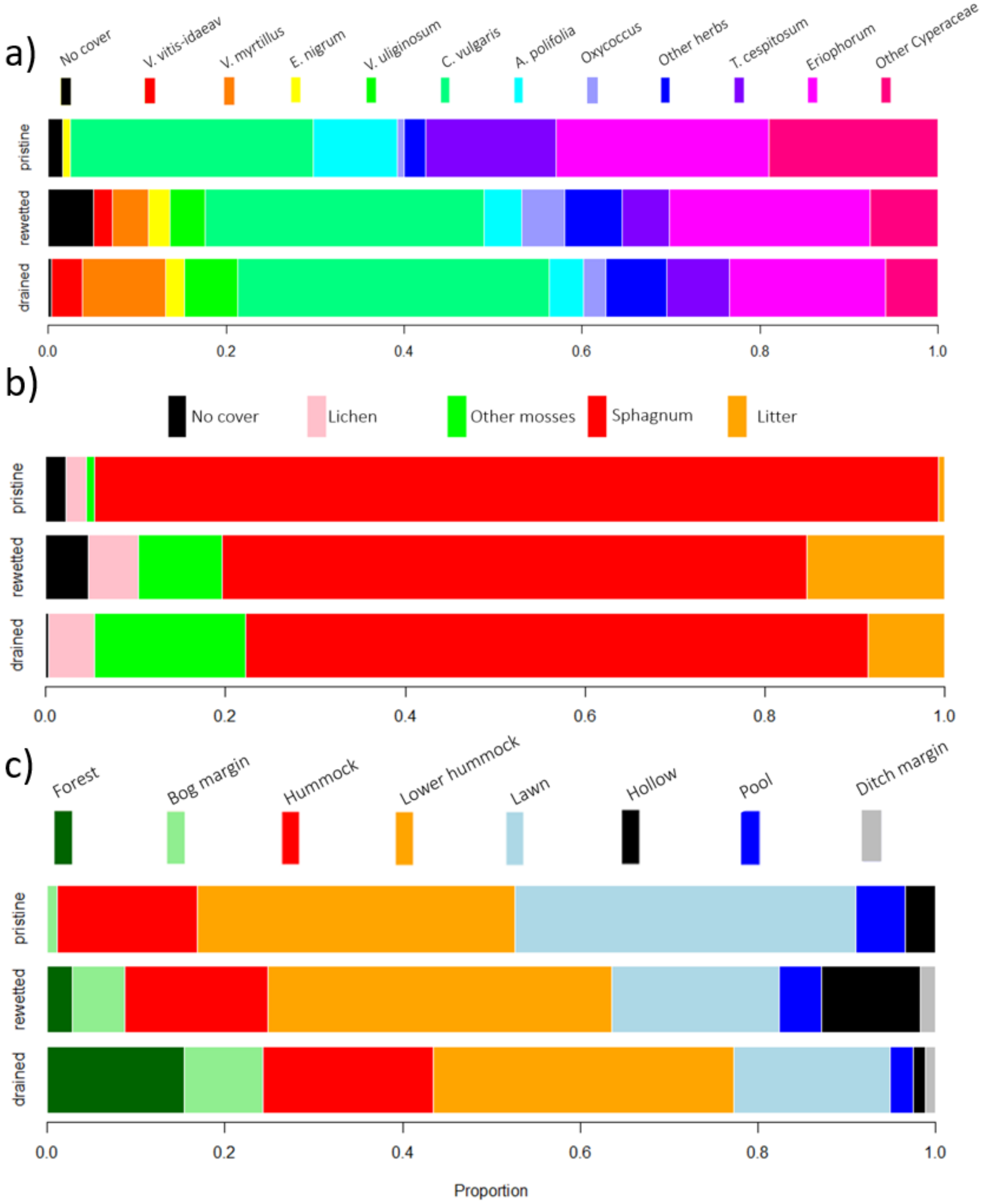

Fig. 4. Composition of vegetation at three levels: a) field-, b) bottom layer and c) surface structures by treatment. Proportion of transects dominated, pooled for all eight locations. Chi square tests show that both drained, rewetted and pristine sites differ in composition at all three levels, $p<0.0001$. Test statistics for pair-wise comparison of drained (d), rewetted (r), pristine (p):
a) Field level d-p χ^2 (8, N = 3871) = 317.58, d-r χ^2 (8, N = 3871) = 106.77, r-p χ^2 (8, N = 3871) = 330.22.
b) Bottom level d-p X^2 (8, N = 3871) = 431.53, d-r X^2 (8, N = 3871) = 118.91
r-p χ^2 (8, N = 3871) = 358.47. c) Surface structures d-p χ^2 (8, N = 3871) = 381.61, d-r χ^2 (8, N = 3871) = 249.55, r-p χ^2 (8, N = 3871) = 231.01.

Along with pools, surface water and exposed peat, who differed between drained and rewetted, also litter and *Oxycoccus* (Cranberries) increased significantly between rewetted sites compared to pristine ones (Fig. 6l). *Oxycoccus* was also the only vegetation variable with a significant effect of years since rewetting: it showed a negative trend (Fig. 5).

Table 5. Frequency and mean proportion of cover of vegetation variables by treatment, pooled over all eight locations. Treatments sharing the same letter do not differ significantly, α=0,05 according to GLMM presented in Appendix Table A3. Frequency is number of 0.5 m sections along transects dominated by variable.

Layer	**Variable**	**Treatment**								
		Drained (n = 1 262)			**Rewetted** (n = 1 480)			**Pristine** (n =1 140)		
		Freq.	**Prop.**		**Freq.**	**Prop.**		**Freq.**	**Prop.**	
Surface structures										
	Pool	18	0.01	a	164	0.11	b	39	0.03	a
	Hollow	33	0.03	a	71	0.05	a	64	0.06	a
	Lawn	221	0.18	a	279	0.19	a	437	0.38	b
	Lower hummock	427	0.34	a	571	0.39	a	407	0.36	a
	Hummock	242	0.19	a	239	0.16	a	180	0.16	a
	Bog margin	111	0.09	a	87	0.06	a	12	0.01	a
	Forest	195	0.15		41	0.03		0	0.00	
	Ditch verge	14	0.01		25	0.02		0	0.00	
Bottom layer										
	Sphagnum	871	0.69	a	961	0.65	a	1067	0.94	b
	Mosses	212	0.17	a	137	0.09	a	10	0.01	b
	Lichen	64	0.05	a	82	0.06	a	25	0.02	b
	Litter	108	0.09	a	226	0.15	a	8	0.01	b
	No cover	4	0.00		70	0.05		26	0.02	
Field layer										
	*Eriophorum spp.**	222	0.18	a	333	0.23	a	272	0.24	a
	Other Cyperaceae	74	0.06	a	113	0.08	a	217	0.19	b
	T. cespitosum	89	0.07	a	79	0.05	a	167	0.15	a
	Andromeda polifolia	49	0.04	a	63	0.04	ab	107	0.09	b
	Oxycoccus spp.	31	0.02	ab	72	0.05	a	9	0.01	b
	Calluna vulgaris	441	0.35	a	463	0.31	a	312	0.27	a
	Other herbs**	86	0.07	a	95	0.06	a	28	0.02	a
	Empetrum nigrum	27	0.02		36	0.02		10	0.01	
	Vaccinium vitis-idaea	43	0.03		31	0.02		0	0.00	
	Vaccinium myrtillus	118	0.09		60	0.04		0	0.00	
	Vaccinium uliginosum	76	0.06		59	0.04		0	0.00	
	No cover	5	0.00		75	0.05		18	0.02	
Other										
	Exposed peat present	14	0.01	a	169	0.11	b	43	0.04	a
	Surface water present	19	0.02	a	115	0.08	b	4	0.00	a

