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Restoration for the future
WETLANDS
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Recommendations for wetland restoration

Deliverable D1.5

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Short Description
Meta-study of restoration measures and approaches in wetlands during past 40 years in Europe, including citizen science initiatives

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List of Acronyms and Abbreviations

CLC	Corine Land Cover
CLMS	Copernicus Land Monitoring Service
EEA	European Environmental Agency
GIS	Geographical Information System
GHG	Greenhouse Gas
HPZ	Hydrological Protection Zone
IUCN	International Union for Conservation of Nature
LULC	Land Use Land Cover

Executive Summary

This deliverable synthesizes past peatland restoration projects, analysing their goals, methodologies, and outcomes. A comprehensive database was developed from various sources, focusing on European peatlands. The study explores restoration goals, wetland types, restoration measures, monitoring variables, and stakeholder engagement.

The report evaluates restoration success, highlighting factors like water level restoration, vegetation recovery, and peat formation. Challenges include varying restoration effectiveness, the complexity of peatland classification, and the influence of global change. The study emphasizes the importance of long-term monitoring, stakeholder involvement, and standardized restoration practices.

The findings underscore the need for tailored restoration approaches, considering the specific ecological conditions and degradation status of each site. Effective peatland restoration is essential for climate change mitigation, biodiversity conservation, and the preservation of crucial ecosystem services. The deliverable also identifies knowledge gaps and suggests directions for future research and restoration.

1 Introduction

1.1 The ALFAwetlands project

The ALFAwetlands project is an ambitious initiative exploring how wetland restoration can help Europe become climate-neutral and resilient. This project takes an interdisciplinary approach, combining environmental, ecosystem, climate, life, social, and economic sciences to understand and enhance the role of wetlands.

The project's key aims include supporting EU policy on climate change adaptation, mitigation, and biodiversity, while also contributing to the UN Sustainable Development Goals. It strives to improve our understanding of European wetlands by refining methods for projecting greenhouse gas emissions and removals, leading to more accurate reporting. ALFAwetlands also seeks to quantify the benefits of wetland restoration for both climate change mitigation and biodiversity, ultimately encouraging its wider use. The project aims to provide evidence-based insights to help policymakers design more effective wetland strategies and promote best practices in restoration.

As part of its structure, Work Package 1 is specifically focused on enhancing geospatial knowledge of European wetlands, developing crucial data and maps for restoration efforts, with a particular focus on peatlands. This deliverable contributes to WP1's objectives.

1.2 Deliverable goal

This deliverable synthesises past peatland restoration projects compiled from a broad range of sources, e.g., journal articles, project reports, project websites, books and restoration guidelines. Through critical and iterative analyses of these sources, we furthermore developed a comprehensive and in-depth understanding of restoration projects - their goals and objectives, methodology, risks and challenges, outcomes and impact, lessons learned and best practices presented in this deliverable report. Moreover, we draw informed conclusions about the successes, failures, and overall effectiveness of restoration projects in peatlands. All compiled information is stored in a database, which is part of Deliverable 1.6, and will be published on the ALFAwetlands Zenodo[1] community.

The focus of the database are **peatlands and mires** on the European continent. The database is considered an ever-evolving knowledge base that can be continuously updated with additional information or projects not included so far. Chapter 2 of this document discusses the information basis (‘sources’) used to sustain the database. For Chapter 3, we exploited the GIS dataset while exploring the major goals of restoration, the wetland types considered, the restoration measures taken, the monitored variables, stakeholder engagement and citizen science initiatives. In the final chapter, we review the project conclusions and assess how they attribute to define a restoration project as a ‘success’.

[1] https://zenodo.org/communities/alfawetlands/

2 Data collection

2.1 Literature review and GIS database input

An extensive literature and data search was conducted in October and November 2022, focusing on restorative practices over the past 40 years in peatlands and mires on the European continent. A web of knowledge search was performed based on (a combination of) the following terms: peat* (asterisk as "joker" token), wetland, restoration, conservation, failure and success. Abstracts and summaries of the resulting sources were screened in a first round to check their relevance. Relevant articles were stored in a reference manager for full text reading to extract additional criteria like description of restorative practices, monitoring variables and restoration outcomes. Articles that did not contain information about restorative practices were excluded. Relevant articles found after this literature review (2022) were directly incorporated into the database. Several sources can be distinct within the database:

Journal Articles provide in-depth analysis, critical evaluation, and theoretical frameworks related to project management, specific methodologies, or case studies. Their critical peer review ensures the quality and validity of the research. Moreover, journal articles offer broader insights as benchmarks for comparison of various projects.

Project Reports, **Websites and Databases can** provide detailed information for a specific project, its goals and impacts, while focusing on the practicalities of project implementation, challenges, solutions, and lessons learned. They often include quantitative and qualitative data and add information about stakeholder perspectives. These sources can be analysed to assess project performance and success and to validate and refine theoretical concepts and regulatory policies.

Books and Guidelines offer detailed insights into specific project management topics or methodologies, often illustrated with case studies. They aggregate established knowledge, which can be used as reference materials for future restoration project implementation and related research.

We performed a comprehensive review of past wetland restoration projects encompassing 247 distinct sources. Specifically, 173 websites were consulted, consisting of 75 from the IUCN peatland database, 66 from the LIFE public database, 32 project-specific websites maintained by involved partners, and 2 news-oriented websites. Additionally, 44 journal articles, 20 reports, and 15 books or book chapters contributed to the dataset. From this compilation, a total of 721 project sites were identified, with 680 subsequently utilized for analysis in this deliverable. Figure 1 (depicted by pink and yellow squares) illustrates the distribution of these 680 project sites. Further details regarding the database and its attribute tables are provided in D1.6.

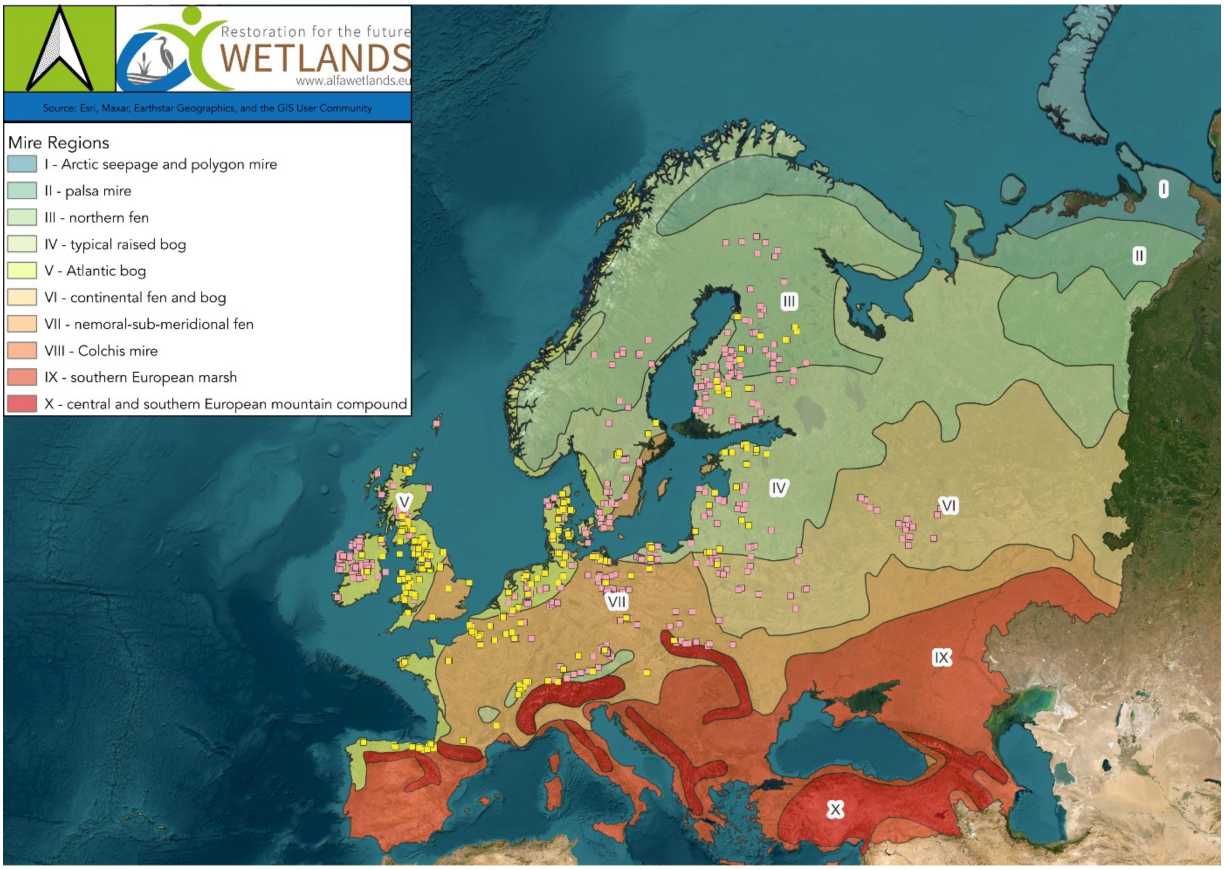

Figure 1. Overview of the project sites (pink + yellow squares) within the past wetland restoration database. Yellow squares indicate the 'core sites' (see below). The European Mire regions (Moen et al.*, 2017; Tanneberger* et al.*, 2021) are shown in the background.*

A project site is defined as a distinct geographical unit where restoration measures can be clearly identified and differentiated. It is identified by a unique project key in the database, starting either with "p" or "RES". Project keys starting with "p" refer to projects that were found through the literature review. Projects starting with project key "RES" are additions from a master thesis inventory performed at the University of Greifswald (Robert Mahara, 2022). Each project site is associated with a GPS point coordinate, sourced either from the original publication or through additional research with the help of maps and toponyms. A visual verification process was conducted to confirm whether the GPS point coordinate accurately represents a location within the restored area or is merely an approximation. Project sites with accurate coordinates were labelled as 'core sites' (yellow dots in Figure 1).

The project sites (red and yellow dots in Figure 1) are distributed across 21 European countries, including 16 EU and 5 non- EU countries. The consulted sources were stored in the past restoration database (D1.6). Each project site has a unique tag to facilitate consultation of the references and metadata tables.

3 Data exploration

3.1 Data processing

From the collected sources on restoration projects (Chapter 2) we extracted and integrated information on peatland type, peatland stress, location, restoration goals, restoration practices, conclusions & lessons learned, monitoring indicators and community involvement. Our insights from these efforts are presented in detail below.

3.2 Restoration goals

An urge for effective management and restoration rises when peatlands move away from their natural baseline (Swindles *et al.*, 2019). Restoration goals must be formulated as concretely as possible and in priority order to provide guidance in case goals conflict with each other (Convention on Wetlands, 2021). This involves understanding the current degradation situation, natural baseline conditions, and potential for recovery (Swindles *et al.*, 2019). Natural baseline conditions function as a reference ecosystem against which short-term and long-term effects of interventions can be understood and defined (Goebel *et al.*, 2005). The careful supervision of the recovery process is essential to assess the effectiveness of the applied measures.

The ‘Restorative Continuum” concept can be used to visualise goals and pathways along the recovery process (see Figure 2 and Box 1, Gann *et al.*, 2019). Additionally, Liu *et al.* (2024) proposed a stepwise framework for improving restoration outcomes based on 4 key characteristics: tailored modes, clear targets, systematic thinking and continuous monitoring. Tailored *restorative modes* can address the unique requirements of a potential restoration site, it’s water supply and its typical biota. *Systematic thinking* considers the entire landscape or watershed while bridging scaling issues of less resilient smaller and fragmented wetland patches. It allows for a more comprehensive understanding of the interrelationships between climate, soil, water, flora, fauna, and human activities. Such integrated approaches to site-related problem-solving and solution development can enhance the overall effectiveness of restoration measures and the project success in terms of the set restoration goals. Furthermore, integrated approaches enable multifunctional wetlands use that cannot be reached at individual wetland level due to trade-offs (Hambäck *et al.*, 2023).

While exploring our compiled database (Chapter 2), we found that **hydrological restoration** as major goal**,** aiming to re-establish baseline hydrological regimes and thus, conserving water, carbon stocks and typical wetland vegetation. Second, **biodiversity conservation** aims to improve conditions for wetland fauna and flora, mainly by controlling land use pressures like erosion, grazing and eutrophication. Recovery towards native vegetation often includes removing invasive species and reintroducing native peat-forming vegetation. **Climate change mitigation** goals focus on the reduction of GHG emissions and the sequestration of carbon and are strongly intertwined with the hydrological and biodiversity goals.