*mainly *E. vaginatum*

** mainly *Rubus chamaemorus*

Most of the wet (pool, hollow) and the dry (hummock, lower hummock, and bog margin) surface structures showed no significant difference between drained and pristine sites. Only the structure lawn had a significant lower cover of 18% (Table 5, Fig. 6d) in drained bogs compared to 38% in pristine sites (beta = -1.4274 ±0.5267, p= 0.00672, Appendix Table A3). Ditch verge and forest had low abundance and were unfit for modelling. Forest had a higher mean proportion in drained sites (15%) while being absent in pristine. The difference between rewetted and drained sites is limited to a higher abundance of pools than in the pristine sites (beta=1.4946 ±0.3454, p<0.001; Appendix Table A3). Equally, exposed peat and surface water also stands out as significantly higher in rewetted than pristine sites (Fig. 6b-c). Both displayed a low presence in pristine (<4%) and drained bogs (<2%). There was no significant difference in abundance of any other surface structure between rewetted and drained sites.

The bottom layer of drained bogs had less *Sphagnum*, and a higher proportion of other mosses, lichen, and litter, compared to pristine sites (Fig. 6e-h). There was no significant difference between rewetted and drained sites for *Sphagnum*, other mosses, lichen, or litter. The mean cover of sphagnum was 69% in drained, 65 % in rewetted and 94% in pristine sites (Table 5). Lichen had a low occurrence in the sample transects across treatments, but occupied significantly larger proportion of the rewetted sites than the pristine. Litter covered 1% in pristine sites and significantly higher in rewetted sites (15%, Table 5).

Of the eleven species in the field level, three were not fit for modelling (*V. vitis-idaea, V. myrtillus and V. uloginosum)* and none of the other showed a significant difference between rewetted and drained. Drained bogs had significantly less other Cyperaceae (mean cover of 2%, table 5) and 4% *A. polifolia* (Bog-rosemary) than pristine sites with respectively 19% and 9% (Fig. 6i-j). The unmodeled *Vaccinium* species were absent in pristine sites and occurred infrequently in drained and rewetted bogs (Fig. 6k). Other Cyperaceae (Sedges) covered significantly less of rewetted sites (8%) than in pristine ones (19%). *Oxycoccus* was the only taxon occurring significantly more frequently in rewetted compared to pristine sites (Fig 6l).

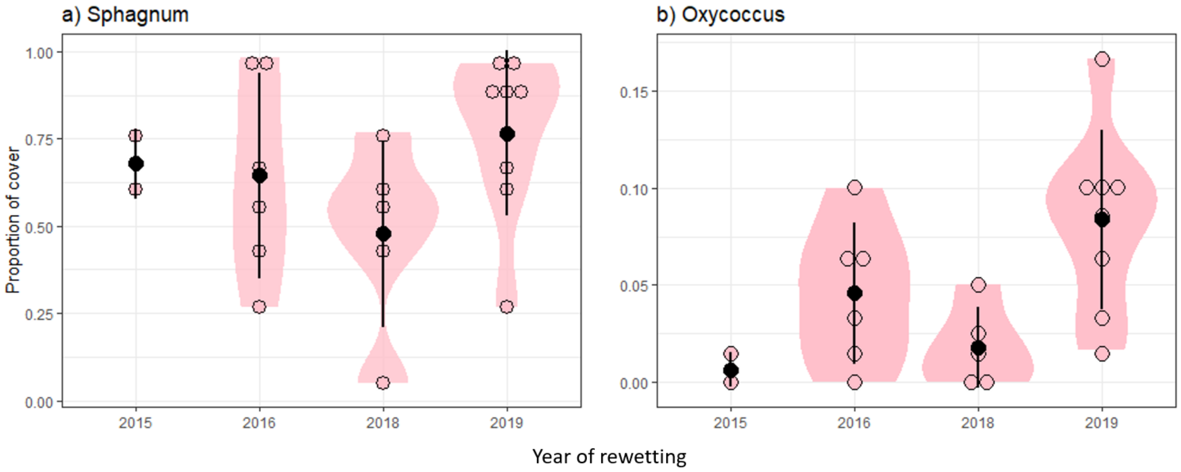

Fig. 5. Proportion of cover of a) *Sphagnum* spp. and b) *Oxycoccus* spp. by year of rewetting, pooled over all eight locations. Mean and standard deviation as solid black dot and bars. Background: Unfilled dots represent mean of individual transects (n = 21) and coloured violin plots (mirrored density plot scaled to have equal width). Note that Y-axis differ between the plots. Gaussian GLMM using location as a random factor, and year since rewetting as fixed, show a significant negative effect of year since rewetting for *Oxycoccus* (beta=0.013, ±0.0064, p=0.041). All other variables had no significant effect, similar to *Sphagnum* cover (beta=0.020, ±0.043, p=0.645).

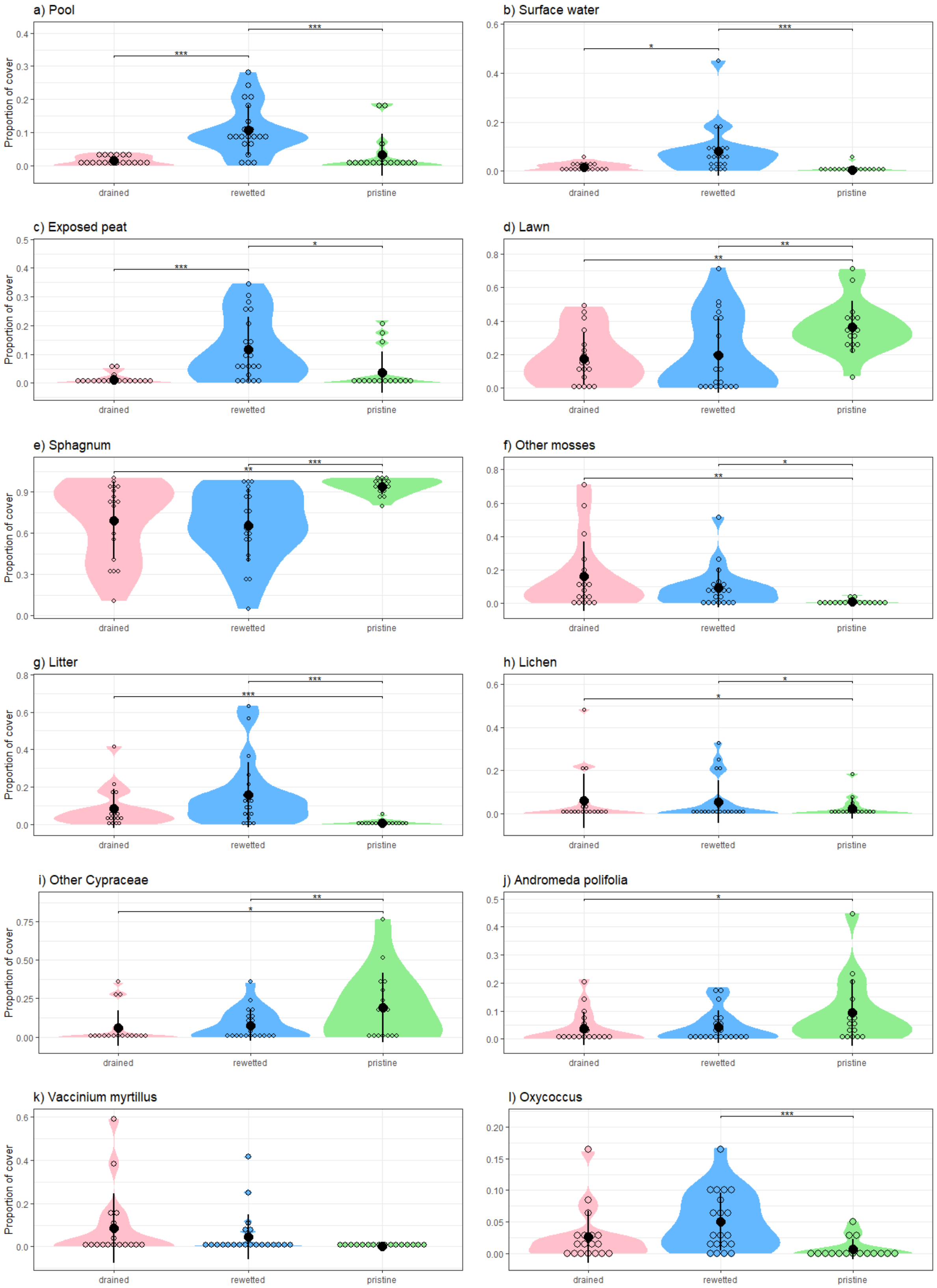

Fig. 6. Proportion of cover of species and surface structures in drained, rewetted and pristine sites, pooled over all eight locations. Mean and standard deviation as solid black dot and bars. Background: Unfilled dots represent mean of individual transects (n = 55), and coloured violin plots (mirrored density plot scaled to have equal width). Level of significance comparing the effects of treatments are GLMM results reported in Table A3. Note that Y-axis differs between the plots. Only vegetation variables with the most important patterns for treatments responses are presented, plots of all variables are presented in Appendix Fig. A1.

Discussion

The composition of the vegetation variables differed between treatments. Between drained and the rewetted sites, only the surface structure pools, presence of surface water and exposed peat differed. Neither a significant increase in *Sphagnum*, *Eriophorum* (Cottongrass), *T. cespitosum* (Deergrass), or other Cyperaceae, nor a decrease of other mosses, lichen, or *C. vulgaris* (Common heather) was seen between rewetted and drained sites. *Oxycoccus* appears to be the only mire species that showed a significant positive response to rewetting. These results support the hypothesis that the gradient in *short-term human disturbance* is the main source of vegetation change at this point, rather than changes in environmental conditions of *wet-dry* and *mire margin-expanse* gradients (Halvorsen, 2015; Halvorsen et al., 2016).

The following discussion will start by comparing drained and pristine sites, discuss the expected speed of recovery, and then compare drained and rewetted sites. The final part will discuss implications of these findings for the further management, monitoring, and planning of rewetting in Norway, touching on: the shift of drained mires to afforested peatlands; intensity of drainage; and a brief note on a potential conflict with outdoor recreation. I will compare my results with relevant studies of degraded and restored bogs. Many studies in North America and Europe focus on former sites of peat excavation (see discussion in (Komulainen et al., 1999). The following discussion will mainly include Finnish studies of bogs drained by ditches for forestry, perhaps more relevant for the results of my study.

Before assessing the effect of rewetting, it is relevant to know the initial difference between the drained sites and the target pristine state. The drained bogs in this study displayed an expected difference in the bottom layer, with less *Sphagnum* and lawns, and more lichen, other mosses, and litter. The change in the bottom layer indicates drier conditions from the lowered water table, as observed in other studies of drained sites (Haapalehto et al., 2011; Jukaine et al., 1995; Punttila et al., 2016). Similarly, changes in the field layer of drained bogs showed an emergence of forest species of genus *Vaccinium*, while mire specialist *A. polifolia* and other Cyperaceae[7] had diminished, as reported elsewhere (Aapala et al., 2014). However, not all species followed this expected pattern; neither *C. vulgaris*, *Eriophorum* spp. nor *T. cespitosum* differed between drained and pristine sites in my results. The parallel study by Johansen (2021), using a point-intercept method for data collection, did however report lower *T. cespitosum* cover in drained than pristine. The result found by Johansen (2021) fits the expectations of *T. cespitosum* not being favoured by drainage, and show how different methods of sampling can yield different results from the same locations.

The composition of surface structures between drained and pristine sites differed less than expected. A study by Punttila et al. (2016), with similar design as my study, used different categories of surface structures, but reported an increase from 46% to 97% hummock cover from pristine to drained bogs. The current study found no significant change in cover of hummocks, lower hummocks or mire margins. Only the wetter structure, lawns, showed a significant decrease in drained sites, an expected response towards dryer surface structures. The reduction of lawn structures along with changes in the bottom layer indicate that drainage has clearly changed the bogs from their pristine state.

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[7] excluding *T. cespitosum* and *Eriophorum* spp.

The degree of change, from pristine to drained, does however seem to be less than Punttila et al. (2016) found for *Sphagnum* cover. While Punttila et al. (2016) reported of similar high (about 90%) mean Sphagnum cover for pristine sites, they observed a cover as low as 30% in drained sites. Haapalehto et al. (2011) reports even lower Sphagnum coverage of 20% in a drained bog, which only increased to 50% cover ten years after rewetting. These low *Sphagnum* covers is less than the mean cover of drained sites of 69%, found in my study (table 5). Part of the difference, between my results and the two mentioned above, could relate to methods of data collection: Punttila et al. (2016) did not report that their transects crossed ditches, and Haapalehto et al. (2011) specifically sampled between ditches. Crossing wet ditches will have increased my observed *Sphagnum* cover to a certain degree. The wet conditions of the bottom of the ditch are however limited to a cross section of a few meters, where *Sphagnum* can dominate. Continuing up, onto the ditch verge, and outwards; the distance to the water table is high and decreasing. Similarly, *Sphagnum* increases further away from the ditch[8] (Paal et al., 2016). Sampling methods are therefore not the likely answer to my high abundance of *Sphagnum* in drained sites. A more plausible explanatory variable is the intensity of ditching, which is known to correlate with vegetation changes following drainage (Aapala et al., 2014). Intensity of ditching is not reported in this study, nor by Haapalehto et al. (2011) or Punttila et al. (2016). The varying degree of drainage could possibly be the explanation to the differences in *Sphagnum* coverage.