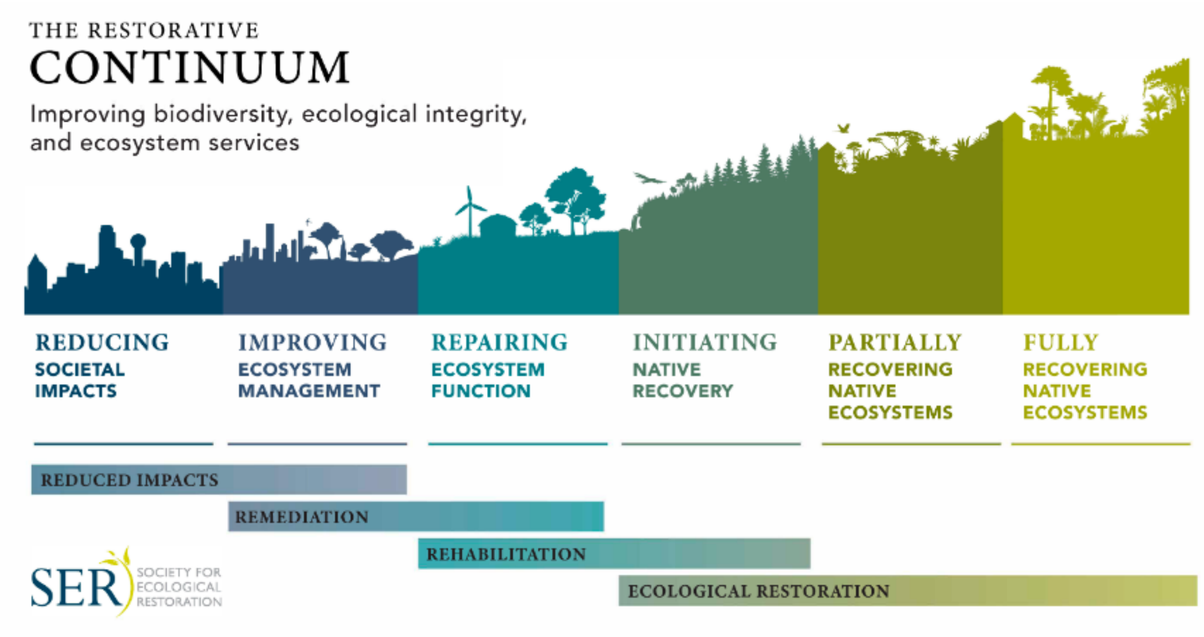

Figure 2. The Restorative Continuum, image taken from (Gann et al.*, 2019).*

Box 1: Restoration practises in a peatland context (after Gann et al. 2019)

Within de restorative continuum (cf. Figure 2), several actions can be taken to recover peatland sites towards native ecosystems. In peatlands, recovering native ecosystem can be very hard or even impossible if sites are heavily degraded and ecosystems irreversibly changed, e.g., in peat properties, nutrient-load, water scarcity through groundwater decline on landscape level, peatland relief and subsidence.

Reducing (societal) impacts and ecosystem consumption would be the first step towards the recovery of ecosystems. To cease peat exploitation or extraction (for horticulture or as fossil fuel) or remove mineral coverages ('Decksand') would be societal impact reducing measures, as well as the reduction of atmospheric nitrogen deposition.

A further step towards ecosystem recovery is **Remediation** - finding solutions to improve ecosystem management and repair its functioning. Examples are the adaption of less intense grazing patterns, fire prevention lanes, removal of deteriorated, nitrogen enriched top soils (highly degraded peat) and removal of exotic species. The most important remediation measure is, however, to eliminate drainage ditches and raising water levels significantly.

Rehabilitation measures further improve ecological site conditions and, thus, overall ecosystem functioning. In peatlands, this can be achieved by stabilizing water levels on surface level, reducing peat erosion, or re-establishing peat forming species. The main goal of rehabilitation is to reinstate a social and ecological resilient peatland ecosystem for renewed or ongoing ecosystem services, weather it is again the native ecosystem or it is different. Rehabilitation can be an intermediate step towards *native recovery* which is the final goal of ecological restoration, especially where native recovery is not possible (often in highly degraded peatlands).

If no further technical, financial, environmental and social barriers occur, further ecological restoration activities can lead to **Recovery towards a native reference ecosystem**. This included attributes like the absence of threats, a native species composition and community structure, appropriate physical conditions and ecosystem function, and external exchanges (eg. genetics). Typical measures on this step are the restoration of native biota and the removal of invasive species.

To arrive at Fully recovered ecosystems in peatlands is sometimes not possible (see above). Moreover, it can require continuous activities as biomass removal and creation of disturbance regimes to support targeted climax vegetation in semi-natural systems. While such measures can also occur in restoration activities, they are not considered as such once full recovery is reached.

In Gann et al. (2019), societal change, remediation and rehabilitation are considered allied activities to ecological restoration since they reduce causes and ongoing effects of degradation, enhance potential for ecosystem recovery, and promote a transition to sustainability. There is a clear interconnectivity between these activities and they often occur simultaneously within restoration frameworks.

3.3 Wetland types

European peatland and mire classification systems are often complex, taking into account a multitude of interacting factors. Fundamentally, peatlands are most commonly distinguished as either fens (sustained mainly by groundwater) or bogs (nourished predominantly by rainwater). Beyond this, further classification can delve into both internal and external characteristics of these unique ecosystems. Internal characteristics describe the internal functioning of the peat system (e.g. water storage and flow), while external characteristics consider the landscape ecological context (e.g. water source, position in the landscape) (Joosten *et al.*, 2017). Table 1 gives an impression of some adjectives and their corresponding classification system used within fen restoration projects. A detailed overview of European peatland types and classification systems can be found in Joosten *et al.*, 2017

In the absence of sufficient supplementary context, harmonization and re-classification from one system to another may not always be feasible. Collating and comparing peatland restoration projects therefor requires certain level of simplification. Crucially, this effort must not diminish the importance of peatland diversity for conservation.

Table 1. Examples of adjectives used together with fens in reports and articles from the database.

adjective	Classification system
(extreme/moderate) rich, minerotrophic, alkaline, calcareous	minerotrophy, acidity
oligotrophic	nutrient status
pine	vegetation
meadow	land use
lagg	topography
pristine, drained	degradation status

While considering the wetland biodiversity gradients across Europe and optimizing our analytical performance, a simplified general classification system of peatland types was used for further analysis. The original peatland description was stored in a separate attribute column of the database. We grouped peatland types into following categories: raised bog, blanket bog, fen, mire (not specified), spruce mire, aapa mire, transition mire and spring mire. Project sites with multiple peatland types were classified as “complex”. The majority of the project sites are raised bogs, followed by blanket bogs and undifferentiated fens (Figure 3).

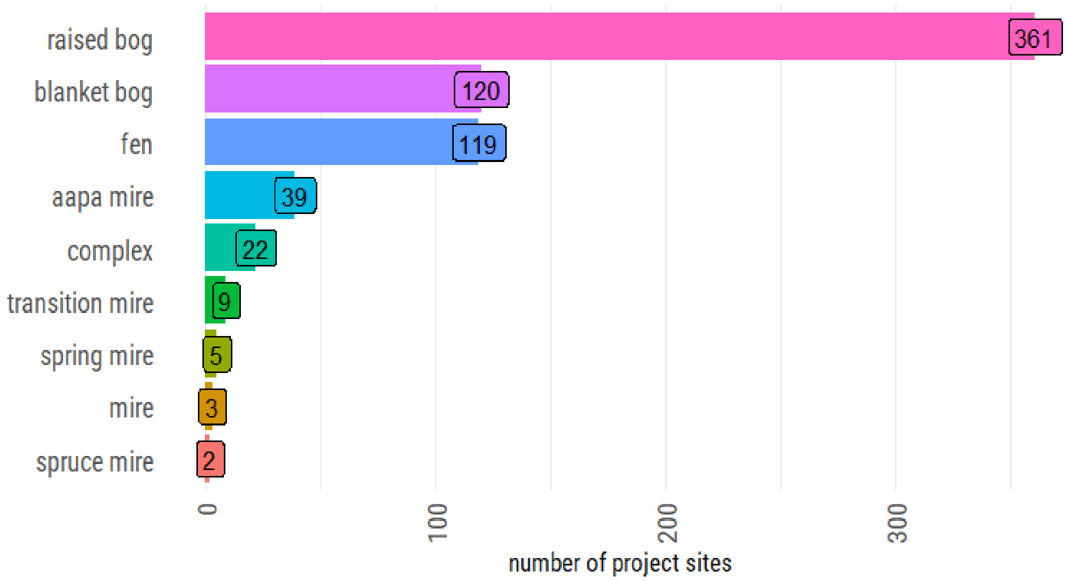

Figure 3. Peatland types (re-classified) in which restoration projects have been implemented.

3.4 Mire region

We identified the mire region for each project site using a simplified version of the European mire regions map (Figure 1, Moen *et al.*, 2017; Tanneberger *et al.*, 2021). No restoration projects were found within the Arctic seepage and polygon mire region (I), palsa mire region (II), Colchis mire region (VIII), southern European marsh region (IX) and central and southern European mountain compound (X).

283 project sites (43%) lie within the Atlantic bog region (V). 145 (21%) in the typical raised bog region (IV), 119 (18%) in the Nemoral-meridional fen region, 69 (10%) in the northern fen region (III), 40 (6%) in the continental fen and bog region (VI). 7 (1%) in the central and southern European mountain region and 3 (<1%) in the southern European marsh region (Figure 4).

3.5 Country

In total twenty-one countries are represented in the database, of which 16 are EU and 5 are non-EU countries (Figure 5). The UK, Finland and Ireland have by far the most restoration project sites (46%) in our database. Eleven EU countries are currently not present in the database: Bulgaria, Croatia, Cyprus, Greece, Italy, Luxembourg, Malta, Portugal, Romania, Slovakia and Slovenia, of which several have no or minor peatlands. The total estimate of European peatland area according to Joosten *et al.*, 2017 is given in Annex 1. Romania and Norway, two countries with significant peatland areas of respectively 7,690 and 44,700 km² are missing in the database.

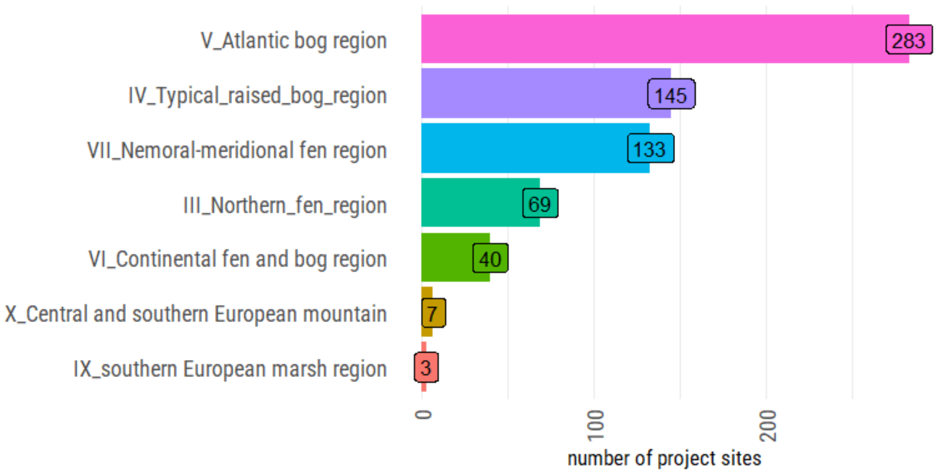

Figure 4. European Mire Regions (Moen et al. 2017, Tanneberger et al.*, 2021) in which restoration projects have been implemented.*

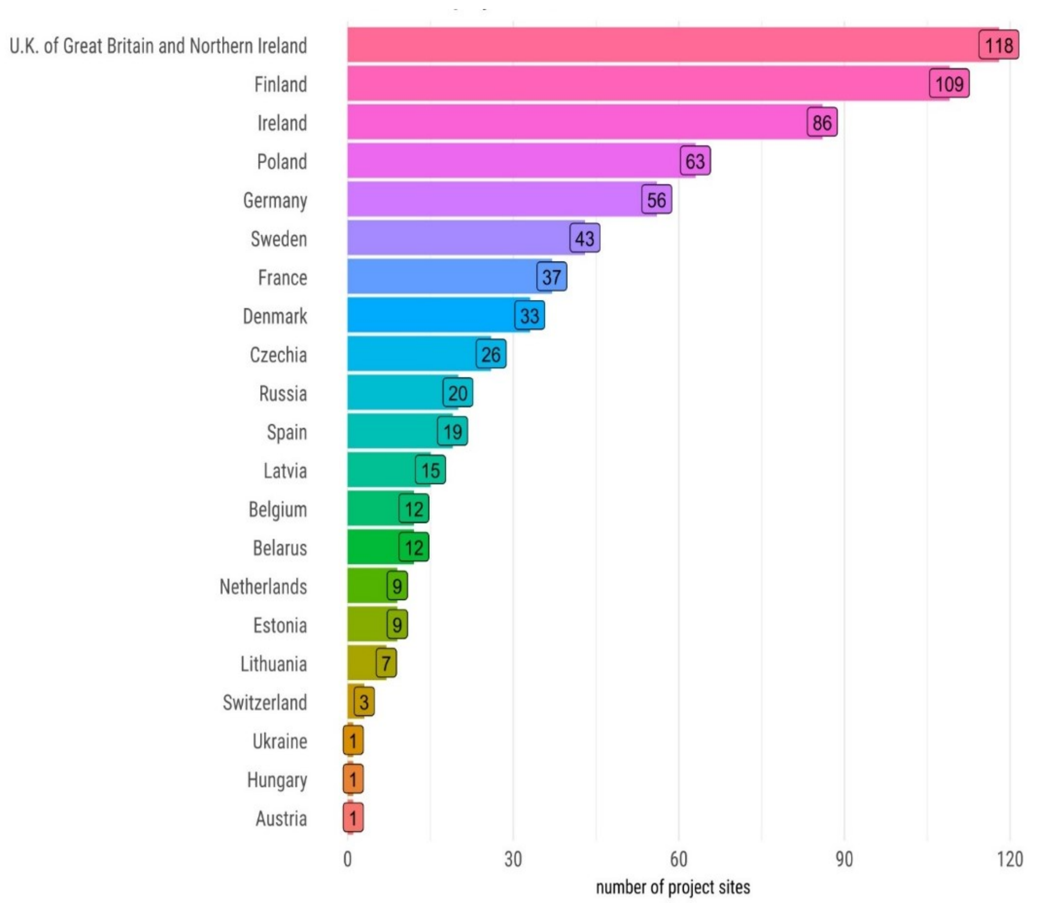

Figure 5. Countries in which restoration projects have been implemented. The number of projects included in the database is given in a box for each country.