The speed of recovery after rewetting bogs is generally described as “slow”, occurring over decades (Aapala et al., 2014). Although several studies report changes within the first years of rewetting, the response in changing plant communities is usually faster in fens than bogs (Haapalehto et al., 2011; Jukaine et al., 1995; Komulainen et al., 1999). Bog vegetation has fewer species, and access to less nutrients and is generally dominated by dryer surface conditions. Ombrotrophic species are also more resilient to drainage (Laine et al., 2011) while minerotrophic species are prune to disappear entirely (Hedberg et al., 2012). This is thought to be the explanation as to why bog vegetation shows small changes in species composition after drainage (Vasander, 1982). As ombrotrophic bog species are able to endure in wet refugia within ditched bogs, one could expect a rapid colonisation after rewetting. While early post rewetting changes are detectable in bogs, it is fens and more nutrient rich sites that display the strongest response. These differences between fens and bogs are reported by Komulainen et al. (1999) two years after rewetting and by Haapalehto et al. (2011) after ten years. This implies that the natural resilience to hydrological changes in bogs, which is also observed in pristine state over decades (Pedrotti et al., 2014), makes these ecosystems respond slowly to “disturbances”, whether this is connected to drainage or rewetting.

The initial changes of species composition shortly after rewetting reported by several studies is not observed in mine. A study across nine bogs found a desired effect on the bottom layer following the 1-3 first years after rewetting, with more *Sphagnum* and less other mosses, lichen and litter (Punttila et al., 2016). Haapalehto et al. (2011) observed an increase of *E. vaginatum* (Tussock cottongrass) the first 3 years after rewetting in one bog. Furthermore, Haapalehto et al. (2011) also showed that the trend of increasing abundance of mire specialists still occurred ten years after rewetting, and that a “pristine state” was not yet

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[8] Unpublished trend also observed in my data.

reached. Non such changes were found to be significant in my study. Similarly, the comparison of single species between the same drained and rewetted sites by Johansen (2021), fond no difference for all plant species except a decrease of *C. vulgaris*.

While no change in species abundance between rewetted and drained were observed, *Oxycoccus* had a higher abundance in rewetted compared to pristine sites. When analysing the different numbers of years since rewetting between the locations, *Oxycoccus* was also the only taxon found to show a significant trend in time: Although our sampled bogs were few, one can speculate that the species seem to decrease in cover as the years pass after rewetting. This apparent positive correlation with more recent rewettings could imply that *Oxycoccus* is able to exploit newly disturbed bogs, making it peak beyond its populations in "pristine" environments. This fits with *Oxycoccus* being described as having generalist properties occupying a wide range of both the gradients dry-wet and mire expanse-margin (Halvorsen et al., 2016, as summarized in Appendix table A1; Serafin et al., 2018). Johansen (2021) reports no difference in frequency between any treatments for *Oxycoccus*. While cautioned by the contradicting results from parallel study of the same bogs (Johansen, 2021), my results point at *Oxycoccus* as a possible indicator for early vegetation responses after rewetting, which should be examined in future monitoring of rewetted projects.

It was unexpected that no significant difference was observed for any species when comparing the rewetted to the drained sites. The cover of the bottom layer cover, *Sphagnum* included, did not show effects of rewetting. Another indicator of rewetting is genus *Eriophorum,* especially *E. vaginatum*, widely reported to show an early response in fens and bogs alike (Haapalehto et al., 2011; Jauhiainen et al., 2002; Komulainen et al., 1999; Aapala et al., 2014). Such increase of *E. vaginatum* is explained by its generalist nature, being able to survive in a wide range of the dry-wet gradient (Økland, 1992), and its wind spread seeds have the potential to rapidly colonize disturbed peat (Salonen et al., 1992). A "boom" of *E. vaginatum* was observed in one of our sites, rewetted four years ago, "L3 Aurstadmåsan W", where the rewetting method appeared to deviate from the other locations. In this site, long dams of bare peat (not plastered with vegetation) created large pools upstream. However, the overall cover of *Eriophorum* for all eight locations did not differ significantly between any of the treatments. Though all *Eriophorum* species were pooled collectively in our data, most hits were made up of *E. vaginatum*. The lacking response of *Sphagnum* and *Eriophorum* species to rewetting could partly be caused by an initial low drainage intensity, an issue discussed further down. A relatively low intensity of ditching would also be combined with a further reduction of drainage effect, as the absence of ditch maintenance will lead to a gradual infilling (Haapalehto et al., 2011; Laine et al., 2011). The lacking response to the rewetting measures must, however, also be seen in the light of the short time passed since rewetting, and the known slow response time of bog vegetation.

The only detected change following rewetting was an increase in pools, surface water and bare peat. Higher abundance of these surface structures in rewetted compared to drained sites are expected initial effects of rewetting. Excavation of peat for dam material and ditch filling leaves holes, damaged vegetation, and exposes bare peat. The increased water table fill holes creating pools, can submerge living vegetation, and thus lead both to the observed increased of surface water and an expected increase in dead vegetation. Especially hummock species such as *C. vulgaris* who are dependent on aerated substrate supporting mycorrhiza symbiosis (Økland, 1992), will if submerged die and contribute to an increase in litter. While the mean cover of litter in my results was highest in rewetted sites, it did not differ significantly from the drained bogs. Nor was there any reduction in *C. vulgaris* after rewetting in my data, but a reduction was reported by Johansen (2021). The increase in pools, surface water and bare peat, associated with short-term disturbance, leave openings that has the potential to be colonized by the peat forming keystone *Sphagnum* species, though longer timespan than the 1-5 years of this study seems to be needed. The following paragraphs will discuss implications of the findings of my study for management, monitoring and planning of mire restoration. Starting with challenges of defining the extent of mires that is transformed to afforested peatlands over time.

The uncertainty of the historic borders of drained mires poses challenges when locating drained reference sites and positioning sampling transects. Natural succession of mires involves both expansion and forestation of open mire expanses (Zobel, 1988). Both are variations in succession that proceed on a longer timescale than the relatively rapid human manipulation of mire hydrology: drainage and rewetting. Historic aerial photos document how drained mires can be transformed to forest in few decades, completely or partly. Thus, present open expanses on drained mires are most likely small remnants of the pre-ditching pristine mire. Limiting sampling transects to such remnant mire expanses would only gather information on the least affected areas and exclude areas with the most effective ditches. The current study took this uncertainty of the historic borders of drained mires into account by; requiring the presence of recognisable mire expanses for the drained reference sites, but also using the visible network of ditches to estimate the historic mire area. Thus, some transects were also placed partly in forest when ditches continuing from mire expanses into afforested peatland. Four of our transects had more than 40% cover of forest. Three[9] of these transects were confirmed as former unforested mire expanses by historic aerial photos. The last transect[10] was located on a bog already diched on the oldest available aerial photo from 1946, and it is therefore uncertain whether all the ditched area initially was mire or non-wetland forest [No. fastmark]. Having an updated map with historic data of mire’s extent could highlight lost mire area. Such a map would make locating and assessing ineffective drainage (present day mires), as done by this study, easier. It would also allow for locating and surveying effectively drained sites (present day afforested peatlands). This is important as choosing more ineffectively drained reference sites could reduce the degree of difference from pristine sites, compared to more effectively drained references.