3.6 Stress and peat deterioration

In this study, stress refers to any factor that has degraded the natural characteristics of peat, water supply, and vegetation at peatland restoration sites. It's common for a single project site to experience multiple types of stress as they relate to each other (for instance drainage and agriculture). We've categorized these into 10 main groups: agriculture, forestry, peat extraction, drainage, erosion, fire, livestock, overgrowing and (nutrient) enrichment. Stress types with low occurrence ($\leqslant$ 5) were categorised as “other”. Figure 7 summarizes the occurrence of various stress categories within each country.

Drainage stands out as a primary cause of degradation, identified in 91% of the project sites (616 locations, Figure 6 (1)). Other substantial contributors include forestry (300 sites, Figure 6 (2)), agriculture (256 sites, Figure 6 (4)), and peat extraction (255 sites, Figure 6 (3)). While forestry-related stress is prevalent in northern European countries such as Ireland, Denmark, Finland, and Sweden, peat extraction and agriculture pose more widespread challenges across the entire European region. Issues stemming from inappropriate livestock management are predominantly observed in the UK and Spain (Figure 6 (5)).

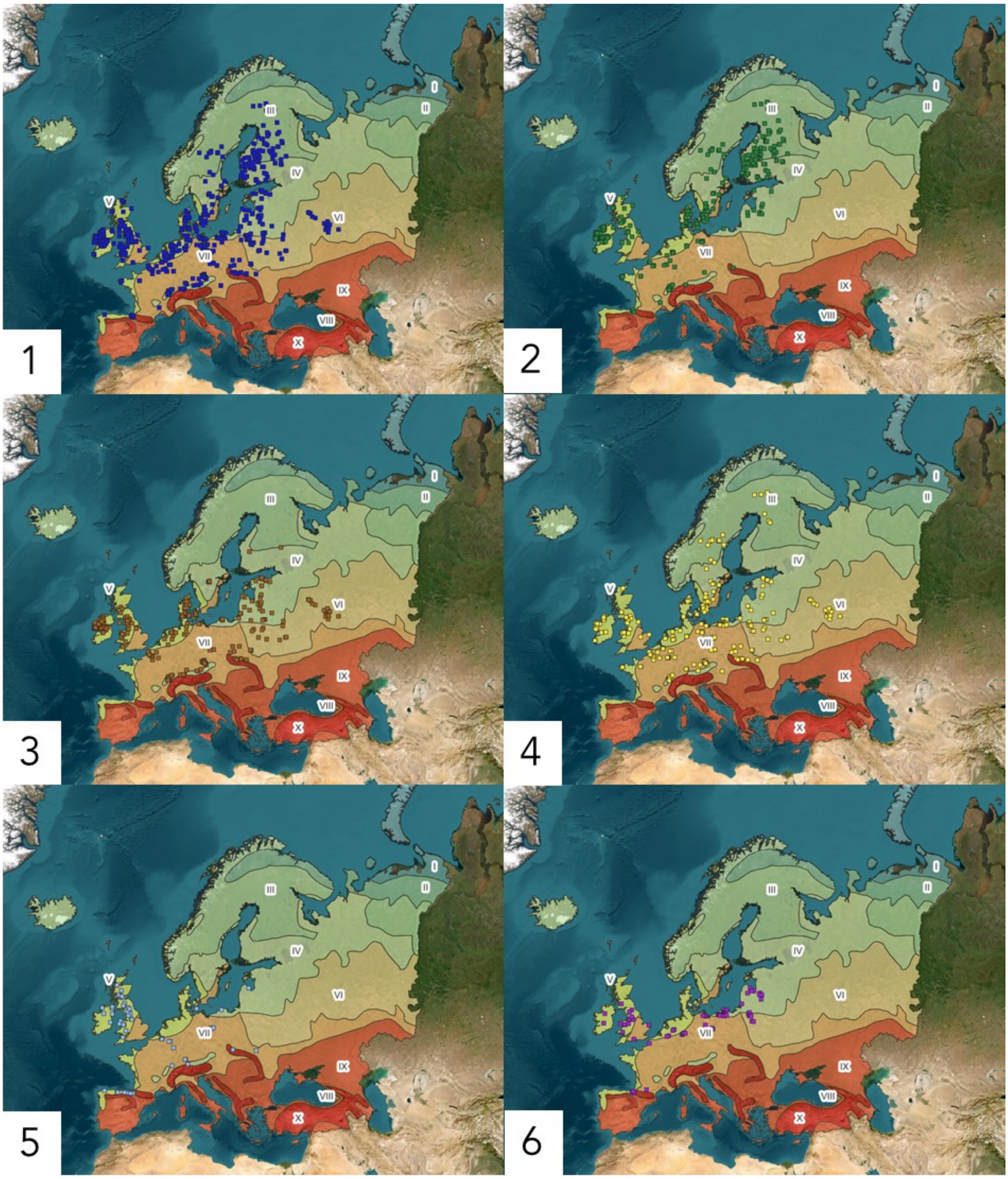

Figure 6. Overview of the six most common stress categories within the project sites. (1: drainage, 2: forestry, 3: peat extraction, 4: agriculture, 5: livestock, 6: other).

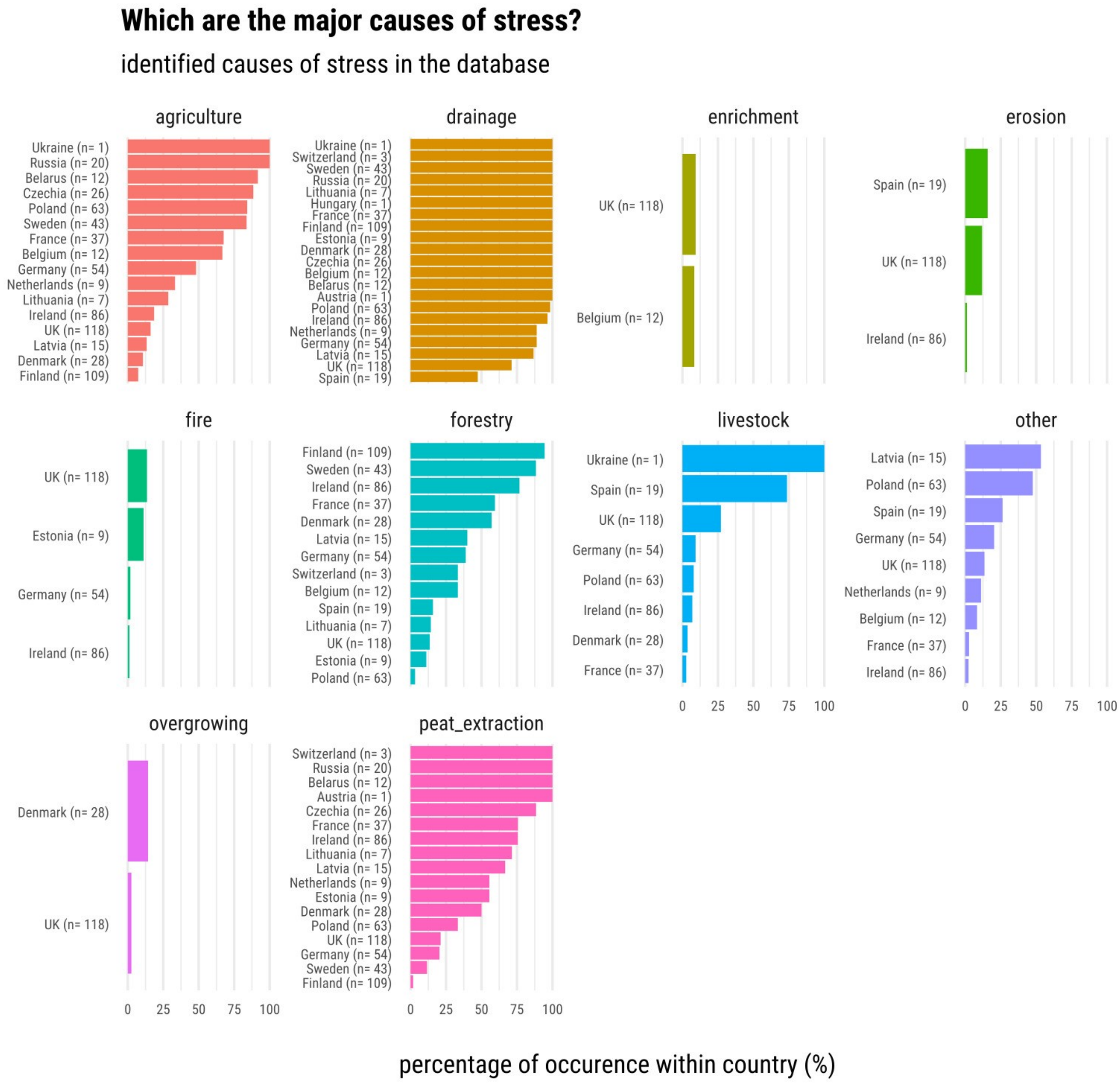

Figure 7. Proportion of wetlands undergoing a form of stress by country. The proportion is in relation to the total occurrence of each country given between brackets on the Y-axis.

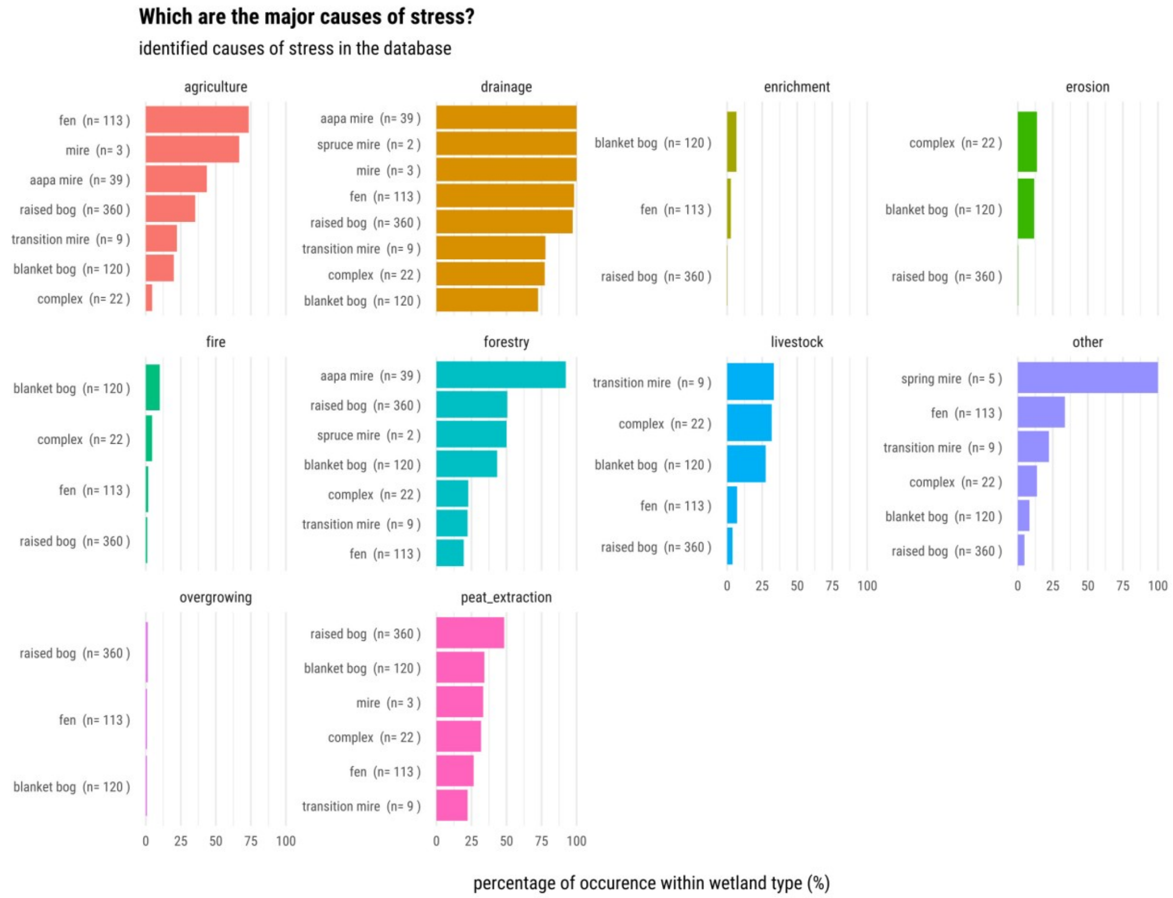

Figure 8. Proportion of wetlands undergoing a form of stress by type. The proportion is in relation to the total occurrence of each wetland type given between brackets on the Y-axis.