Drained mires that are presently still recognizable as open mires are relatively ineffectively drained, while appear to be the main focus of the current rewetting program. A prerequisite for the ongoing mire restoration in Norway is that the rewetting projects are not in conflict with agricultural and forestry interests (Miljødirektoratet, 2021), which afforested peatlands could be. This prerequisite is one of several reasons that most of the rewetted peatlands as of today are drained mires within nature reserves. Most of these peatlands are also still relatively well-functioning mires, and have been protected as reserves because of their ecological value, despite being drained (Nordbakken & Økland, 2004). As the national mire restoration program, up until recently, were restricted to mainly nature reserves, and this study is limited to these relatively inefficiently drained mires; one has excluded some of the mires most strongly affected by drainage. Therefore, the difference between both drained and pristine and drained-rewetted sites is likely less than had otherwise been the case if drained mires outside

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[9] 1 of 2 transects in L10B Starrmåsan and 2 of 2 in L11 Skullerudmåsan W

[10] 1 of 3 in L4 W of Lomtjern

nature reserves were included. Such a smaller difference between drained and pristine sites could also partly explain the higher *Sphagnum* cover in my study compared to Finnish studies.

The intensity of ditching is mentioned as an unreported, but potential explanation of the relative low difference between drained and rewetted sites in my study. Studies that have reported this, like Komulainen et al. (1999) report both year of ditching, spacing and depth. Further quantification of intensity of ditching could be specified by estimating distance ditched per area of the individual mire. Along with a measure of drainage success (e.g., degree/area of afforestation/transformation to dry land), intensity of ditching should be considered in future studies as well as criterions when selecting new restoration sites.

The potential conflicts between outdoor recreation [No. friluftsliv] and mire rewetting was observed during fieldwork, even if was not a focus of this study. Both in systematic sampling and anecdotal observations did we experience a higher concentration of paths and human traffic in drained and rewetted bogs. The constructed dams were noted to attract paths, as both people and wildlife seem to prefer walking on these dryer “bridges” in the surrounding rewetted mire. This traffic can wear on the protective and recovering plastered vegetation, and on the peat dam itself. Breaking of dams in the first years after restoration is a concern mentioned by Haapalehto et al. (2011). If dams break, before the accumulation of sediments and permanent changes in the surrounding mire have restored its ability to retain water, the rewetting effect will be reversed. It is therefore important to take local outdoor recreation into account in connection with rewetting, as mentioned briefly in the 6th appendix of the national Wetland Restoration Plan (Miljødirektoratet, 2021). The usage of board walkways is one such possible measure to protect vegetation and peat dams, which also can be used to direct traffic and compensate existing tracks flooded by rewetting. Though harbouring potential conflicts, rewetting bogs along popular hiking tracks also provide great potential for public education; an important tool to gain both support, and understanding for the need of restoration projects (Soga & Gaston, 2018).

Conclusion

Comparing drained, rewetted and pristine bogs in eight locations in South-eastern Norway, 1-5 years after rewetting, show little response in vegetation following rewetting. The only significant changes after rewetting found in my study were increased pools, surface water and exposed peat, which is attributed to the disturbance of the terrain part of the rewetting activity. Drained sites differed from pristine references in bottom layer, and presence of forest and forest-affiliated species. The difference from drained to pristine sites differed less than expected, particularly in the field layer and surface structures. The explanation for the relatively small difference between the treatments is suggested to be too little time passed since rewetting and possibly a lower ditching intensity than used in similar studies showing faster responses.

This study proposes *Oxycoccus* as a potential rapid colonizer in Norwegian bogs following rewetting. My results, along with Scandinavian studies, indicate that restoration is a slow attempt to reverse damage to bog systems, also in Norway. The most efficient way to gain peat accumulating *Sphagnum* covers, and functioning bog ecosystems, is to prevent initial drainage and degradation of existing mires. Attempts at restoration need patience and long-term monitoring, like the 5 years cycles of resurveying proposed by Hagen et al. (2015), to observe whether desired goals of vegetation recovery will be met.

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Appendices

Table A1. Species and surface structures (column “vegetation variable”) categorized along the two gradients “dry-wet” and “mire expanse - mire margin”. The variables are categorized according to what extreme of the gradient they are specialized or whether they are generalists found across most of the gradient. This categorization is a simplification of the tables of species distributions along gradients in the “Nature Types in Norway” [No. Natur i Norge] (NiN) classification system by Halvorsen et al. (2016)”. The dry-wet gradient is divided in categories “dry”, “generalist” and “wet”. The mire expanse-mire margin gradient is divided in categories “expanse”, “generalist”, “margin” and “forest” (meaning favouring non-wetland ground [No. fastmark]). The designated category of groups of species is a generalization based on overall taxa preferences (eg. Sphagnum placed as “wet” even if there exist hummock specialized species) or most abundant species recorded within the group (eg. *Eriophrum* placed as “generalist” because of *E. vaginatum*). Non-species variables (litter, surface structures) have been categorized based solely on the authors opinion.

Vegetation layer	**Vegetation variable**	**Predicted favoured by drainage**	**Mire expanse - mire margin gradient**	**Dry-wet gradient**
Structure	Pool	no	expanse	wet
	Hollow	no	expanse	wet
	Lawn	no	expanse	wet
	Lower hummock	no	expanse	dry
	Hummock	yes	margin	dry
	Bog margin	yes	margin	dry
	Forest	yes	forest	dry
	Ditch verge	yes	forest	dry
Bottom	*Sphagnum spp.*	no	expanse	wet
	Other mosses	yes	forest	dry
	Litter	yes	forest	dry
	Lichen	yes	forest	dry
Field	*Eriophorum* spp.	no	generalist	generalist
	Other Cyperaceae	no	expanse	wet
	Trichophorum cespitosum	no	expanse	generalist
	Andromeda polifolia	no	generalist	generalist
	Oxycoccus spp.	no	generalist	generalist
	Caluna vulgaris	yes	generalist	dry
	Other herbs	yes	generalist	dry
	Empetrum nigrum	yes	forest	dry
	Vaccinium vitis-idaea	yes	forest	dry
	Vaccinium myrtillus	yes	forest	dry
	Vaccinium uliginosum	yes	margin	dry
Other	Exposed peat present	yes	NA	NA
	Surface water present	no	expanse	wet

Table A2. Individual transects and their start and end coordinates, with corresponding location, site and treatment. Coordinates (°N, °E) given for reference system Euref89 UTM32. Coordinates obtained using mobile phone Global Navigation Satellite System. The precision does not allow for accurate replication of transects, but an approximation of the transects position within the site.

Location		**Site**	**Treatment**	**Transect ID**	**Start coordinate**	**End coordinate**
L1	Sakkhusmåsan	Sakkhusmåsan	rewetted	L1-R1	NA	NA
L1	Sakkhusmåsan	Sakkhusmåsan	rewetted	L1-R2	NA	NA
L1	Sakkhusmåsan	Villpostmåsan	drained	L1-G2	NA	NA
L1	Sakkhusmåsan	Villpostmåsan	drained	L1-G1	NA	NA
L1	Sakkhusmåsan	Sakkhusmåsan	pristine	L1-UG2	NA	NA
L3	Aurstadmåsan	Aurstadmåsan S	rewetted	L3-R1	60.184123, 011.344876	60.183992, 011.345316
L3	Aurstadmåsan	Aurstadmåsan S	rewetted	L3-R2	60.184310, 11.345163	60.184033, 11.345714
L3	Aurstadmåsan	Aurstadmåsan S	rewetted	L3-R3	60.184747, 11.345993	60.184564, 11.346231
L3	Aurstadmåsan	Flakstadmåsan	drained	L3-G1	60.171479, 011.331894	60.171727, 011.331401
L3	Aurstadmåsan	Flakstadmåsan	drained	L3-G2	60.172084, 11.331314	60.172276, 11.330755
L3	Aurstadmåsan	Aurstadmåsan W	pristine	L3-UG1	60.187327, 11.338902	60.187243, 11.339584
L3	Aurstadmåsan	Aurstadmåsan W	pristine	L3-UG2	60.186347, 011.339158	60.186458, 011.339695
L4	Romsmåsan	Romsmåsan	rewetted	L4-R1	59.984939, 010.884198	59.984648, 010.884866
L4	Romsmåsan	Romsmåsan	rewetted	L4-R2	59.985788, 10.884853	59.985604, 10.885044
L4	Romsmåsan	Romsmåsan	rewetted	L4-R3	010.884866, 010.883867	59.986550, 010.883281
L4	Romsmåsan	S of Rudspytten	pristine	L4-UG2.1	60.002778, 10.866177	60.002483, 10.865991
L4	Romsmåsan	S of Rudspytten	pristine	L4-UG2.2	60.002262, 010.865284	60.001937, 010.865265
L4	Romsmåsan	W of Lomtjern	drained	L4-G1	59.995716, 010.878654	59.995997, 010.879023
L4	Romsmåsan	W of Lomtjern	drained	L4-G2	59.995528, 010.879252	59.995490, 010.878619
L4	Romsmåsan	W of Lomtjern	drained	L4-G3	59.9956260, 10.8784050	59.995845, 10.878112
L6	Midtfjellmåsan	E of Langtjern	rewetted	L6-R1	59.951259, 11.683414	59.951051, 11.683250
L6	Midtfjellmåsan	E of Langtjern	rewetted	L6-R2	59.952038, 11.684221	59.552390, 11.684169
L6	Midtfjellmåsan	E of Langtjern	rewetted	L6-R3	59.951468, 11.683991	59.951088, 11.683943
L6	Midtfjellmåsan	Tjennshaugmåsan SW	drained	L6-G1	59.943129, 011.666755	59.942990, 011.667168
L6	Midtfjellmåsan	Tjennshaugmåsan SW	drained	L6-G2	59.942762, 11.666706	59.942634, 11.667116
L6	Midtfjellmåsan	E of Vintertjern	pristine	L6-UG1	59.954480, 011.693798	59.954560, 011.694292

Table A2, continuing.

Location		**Site**	**Treatment**	**Transect ID**	**Start coordinate**	**End coordinate**
L6	Midtfjellmåsan	E of Vintertjern	pristine	L6-UG2	59.956377, 11.694040	59.956244, 11.693661
L6	Midtfjellmåsan	E of Vintertjern	pristine	L6-UG3	59.953558, 11.693544	59.953306, 11.693109
L8	Veggermyra	Veggermyra S	rewetted	L8-R1	59.310722, 10.095210	59.310617, 10.094638
L8	Veggermyra	Veggermyra S	rewetted	L8-R2	59.310459, 10.095234	59.310458, 10.094755
L8	Veggermyra	Strandemyra	drained	L8-G1	59.312039, 10.075883	59.312339, 10.07591
L8	Veggermyra	Strandemyra	drained	L8-G2	59.312414, 10.076747	59.31269, 10.076925
L8	Veggermyra	Veggermyra N	pristine	L8-UG1	59.312025, 10.094633	59.311932, 10.095396
L8	Veggermyra	Veggermyra N	pristine	L8-UG2	59.312412, 10.094548	59.312454, 10.095371
L10	Fjøsmåsan	Fjøsmåsan	rewetted	L10-R1	59.832232, 10.92219	59.832119, 10.921381
L10	Fjøsmåsan	Fjøsmåsan	rewetted	L10-R2	59.831976, 10.921609	NA
L10	Fjøsmåsan	S of Rulleåsene	pristine	L10-UG1	59.844451, 10.913008	59.844333, 10.913040
L10	Fjøsmåsan	Eiriksvannmåsan	rewetted	L10-G1	59.846195, 10.943072	59.846099, 010.942654
L10	Fjøsmåsan	Eiriksvannmåsan	rewetted	L10-G2	59.845864, 10.943277	59.845777, 10.942474
L10	Fjøsmåsan	Eiriksvannmåsan	rewetted	L10-G3	59.845462, 10.943258	59.845479, 10.942867
L10B	Eiriksvannmåsan	Eiriksvannmåsan	rewetted	L10B-R1	59.832735, 10.927911	59.83266, 10.928436
L10B	Eiriksvannmåsan	Eiriksvannmåsan	rewetted	L10B-R2	59.833271, 010.927866	59.833231, 010.928497
L10B	Eiriksvannmåsan	Eiriksvannmåsan	rewetted	L10B-R3	59.833092, 10.927152	59.833092, 10.927152E
L10B	Eiriksvannmåsan	Stormyr	pristine	L10B-UG1	NA	59.819710, 10.927989
L10B	Eiriksvannmåsan	Stormyr	pristine	L10B-UG2	59.820382, 10.927771	59.820552, 10.9284848
L10B	Eiriksvannmåsan	Starrmåsan	drained	L10B-G1	59.823055, 010.932512	NA
L10B	Eiriksvannmåsan	Starrmåsan	drained	L10B-G2	NA, 10.931729	59.822257, 010.932082
L11	Øgårdsmåsan	Skullerudmåsan W	drained	L11-G1	NA	NA
L11	Øgårdsmåsan	Skullerudmåsan W	drained	L11-G2	NA	NA
L11	Øgårdsmåsan	Skullerudmåsan S	pristine	L11-UG1	59.860759, 010.860219	59.860597, 010.859931
L11	Øgårdsmåsan	Skullerudmåsan S	pristine	L11-UG2	59.860866, 010.860514	59.860643, 010.860388
L11	Øgårdsmåsan	Øgårdsmåsan	rewetted	L11-R1	59.865237, 010.893689	59.865237, 010.894416
L11	Øgårdsmåsan	Øgårdsmåsan	rewetted	L11-R2	59.8657413, 10.8928119	59.865556, 10.893087
L11	Øgårdsmåsan	Øgårdsmåsan	rewetted	L11-R3	59.865822, 010.893612	59.865763, 010.894277

Table A3. General linear mixed model for proportion of cover for species and surface structures. Treatment (drained, rewetted, pristine) as fixed factor with sites nested within locations as random factor. Model estimates and standard error (SE) is given for the comparison of all three treatment levels. P-values indicated '***'<0.001, '**'<0.01, '*'<0.05, '.' 0.1. Models marked with "zi" have included zero inflation (ziformula=~1) to achieve normality of model residuals. Continues on next page.