Figure 8 illustrates that drainage is the predominant stressor across most wetland types. However, approximately 25% of the transition mires, wetland complexes, and blanket bogs are primarily impacted by inappropriate livestock management, fire, and erosion. While agriculture, forestry, and peat extraction affect various wetland types, their distribution is uneven. Agricultural land use mainly impacts fens, while forestry is more prevalent in aapa mires, raised bogs and blanket bogs. Erosion primarily affects raised and blanket bogs, which typically exhibit a degree of slope.

3.7 Wetland restoration measures

To better understand wetland restoration, we've organized practical measures around three major restoration components: hydrology, vegetation, and peat. This framework allows us to effectively analyse the variety of restoration efforts, considering their relevance to specific wetland types and their geographic spread. The technical implementation of these measures is considered beyond the scope of this deliverable.

3.7.1 Hydrological measures

Hydrological restoration measures are the most common practice conducted on the sites collated in the database. This correlates well with the main stressor, drainage (Figure 8). In total, 7 categories of restoration measures related to hydrology were distinct. The most prevalent interventions are **blocking drains**, **filling in drains**, and **compartment creation** techniques like bunding (Figure 9). Implementation approaches range from simple, low-cost, locally constructed structures to more complex, engineered designs. While general implementing guidelines exist, restoration techniques often require adaptation to local conditions. For instance, filling in drains with local material can be challenging in blanket bogs due to the relatively thin peat layer characteristics and presence of protected species (Calvar *et al.*, 2021). The creation of bunds and compartments is a commonly adopted strategy within bog landscapes to aim for reconstructing their dome-shaped relief. The **creation of ponds** and the **alteration of the river morphology** are less common in restoration projects. Removal of vegetation can also be considered a hydrological measure, as it reduces evapotranspiration and may raise water levels. We classified this measure however with vegetation measures.

Figure 9 presents an overview of all categories related to hydrological restoration. Measures with low-occurrence ($\leqslant$ 5), ranging from re-routing nutrient-rich water to land acquisition are consolidated under the "other" category. Importantly, not all restoration projects incorporate hydrological measures; this is particularly true for passive restoration initiatives or those solely focussed on vegetation management for biodiversity.

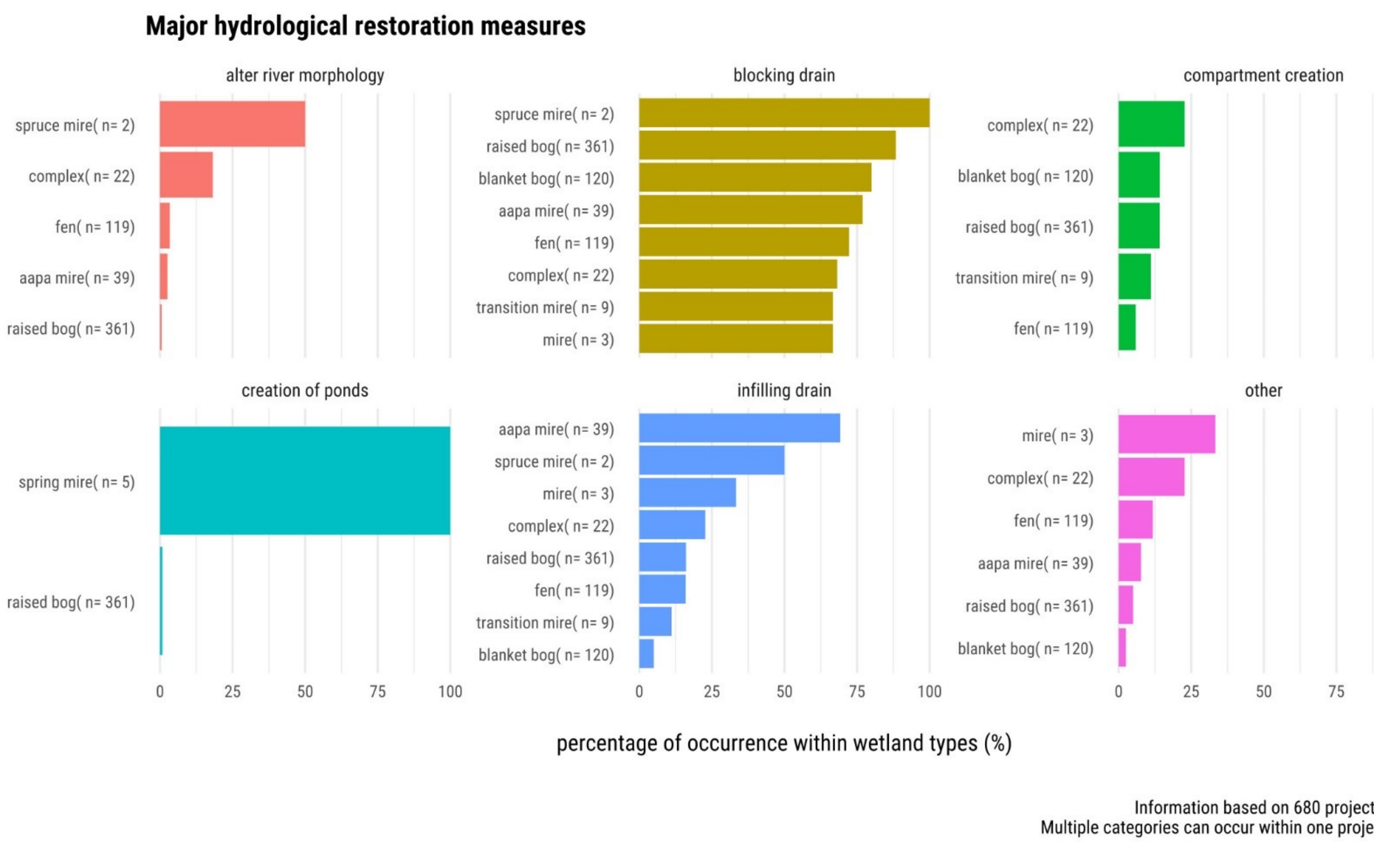

Figure 9. Proportion of wetlands undergoing hydrological restoration measures by type. The proportion is in relation to the total occurrence of each wetland type given between brackets on the Y-axis.

3.7.2 Vegetation measures

Removal of vegetation (incl. invasive species) is the most common restorative practice related to vegetation (Figure 10) and is mainly applied for biodiversity purposes. It can also be a practical necessity while providing access to areas with machinery and equipment. Some projects mention the removal of vegetation as a hydrological measure (see above).

Adapting **grazing management** and **fencing** are key strategies for managing both wild and domesticated herbivores on peatlands. In areas experiencing high grazing pressure, where excessive grazing leads to peat and vegetation damage and biodiversity loss, shifting to a less intensive grazing management approach can be an effective solution. This might involve reducing animal numbers or rotating grazing areas. If specific peatland sections are frequently visited by grazers, for example, for drinking, fencing can exclude them from sensitive areas. However, this often necessitates providing an artificial water basin to ensure drinking water access.

Conversely, in some areas, the abandonment of traditional extensive grazing has led to the overgrowth of desired vegetation. Here, reintroducing grazing regimes, often in close collaboration with local stakeholders, can be beneficial for preserving specific biodiversity. Moreover, deliberately fencing grazers into small areas elevates grazing pressure, either to manage overgrown sections or to specifically target invasive plant species.

Besides grazing, regular **mowing** prevents overgrowing and succession for biodiversity purposes. After restoration activities, mowing can be a temporary "maintenance" management to reduce competition and favour the establishment of peat-forming vegetation. On (slightly) mineralised peat soils, mowing can be used to reduce nutrient levels. Mowing activities are often performed on traditional semi-natural fen ecosystems for fodder collection.

In addition to removal, **species can be (re)introduced**. This involves methods such as transplanting *Sphagnum* nodules or utilizing donor seeds from nearby, ecologically similar sites. These approaches can enhance biodiversity and accelerate the establishment of peat-forming vegetation, particularly in areas with bare peat. **Fertilisation (often together with liming)** is performed in several ombrotrophic systems to give the peat-forming vegetation a head start.

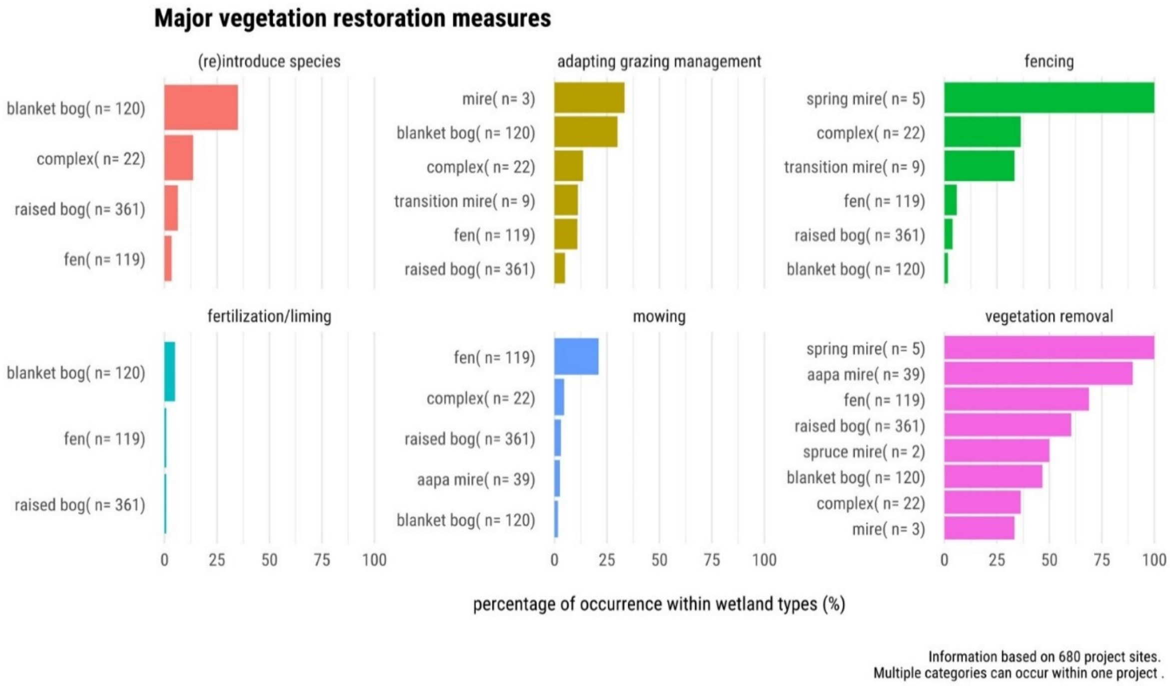

Figure 10. Proportion of wetlands undergoing vegetation restoration measures by type. The proportion is in relation to the total occurrence of each wetland type given between brackets on the Y-axis.

3.7.3 Peat measures

Restoration measures directly targeting the peat are the least commonly practised (Figure 11). Most projects don't mention any direct intervention in the peat soil. **Levelling or sculpting** the peat layer is primarily employed in blanket and raised bogs with bare and unstable peat due to vegetation damage. These areas are susceptible to wind and water erosion, often resulting in the formation of hags and gullies. Levelling may also be necessary in former peat mining areas to ensure even water distribution, preventing areas from becoming excessively submerged or excessively dry due to elevation differences. The erosion of bare peat soil on sloping terrain can be mitigated through the application of stabilizing materials (e.g. geotextile) and the encouragement of vegetation establishment. **Removal of the topsoil** can re-establish favourable nutrient conditions and hydraulic characteristics for the re-establishment of peat-forming vegetation. It is mainly performed in fen ecosystems, where agricultural use led to compaction and nutrient enrichment of the top soil layer.