Vegetation layer	**Vegetation variable**	**Comparison**	**Estimate**	**SE**	**P-value**		
Structure	Pool	drained-pristine	0.1743	0.3722	0.6400		
		rewetted-pristine	1.4946	0.3454	0.0000	***	
		rewetted-drained	476278	0.3397	0.0001	***	
	Hollow	drained-pristine	-0.4023	0.3571	0.2600		zi
		rewetted-pristine	0.2195	0.3305	0.5070		zi
		rewetted-drained	0.6218	0.3576	0.0821	.	zi
	Lawn	drained-pristine	-1.4274	0.5267	0.0070	**	
		rewetted-pristine	-1.5457	0.5205	0.0030	**	
		rewetted-drained	-0.1183	0.5202	0.8201		
	Lower hummock	drained-pristine	-0.26133	0.3803	0.4919		
		rewetted-pristine	-0.03849	0.3732	0.9179		
		rewetted-drained	0.2228	0.3697	0.5466		
	Hummock	drained-pristine	0.16772	0.3878	0.6650		
		rewetted-pristine	0.00534	0.3845	0.9890		
		rewetted-drained	-0.1624	0.3628	0.6550		
	Bog margin	drained-pristine	-0.7995	0.8183	0.3290		zi
		rewetted-pristine	-0.5942	0.8302	0.4740		zi
		rewetted-drained	0.2054	0.3770	0.5860		zi
	Forest		*data unfit for modelling*				
	Ditch verge		*data unfit for modelling*				
Bottom	*Sphagnum* spp.	drained-pristine	-1.3843	0.4429	0.0018	**	
		rewetted-pristine	-1.5033	0.4343	0.0005	***	
		rewetted-drained	-0.1190	0.3697	0.7476		
	Other mosses	drained-pristine	1.4999	0.5002	0.0027	**	
		rewetted-pristine	1.0076	0.4702	0.0321	*	
		rewetted-drained	-0.4923	0.4468	0.2706		
	Lichen	drained-pristine	0.8582	0.4291	0.0455	*	zi
		rewetted-pristine	0.8647	0.3764	0.0216	*	zi
		rewetted-drained	0.0065	0.3570	0.9855		zi
	Litter	drained-pristine	1.4569	0.3887	0.0000	***	
		rewetted-pristine	1.8201	0.3887	0.0000	***	
		rewetted-drained	0.3631	0.3319	0.2740		
Field	*Eriophorum* spp.	drained-pristine	-0.0137	0.3604	0.9700		
		rewetted-pristine	0.1382	0.3519	0.6950		
		rewetted-drained	0.1518	0.3484	0.6630		
	Other Cyperaceae	drained-pristine	-1.0625	0.4139	0.0103	*	zi
		rewetted-pristine	-1.0983	0.3476	0.0016	**	zi
		rewetted-drained	-0.0358	0.4198	0.9321		zi

Table A3, continuing.

Vegetation layer	**Vegetation variable**	**Comparison**	**Estimate**	**SE**	**P-value**		
Field	*T. cespitosum*	drained-pristine	-0.0119	0.3674	0.9740		zi
		rewetted-pristine	-0.1590	0.3741	0.6710		zi
		rewetted-drained	-0.1296	0.3268	0.6920		zi
	A. polifolia	drained-pristine	-0.7404	0.3484	0.0336	*	
		rewetted-pristine	-0.4830	0.3348	0.1491		
		rewetted-drained	0.2574	0.3257	0.4293		
	Oxycoccus spp.	drained-pristine	0.5858	0.3430	0.0877	.	
		rewetted-pristine	1.1502	0.3323	0.0005	***	
		rewetted-drained	0.5644	0.3153	0.0734	.	
	C. vulgaris	drained-pristine	0.1083	0.4095	0.7914		
		rewetted-pristine	0.0798	0.4032	0.8431		
		rewetted-drained	-0.0285	0.3915	0.9420		
	Other herbs	drained-pristine	0.3407	0.4790	0.4770		
		rewetted-pristine	0.3797	0.4708	0.4200		
		rewetted-drained	0.0391	0.4495	0.9310		
	E. nigrum	drained-pristine	-0.2176	0.4285	0.6120		zi
		rewetted-pristine	0.1911	0.4188	0.6480		zi
		rewetted-drained	0.4087	0.3077	0.1840		zi
	V. vitis-idaea		*data unfit for modelling*				
	V. myrtillus		*data unfit for modelling*				
	V. uliginosum		*data unfit for modelling*				
Other	Exposed peat present	drained-pristine	-0.1597	0.3604	0.6576		
		rewetted-pristine	0.9579	0.3848	0.0128	*	
		rewetted-drained	1.1176	0.3753	0.0029	**	
	Surface water present	drained-pristine	0.6981	0.4231	0.098934	.	
		rewetted-pristine	1.70058	0.4387	0.000101	***	
		rewetted-drained	1.0077	0.4003	0.0118	*	

Fig A1 continues onto next page.