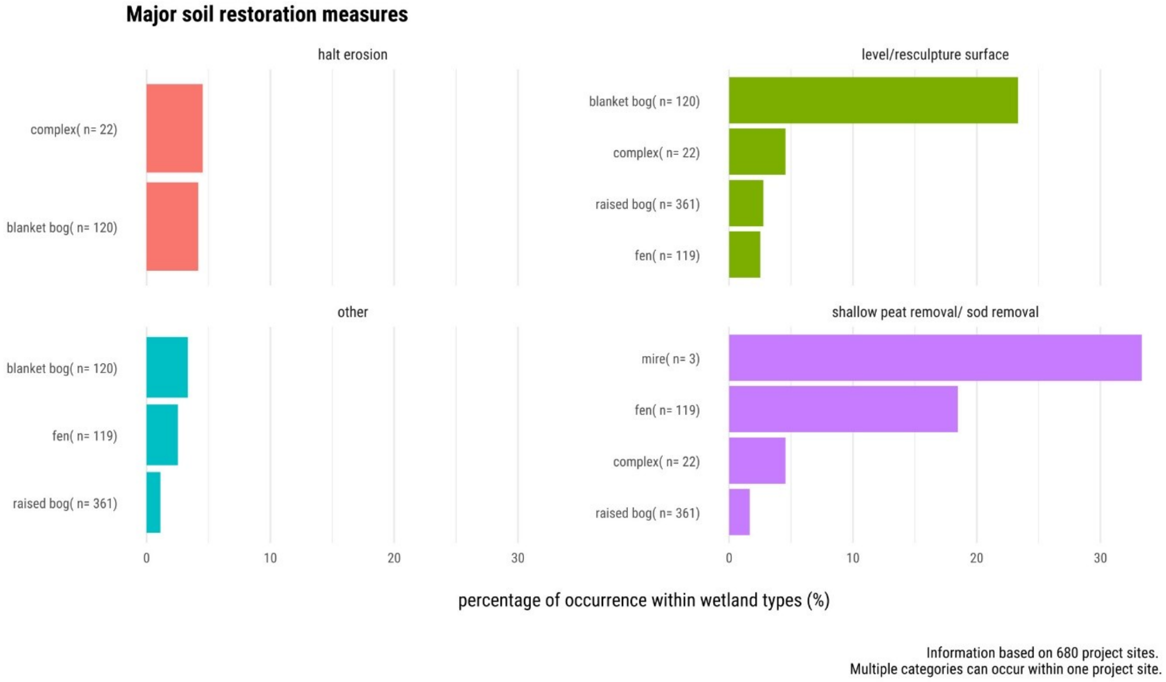

Figure 11. Proportion of wetlands undergoing peat restoration measures by type. The proportion is in relation to the total occurrence of each wetland type given between brackets on the Y-axis. The X-axis ticks are cut at 30%.

3.8 Monitoring

Monitoring is crucial to assess the impact of restoration measures and compare them to a reference ecosystem. Monitoring activities should be tailored to restoration goals to evaluate both short-term and long-term goals. Short-term goals can confirm the immediate effectiveness of restoration efforts and ensure that the peatland habitats initially progress towards their long-term reference state. Long-term monitoring should evaluate the resilience of the ecosystem change over time, as the evolution of ecosystem structure and community composition (Liu *et al.*, 2024). Ideally, monitoring takes place before and after restoration with at least one additional external control without treatment. This method, known as BACI (Before-After, Control-Impact), was originally described by Green (1979) and has since been refined through critical evaluation and subsequent suggestions. A well-designed BACI remains one of the best models for environmental effects monitoring programs (Smokorowski & Randall, 2017).

Monitoring information was available for a subset of 170 project sites within the restoration database (see Chapter 2), representing roughly one-quarter of the total. Five major monitoring categories were distinguished: 1) carbon, 2) fauna, 3) flora, 4) hydrology, and 5) other monitoring variables. Project sites typically measure variables across multiple categories. Flora and (quantitative) hydrology are the most frequently monitored categories (e.g., plant surveys and measuring water level). The number of categories measured varies widely across the analysed restoration sites, with 24 sites measuring components of 1 category, 54 sites of 2 categories, 73 sites of 3 categories, and 18 sites of 4 categories, respectively (Figure 14). A detailed composition of restoration categories is given in Figure 13. Monitoring categories are discussed in detail below.

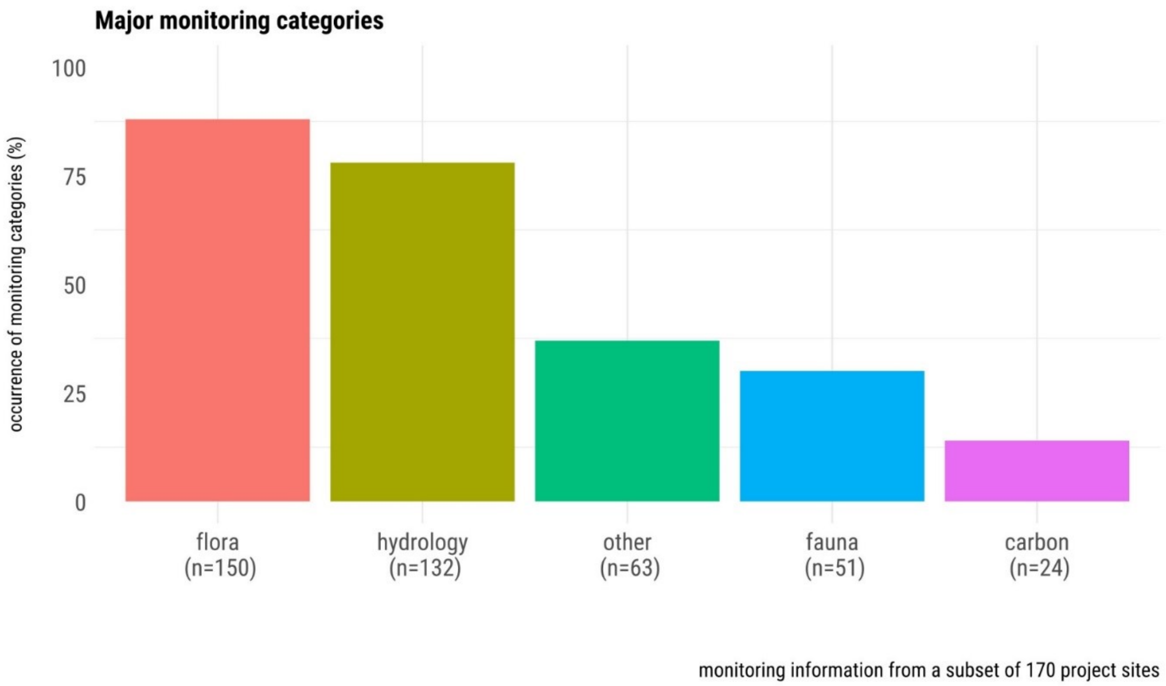

Figure 12. Occurrence of monitoring categories (%) within a subset of 170 project sites.

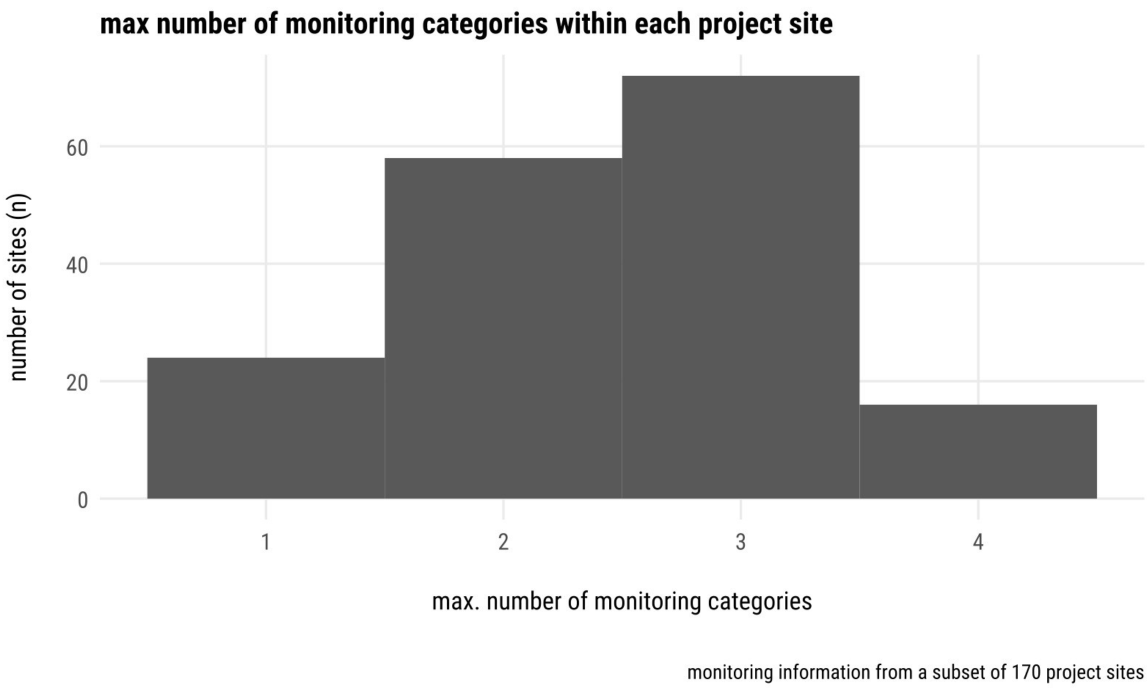

Figure 14. Coverage of 1 to 4 monitoring categories across 170 project sites.

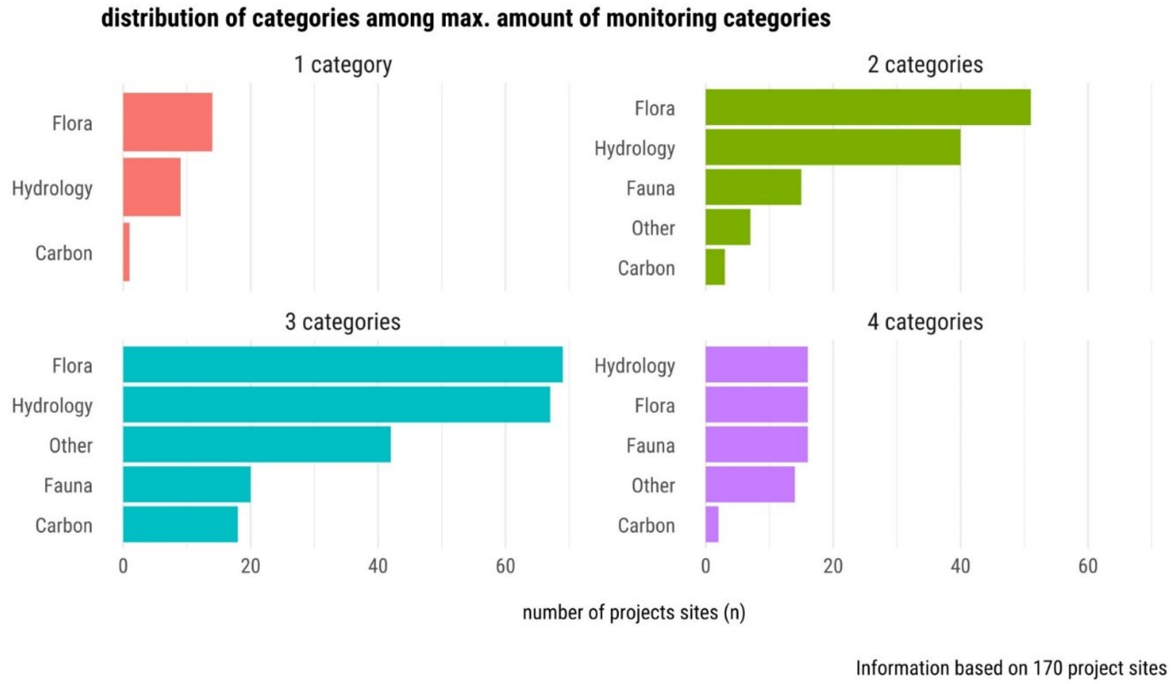

Figure 13. Composition of 1 to 4 categories for monitoring in restoration sites.

3.8.1 Monitoring period

Information about the monitoring period was found in 98 of the 170 project sites, with monitoring periods ranging from several months to 30 years (Figure 14). The median monitoring period was 5 years, while the average was 6.52 years for single project sites. It's important to note that the multiple LIFE projects target several separate restoration sites, which might skew the distribution towards shorter monitoring periods. When analysing monitoring periods at the overall project level rather than the site level, the frequency of short-term monitoring decreases. However, the median monitoring period remains at 5 years, while the average increases to 7.76 years. This suggests that most available monitoring data from these restoration sites/projects is mainly suitable for assessing short-term restoration goals.

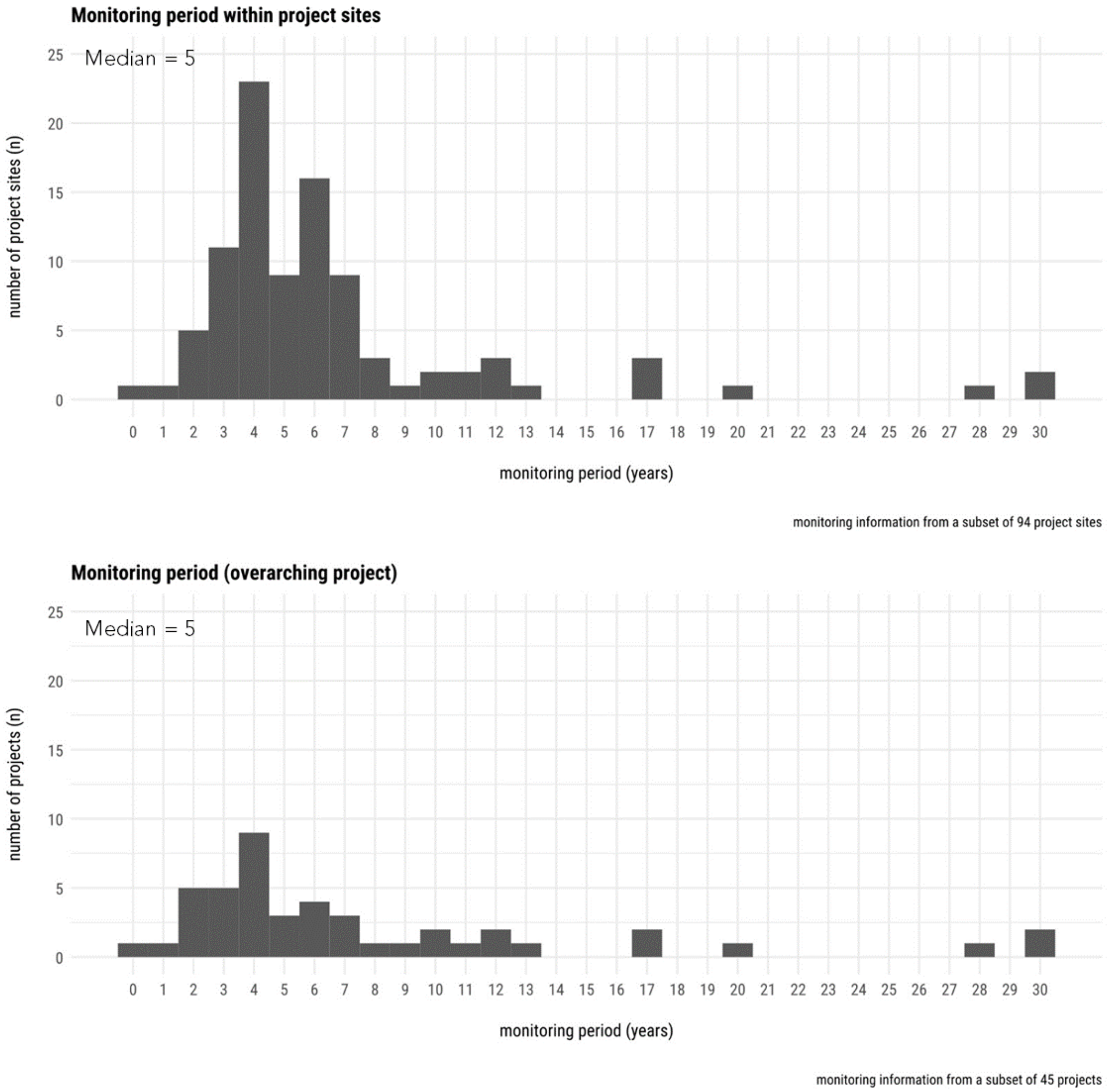

Figure 14. Frequency of monitoring period based on individual project sites (upper figure; n=98) and overarching projects (lower figure; n=45).

3.8.2 Monitoring Flora

Of the 170 restoration sites surveyed, 150 monitored one or more flora variables as a common metric for assessing both biodiversity and ecosystem health. In peatlands, the latter often involves tracking peat-forming vegetation. Indicator species and keystone species are used as a measure of habitat quality and ecosystem functioning.

We noted that in half of the flora monitoring sites, specific flora variables were not specified (
Figure 15, column 1). Approximately one-third of the sites employed **vegetation plot** surveys to assess vegetation dynamics. This likely represents an underestimation, as several other sites documented the measured variables (e.g., **species presence/absence**) without specifying the methodology. The Braun-Blanquet scale (e.g. Westhoff & Van Der Maarel, 1978) is the most commonly employed survey method for vegetation plot assessments. Mapping **habitats surface** (e.g., Natura 2000 network) is crucial for complying with the legal requirements of the Habitats Directive, tracking the site's advances towards the European Biodiversity 2030 targets, and fulfilling the objectives of the Nature Restoration Law. **Airborne vegetation surveys** (e.g. with drones) can support conservation planning by creating high-resolution, multi-sensor data, enabling accurate habitat classification and tracking habitat change. Airborne surveys were mentioned for a limited number of project sites. (10 sites).

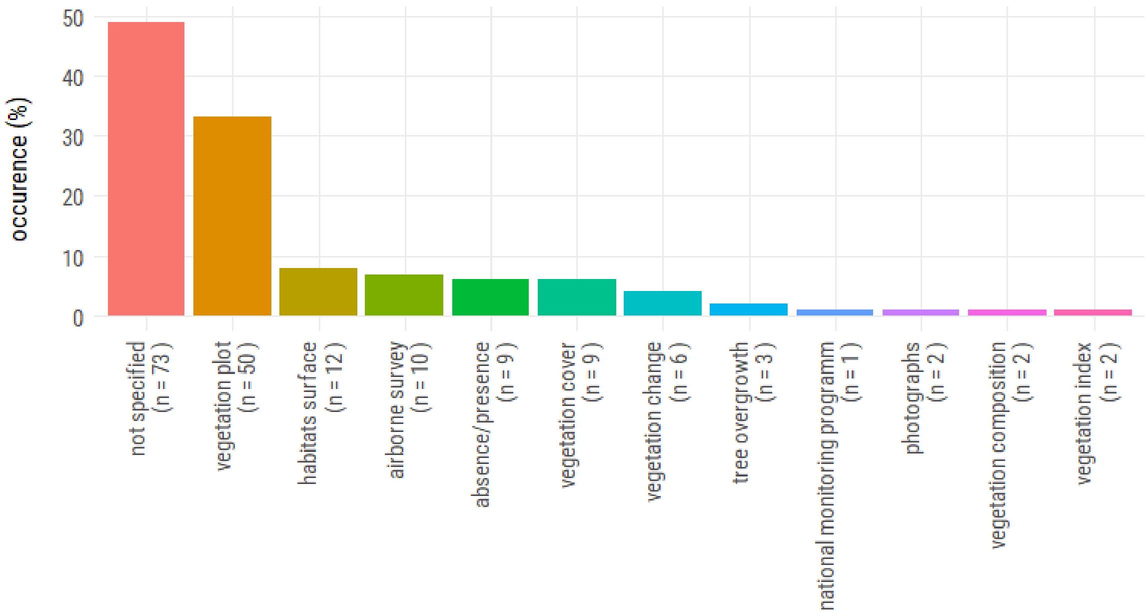

Figure 15. Occurrence of flora monitoring variables (%) within a subset of 150 project sites. Multiple categories can occur within one project site.

3.8.3 Monitoring Hydrology

Hydrological monitoring of restoration variables within the collated restoration project dataset was categorized into **qualitative and quantitative measurements**, with the latter being reported for 132 out of 170 restoration sites only. Qualitative measurements provided more detailed information on their monitoring methodologies, like the use of **piezometers**, and automated vs. manual measurements**. Water level** was the most commonly identified variable (n=65), though it was often unclear whether it referred to groundwater or surface water levels. **Water quality** was monitored in 23 projects, encompassing both groundwater and surface water. Other hydrological variables are monitored in fewer projects, but manifold (e.g., **inflow, outflow, eco-hydrological functioning, water flow**).

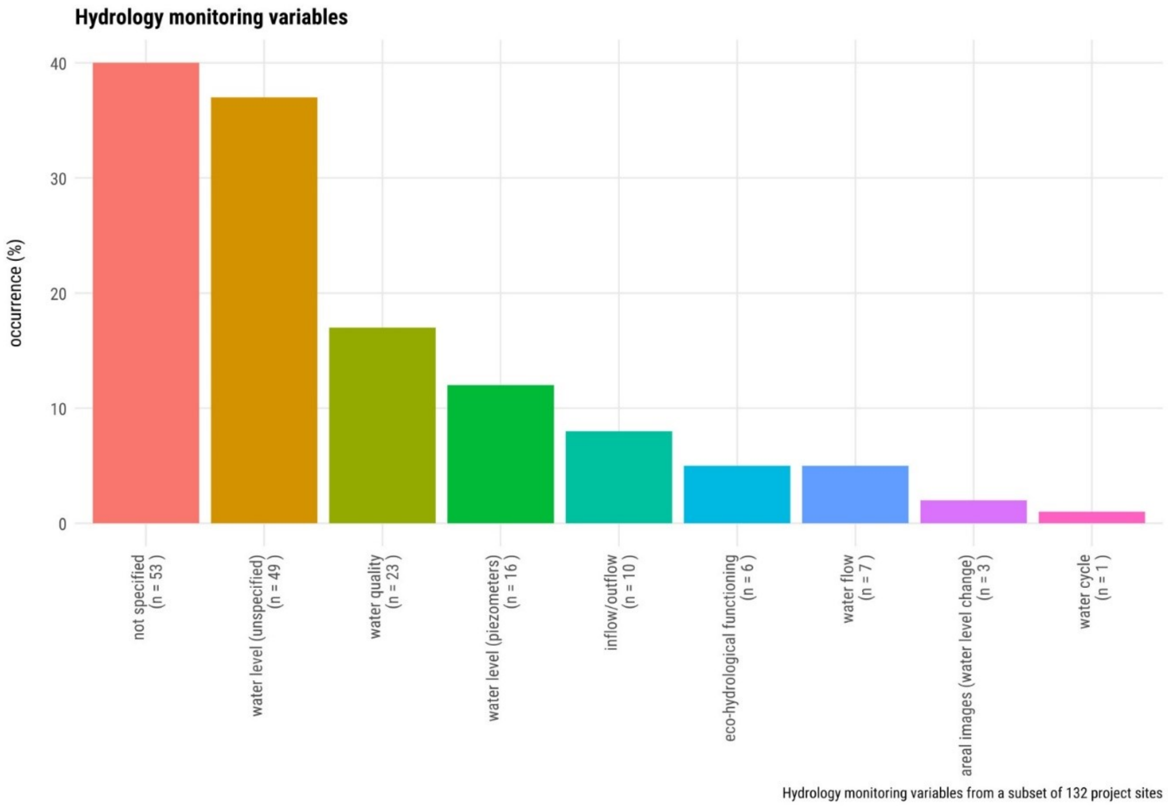

Figure 16. Occurrence of hydrology monitoring variables (%) within a subset of 132 project sites. Multiple categories can occur within one project site.

3.8.4 Monitoring Fauna

Fauna monitoring can be conducted at various taxonomic levels, from broad categories like ‘class’ or ‘order’ to ‘specific functional groups’ such as pollinators (Figure 18). While a single species may be relevant to multiple monitoring variables, the specific monitoring goals can vary. Based on the database, **Lepidoptera (butterflies and moths)**, **Odonata (dragonflies and damselflies)** and **birds** are the most commonly monitored faunal groups in peatlands because of their easy recognition, visibility, likability and indicator value. In particular, Odonata species depend on water for reproduction and show a rapid response to rewetting, making them frequently monitored in wetlands. Lepidoptera are well-suited for open environments. Orthoptera (grasshoppers, locusts, and crickets) can be used as indicators for open environments and forest edges. Hoverflies (*Syrphidae*) are versatile and used in various habitats, including forests and open habitats. At the larval stage, hoverflies use restricted ecological niches and have strict requirements. They are considered as excellent bioindicators of the state of the environment (Calvar *et al.*, 2021; Speight, 2012, 2024).

Faunal migration within and across (large) habitats can significantly impact restoration outcomes and success evaluation. The proximity of relict populations to restoration sites should be considered when selecting monitoring species. Additionally, species selection should be tailored to specific peatland types, as faunal communities are closely linked to specific vegetation structure and composition.

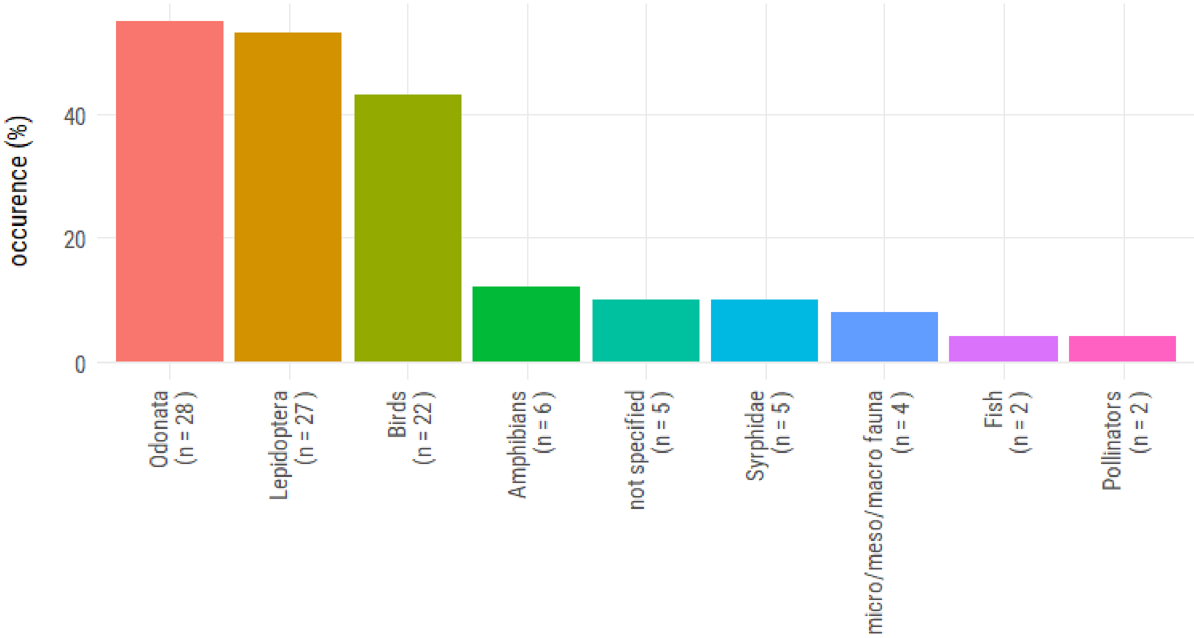

Figure 17. Occurrence of fauna monitoring variables (%) within a subset of 51 project sites.