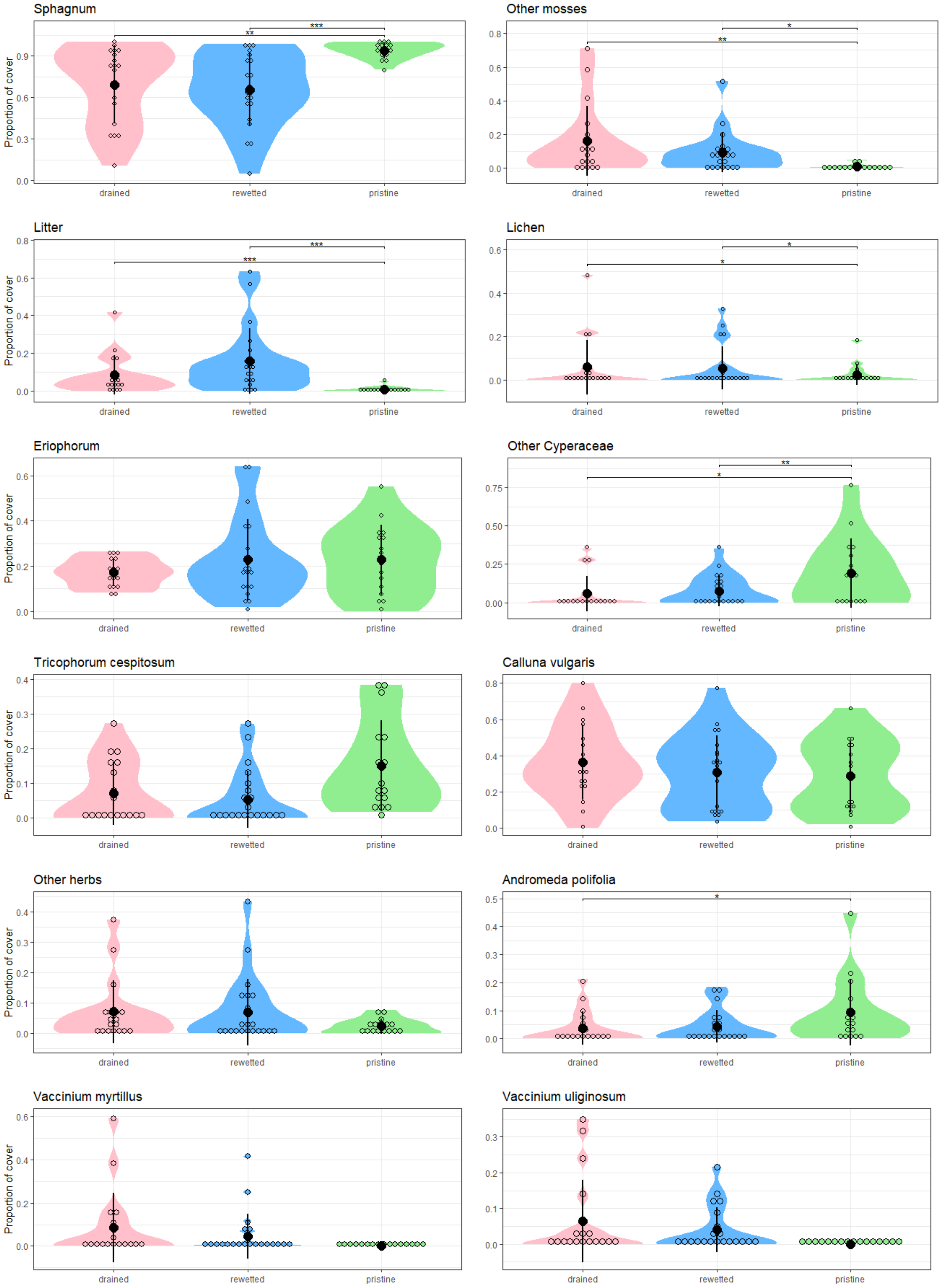

Fig A1, continuing.

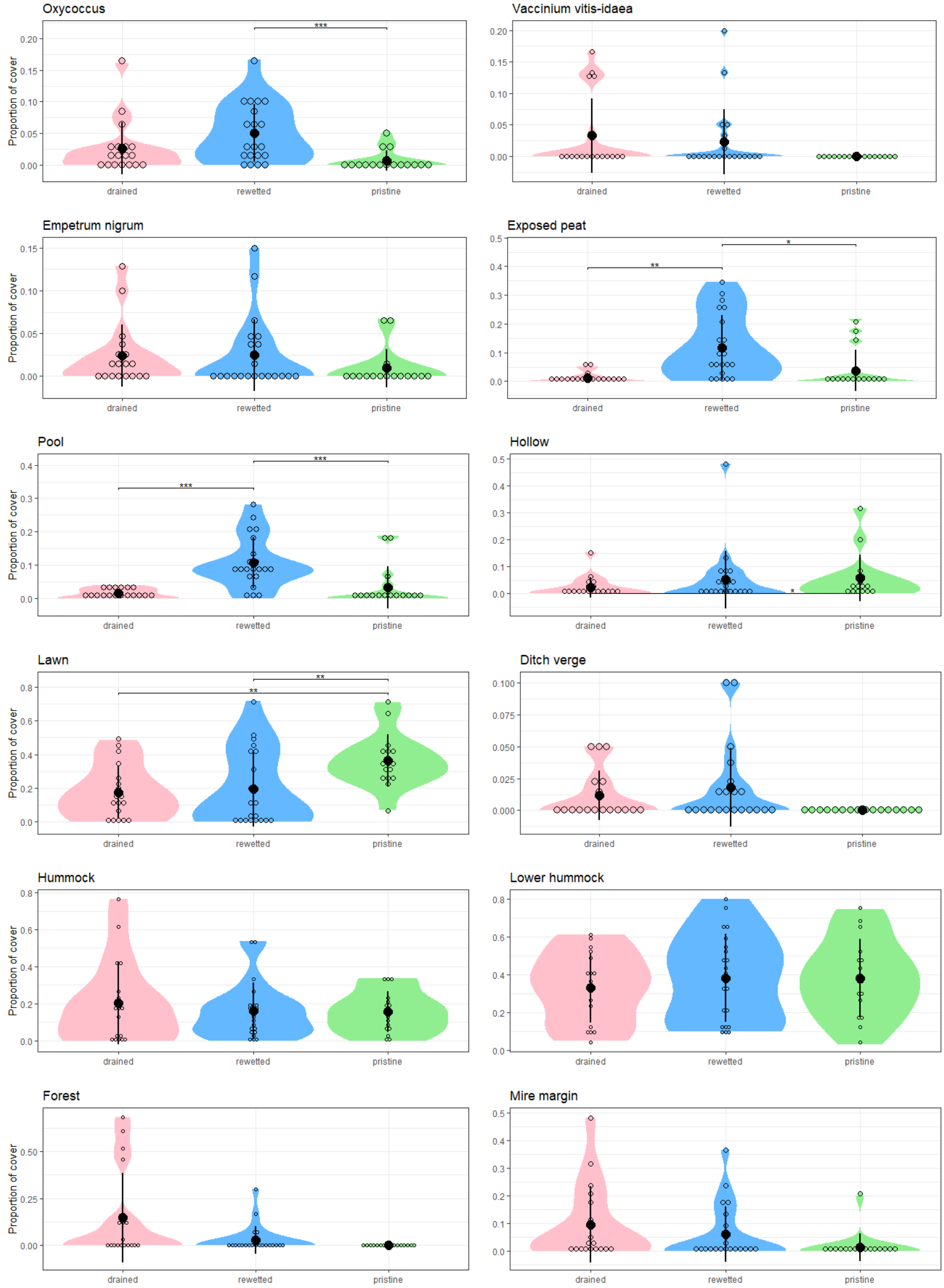

Fig. A1 Proportion of cover for species and surface structures between drained, rewetted and pristine sites, all eight locations. Mean and standard deviation as solid black dot and bars. Background: Unfilled dots represent mean of individual transects (n = 55) and coloured violin plots (mirrored density plot scaled to have equal width). Level of significant comparing sites conditions are GLMM results reported in Table A3. Note that Y-axis differ between the plots. Variable "surface water" is presented in Fig. 6, having similar patterns as pools.

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