3.8.5 Monitoring Carbon

Carbon-related monitoring was observed in only 24 projects with a focus on **greenhouse gases** (GHG), primarily CO_2 and CH_4, measured through manual/automated chambers campaigns or the eddy covariance method (Figure 19). Several projects surveyed **soil/peat chemistry**, including carbon content. One project mentioned **biomass monitoring**, while another addressed **carbon cycles**. The limited number of carbon monitoring activities, particularly for GHG emissions, is likely attributed to the high costs, complex setups, and intensive field campaigns required.

Moreover, the focus on peatland restoration as a contribution to climate change mitigation has only gained increased relevance during recent years.

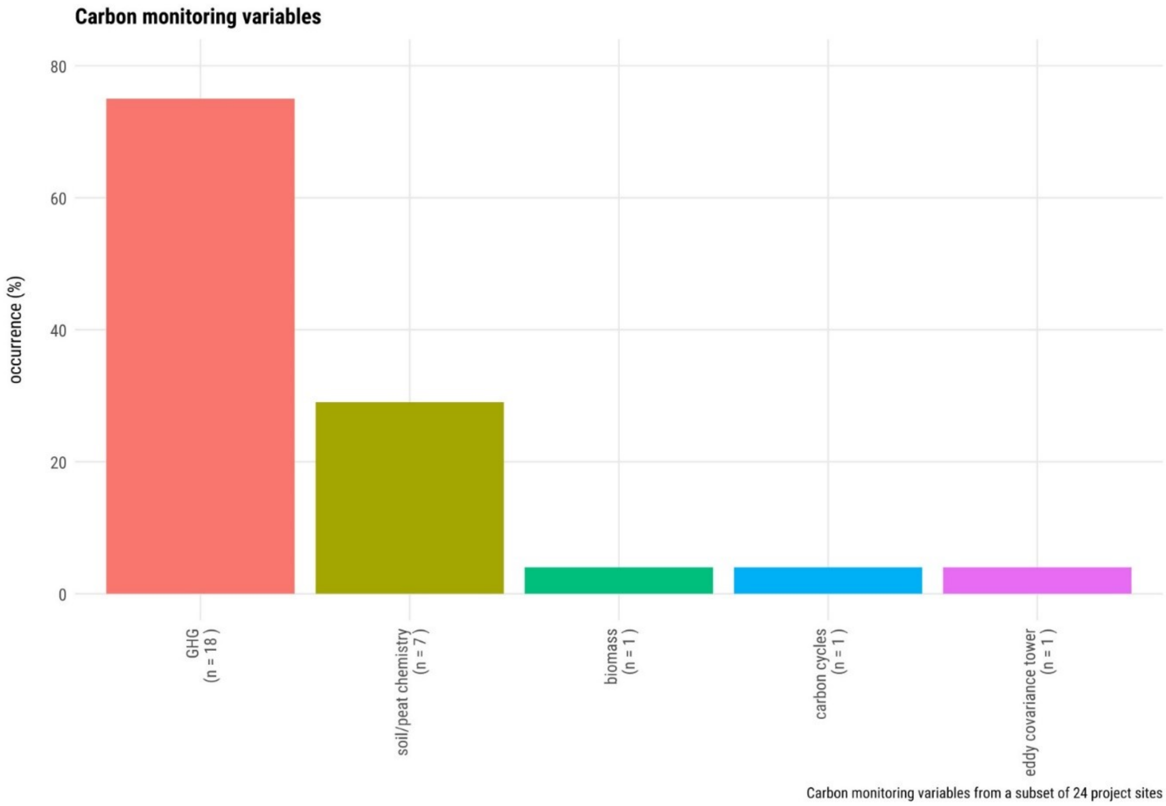

Figure 18. Occurrence of carbon monitoring variables (%) within a subset of 24 project sites.

3.8.6 Monitoring Other

The remaining monitoring variables from 63 project sites were grouped under "Other" (Figure 19). The most frequently monitored variable in this category was **infrastructure status** (e.g., dam stability, overflows, erosion damage, and vandalism). Regular check-ups for infrastructure are highly recommended, especially in the initial years after restoration. Other variables in this "Other" category included general climatic factors, livestock impact, and peat stability.

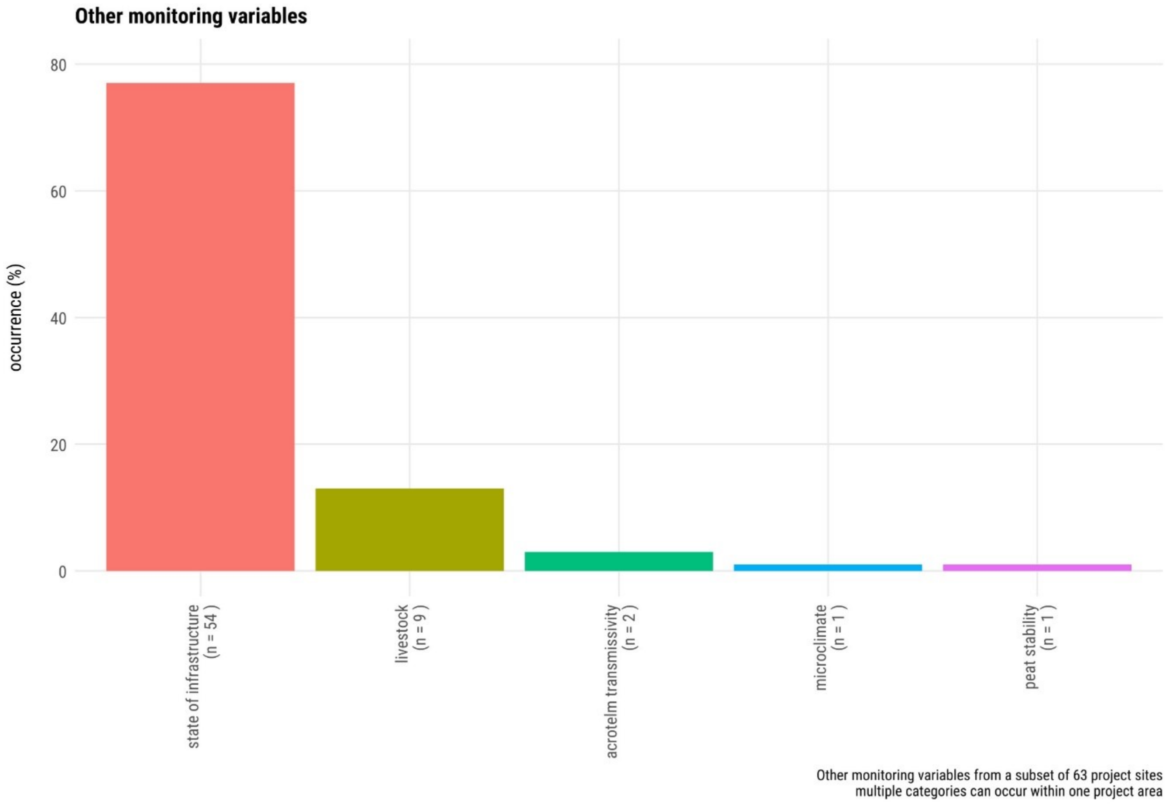

Figure 20. Occurrence of "other" monitoring variables (%) within a subset of 63 project sites.

3.9 Stakeholder Engagement and Citizen Science

For lasting restoration success, active participation and support from the local community and stakeholders are crucial throughout a project's lifecycle. Community involvement can take many forms, targeting diverse stakeholders and ranging from very site-specific efforts to broader regional initiatives. It's essential to engage stakeholders from the project's outset to gather their invaluable input, which helps shape project goals and methods and fosters acceptance. A wide audience can be targeted through general outreach methods like brochures, presentations, information boards and organized excursions to the restoration site. Integrating ecological restoration into education will foster early understanding of the importance of wetlands.

Regular updates should be scheduled through the project duration, as e.g., community visits to witness the restoration work first-hand, education trips (e.g., school field trips) and direct participation in implementation of restoration measures ('public workdays'). Parts of restoration sites should be accessible for the public during and following the implementation of restoration measures (with e.g. educational boardwalks, viewing platforms or dedicated information centres).

Stakeholder involvement in monitoring is a powerful engagement tool. The database provides examples of Citizen Science initiatives that track bird, butterfly, or amphibian populations, as well as joint efforts by experts and volunteers to read groundwater monitoring wells. Some restoration projects have tailored monitoring activities, such as the LIFE mire Estonia project's (P254) monitoring of Western capercaillie (*Tetrao* *urogallus*). More general "Bioblitzes' can also be organised where volunteers gather as much species data as possible in a specific area over a short period.

There are also entirely citizen science-driven projects for peatlands, like the UK's "Eyes on the Bog"[2] project or the "Tracking the Colour of Peatlands"[3] project. Also, general Citizen Science initiatives like species inventories with apps and online observation platforms like Inaturalist[4] and Observation[5] can be useful tools. In Scotland, an app[6] was developed to map soil erosion. Several online platforms[7] provide a central hub to support, promote and connect citizen science initiatives.

Working closely with the community and giving them a role in the restoration project can not only ensure lasting success, but also cultivate a sense of stewardship and appreciation for the restored environment.

[2] https://www.iucn-uk-peatlandprogramme.org/get-involved/eyes-bog
[3] https://www.plymouth.ac.uk/news/citizen-science-project-tracks-the-health-of-planets-peatlands
[4] https://www.inaturalist.org/
[5] https://observation-international.org/en/
[6] https://soilerosion.hutton.ac.uk
[7] E.g. https://eu-citizen.science/, https://www.scivil.be/en

4 Restoration Success

In this chapter, we're zooming in on the success factors of peatland restoration projects. What makes a project successful, and how do we evaluate the restoration success?

Section 4.1 presents an analysis of successes and obstacles from the project sites compiled in our database. We've noted that many project reports, often completed shortly after restoration measures, lack thorough conclusions. To organize these findings, we tagged each conclusion in the database with its relevant monitoring category (see paragraph 3.8), using the label "general" for conclusions that encompassed the entire project. The upcoming chapters will summarize these successes and obstacles for each wetland type (as defined in paragraph 3.2) in a table. Further details on restoration success are available in the database's "restoration success" tab.

In 4.2, we analyse the temporal change of Corine Land Cover (CLC)[8] pixels within each project site across five reference years (1990, 2000, 2006, 2012, 2018). This analysis tests whether changes in land cover data can be used to detect the impacts of restoration measures. Remote Sensing potentially offers powerful tools for monitoring wetland development over time. We will discuss the inter-annual flows with a focus on wetlands. We'll end in 4.3 with a final discussion.

4.1 Successes and obstacles from the restoration project database

[8] https://land.copernicus.eu/en/products/corine-land-cover

4.1.1 Fen restoration successes & obstacles

Category	Successes	Obstacles	Pages
Vegetation	- Positive response of degraded plant communities to groundwater restoration - Peat-forming plants spread in shallow inundated sites - New microhabitats initiate succession - Topsoil removal and hay transfer establish new plant populations	- Trade-offs between peat systems and species-rich fen grasslands - Residual peat thickness affects revegetation - High nutrient heterogeneity complicates restoration - Desired species may take decades to establish or fail due to competition - Limited success in highly degraded areas - Deviations from pristine fen vegetation - Rich fen indicators may not respond to rewetting - Mowing can degrade undisturbed fens	p17, p22–24, p30, p42–46, p57–58, p172
Fauna	- Odonates colonize water pools rapidly - Mire butterflies increase after restoration - Mire bird diversity and abundance improve in restored sites		p247, p252–253
Peat Conservation & GHG	- Rewetting restores net GHG balance similar to pristine fens - Peat-forming plants indicate peat accumulation potential	- Increased water levels can alter soil and water chemistry, affecting peat formation	p43–46, p57, p59
Hydrology	- Water levels successfully restored - Vegetation responds positively to groundwater restoration	- Water table depth differences reduce over time - Rewetting effectiveness decreases with distance from ditches - Increased water levels can affect soil and water chemistry	p17, p22–24, p27–29, p42, p57, p190, p192, p237

4.1.2 Raised bog restoration successes & obstacles

Category	Successes	Obstacles	Projects
Vegetation	- Rewetting favours typical bog species like *Eriophorum* and *Sphagnum* in multiple projects. - General increase in mire plant coverage is observed. - Vegetation changes can occur rapidly and align with project objectives. - Development of characteristic hummock-hollow vegetation patterns indicates recovery. - Die-back or decline of degradation indicators like *Molinia caerulea* and *Calluna* noted.	- Insufficient rewetting can increase tree seedlings in cut-over areas. - High nitrogen and phosphorus levels favour undesirable species. - Dense vascular plant layers shade *Sphagnum sp*. - New peat conditions in rewetted areas may prevent natural bog recovery for decades. - Fen species may dominate if ombrogenous peat is lost.	p2–p3, p5–p6, p7–p10, p13, p31–p33, p37–p38, p40–p41, p52–p53, p206, p254
Fauna	- Indicator species like birds, dragonflies, mire butterflies, and moor frogs show recovery. - Positive fauna changes visible within the first few years.	- Some species take longer to return due to isolation of populations or slow vegetation adaptation post-restoration.	p53, p253–p256
Peat conservation & GHG	- Rewetted peat swells or forms floating rafts, favouring bog species colonization. - Peat accumulation rates of 2–10 mm/year reported post-rewetting. - CO_2 emissions decrease, but CH_4 emissions increase substantially.	- Peat formation effects are less in drained and afforested sites - Nutrient mobilization may alter chemistry (e.g., phosphate release due to sulphur reduction). - Elevated NH_4^+-N and PO_4^{3-}-P levels can persist for decades. - Hot, dry summers may accelerate surface peat decomposition.	p6, p11–p12, p33, p47, p169
Hydrology	- Most projects report positive impacts on water levels. - Raised water tables aid bog acrotelm recovery and vegetation development. - Some sites reach water levels close to pristine bogs.	- Water level rise can be minor post-restoration. - Infrastructure can fail if poorly designed or positioned. - Minor drains, if ignored, hinder water recovery. - Some sites show inconsistent water level improvements. - Deep flooding can harm desired (present) vegetation via light and carbon limitations or wave action. - Nutrient mobilization post-rewetting can occur.	p2, p4–p5, p6, p7–p10, p12–p13, p18, p32, p37, p39–p41, p52–p53, p254–p255

4.1.3 Blanket bog restoration successes & obstacles

Category	Successes	Obstacles	Projects
Vegetation	- Water level rise encourages revegetation and the growth of target species like *Sphagnum* mosses and cotton grasses. - Use of grass seeds, plant plugs, and geotextile is effective for stabilising and revegetating eroded peat. - Higher water tables reduce species indicative of drier conditions and bog degradation. - Raised water tables help prevent tree re-colonization.		p49, p173, p175, p176, p178, p207, p210, p239, p244
Fauna	- Positive effects on fauna include return of Red Grouse, Common Cranes, and increase in Nightjars. - Farming practices can coexist with conservation, supporting local economy.		p207, p212, p244
Hydrology	- Damming, cell bunding, and drain blocking successfully retain water and raise water levels. - Increased water storage stabilizes the water table and reduces flow discharge after rainfall. - Longer periods of drain blocking enhance bog recovery. - Rewetting measures aid wildfire risk mitigation. - Dams reduce erosion and retain sediment by slowing water movement.	- Local water tables show high spatial diversity after ditch blocking, with only small overall effects. - Drain blocking can temporarily increase water colour due to dissolved organic carbon release (although no catchment-scale changes in river water colour).	p48, p49, p50, p51, p54, p153, p173, p175, p207, p210, p218, p232, p239

4.1.4 Aapa mire restoration successes & obstacles

Category	Successes	Obstacles	Projects
Vegetation	- Rewetted sites show higher abundance and species richness than drained sites. - Plant assemblages can rapidly revert towards natural flark fens. - Rare and threatened rich fen mosses have spread in many restored rich fens - Plant species show reversion towards wetter habitats and increased Sphagnum cover.	- The developing ecosystem may differ from the original in heavily drained areas. - Some sites show limited change, indicating the need for more effective methods. - Sphagnum cover may remain below natural levels.	p247, p249, p250, p251
Fauna	- Mire butterflies, dragonflies, and birds benefit from restoration. - Dragonflies can rapidly colonize new water pools. - Restoration shows an initial increase in mire bird species, though the trend becomes less clear over time.		p247, p251 p247, p248, p249, p250, p251, p252, p253
Peat Formation & GHG	- Increased Sphagnum cover indicates potential for peat formation.	- Low calcium availability can slow down the reversion process, potentially affecting peat formation.	p247, p251
Hydrology	- Restoration measures promote the re-establishment of springs and near-natural hydrological conditions.	- More effective restoration methods may be required beyond ditch damming alone (e.g., infilling ditches with peat, constructing peat embankments). - Preventing waterlogging on neighbouring land can limit rewetting success.	p248, p250, p251, p252

4.1.5 Spruce mire restoration successes & obstacles

Category	Successes	Obstacles	Projects
Vegetation	- Successful restoration after ditch blocking with palisade dams, lead to development towards spruce mire forest. - Rewetting achieves near-pristine *Sphagnum* accumulation rates within years		p25–26
Fauna		- Drained sites have lower abundance and species richness compared to pristine references.	p249
Hydrology	- Ditch blocking with palisade dams effectively raise water levels.	- Old, dried-out depressions can remain visible, indicating that groundwater has not fully recovered to natural levels.	p25, p248

4.1.6 Mire restoration successes & obstacles

Category	Successes	Obstacles	Projects
Vegetation		- Internal eutrophication and lack of gap creation can hinder germination.	p171
Peat Formation & GHG	- One study in Finland found that 10 years after restoration, a cut-away peatland became a large sink for atmospheric CO_2.	- Internal eutrophication can negatively impact peat formation.	p171
Hydrology	- A study in the Netherlands mentions an overall rewetting success, but with both positive and negative effects locally.		p170

4.1.7 "Complex" restoration successes & obstacles

Category	Successes	Obstacles	Pages
Vegetation	- Introduction of *Carex rostrata* and *Sphagnum* species shows good initial development in a Spanish study site.	- Community assembly can be slow and vulnerable to extreme events such as spring snowmelt, heavy rain, or drought. - In a German study, an unblocked ditch caused incomplete hydrological protection, leading to die-off of *S. magellanicum.*	p56, p168
Peat Formation & GHG	- Good development of introduced peat-forming species suggests potential for peat accumulation.	- Extreme events can constrain community development. - Incomplete hydrological protection zones (HPZs) can negatively impact peat-forming species.	p56, p168
Hydrology	-	- Water table is vulnerable to drought. - Unblocked ditches can lead to local drying. - Extreme water flow events (e.g. snowmelt or heavy rains) can hinder restoration success.	p20, p56, p168

4.2 Observations and conclusions from the CLC change analyses

CORINE Land Cover (CLC) is the established standard for pan-European land use and land cover (LULC) monitoring. It comprises a series of inter-annual LULC datasets for Europe, generated by national agencies under the coordination of the European Environment Agency (EEA). We linked the core dataset (249 project sites) of the database to the 6-yearly Corine Land Cover change raster datasets of reference years 1990-2000-2006-2012-2018, version 2020. Data was downloaded through the Copernicus Land Monitoring Service Portal (CLMS) for EU countries, the UK and Switzerland.

A simple 3x3 dot matrix was created based on the coordinates of the database. The database coordinate was considered as the central point, surrounded by 8 additional points. Each point covers a 100x100 raster cell; thus, a total area of 300x300 meter was analysed for each project site. CLC change was visualised with the help of alluvial plots. CLC changes were visualized using alluvial plots. We compared changes across three CLC levels (levels 1, 2, and 3), as detailed in (Kosztra *et al.*, 2017).

As stated above, 5 reference years for the EU countries, the UK and Switzerland. Coverage for the UK and Switzerland and several sites in Finland, Sweden and Ireland is limited in the first reference year (1990), leaving numerous NA-values in the dataset (Figure 19). From 2000 onwards, all considered projects sites are covered by CLC data. Additional CLC tables for each CLC-Level are listed in Annex 8.

At the highest hierarchical level (Level 1), 42% of the sample points have no coverage (Figure 19). The flow from 1990 towards 2000 shows that these points are mainly forests and natural areas, wetlands and agricultural lands. The points with coverage in 1990 show a flow from forest and natural areas towards wetlands, and from wetlands towards forests and natural areas and agricultural areas.

The next flow, from 2000 towards 2006, is the most dynamic flow from the CLC time series. Here, the overall number of points identified as forests and natural areas decreases by 6% and the number of points identified as agricultural area decreases by 5%. The flows of these categories go mainly towards wetlands, where an increase of 9% is noted. A deeper dive into the data showed that UK data points are the main attribute to this change. Excluding these points from the dataset, there is only a drop in the percentage of agricultural land by 4% and an increase in wetland area by 4%. When we look at the more detailed CLC Level 3 (Figure 21), we noted that the shifts can be attributed from non-irrigated arable land and moors an heathland towards peat bog. Further investigation is needed to verify if this change is related to land cover change or the use of a different classification system, but is considered out of scope of this report.

In the next flow from 2006 towards 2012, a net decrease of 1% in agricultural area and an increase of 1% in wetland area was noted (level 1, Figure 19). Other land cover classes have limited net change (<1%), though there are some shift towards other land cover classes.

Surprisingly, the last flow from 2012 towards 2018 indicates no change on CLC level 1. Within subcategories there are however some internal shifts, as can be noted in the alluvial plots of the Level 2 (Figure 20) and Level 3 (Figure 21) classification.

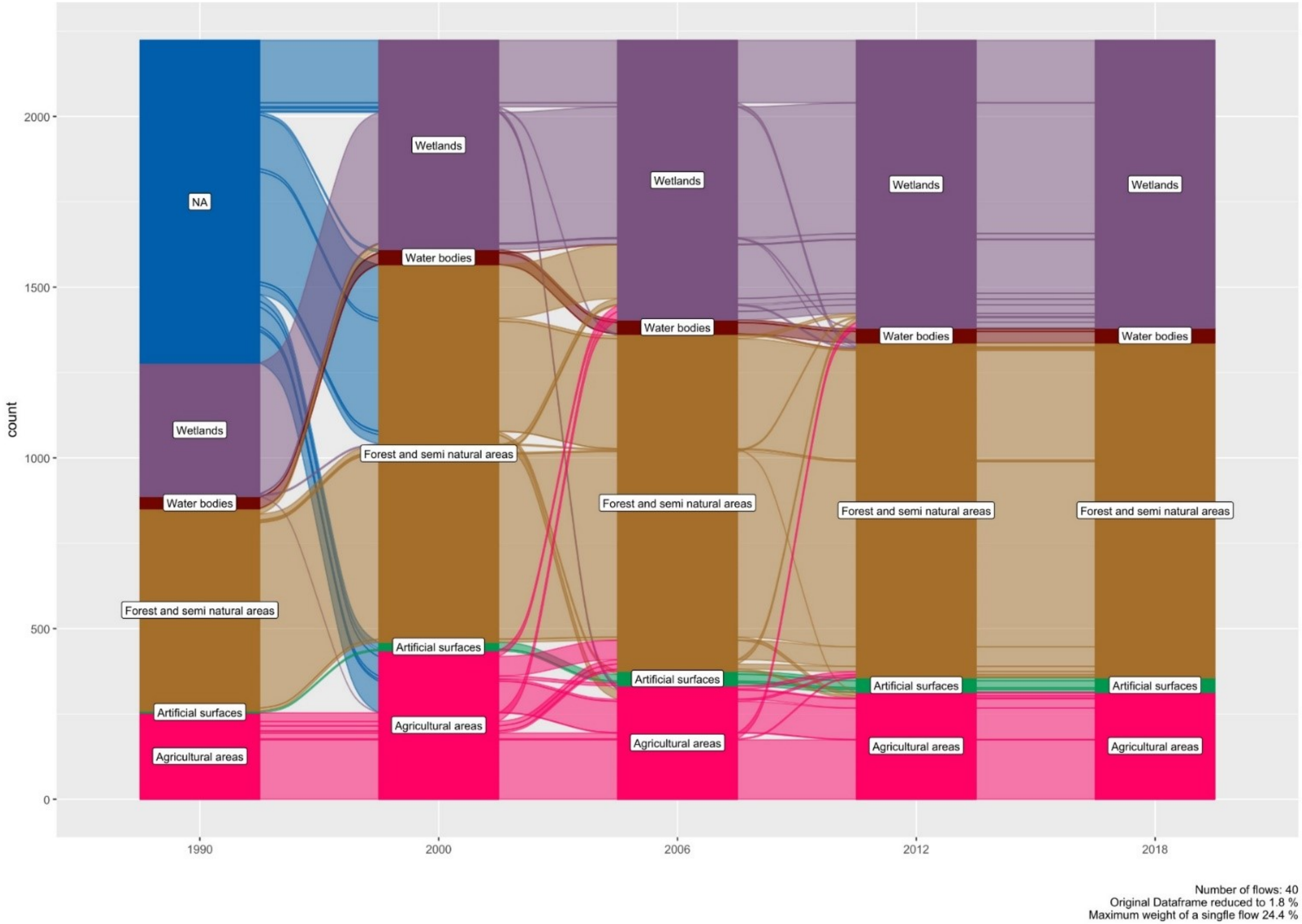

Figure 19. Alluvial plot of Corine Land Cover change in restored project sites, based on CLC classification level 1.

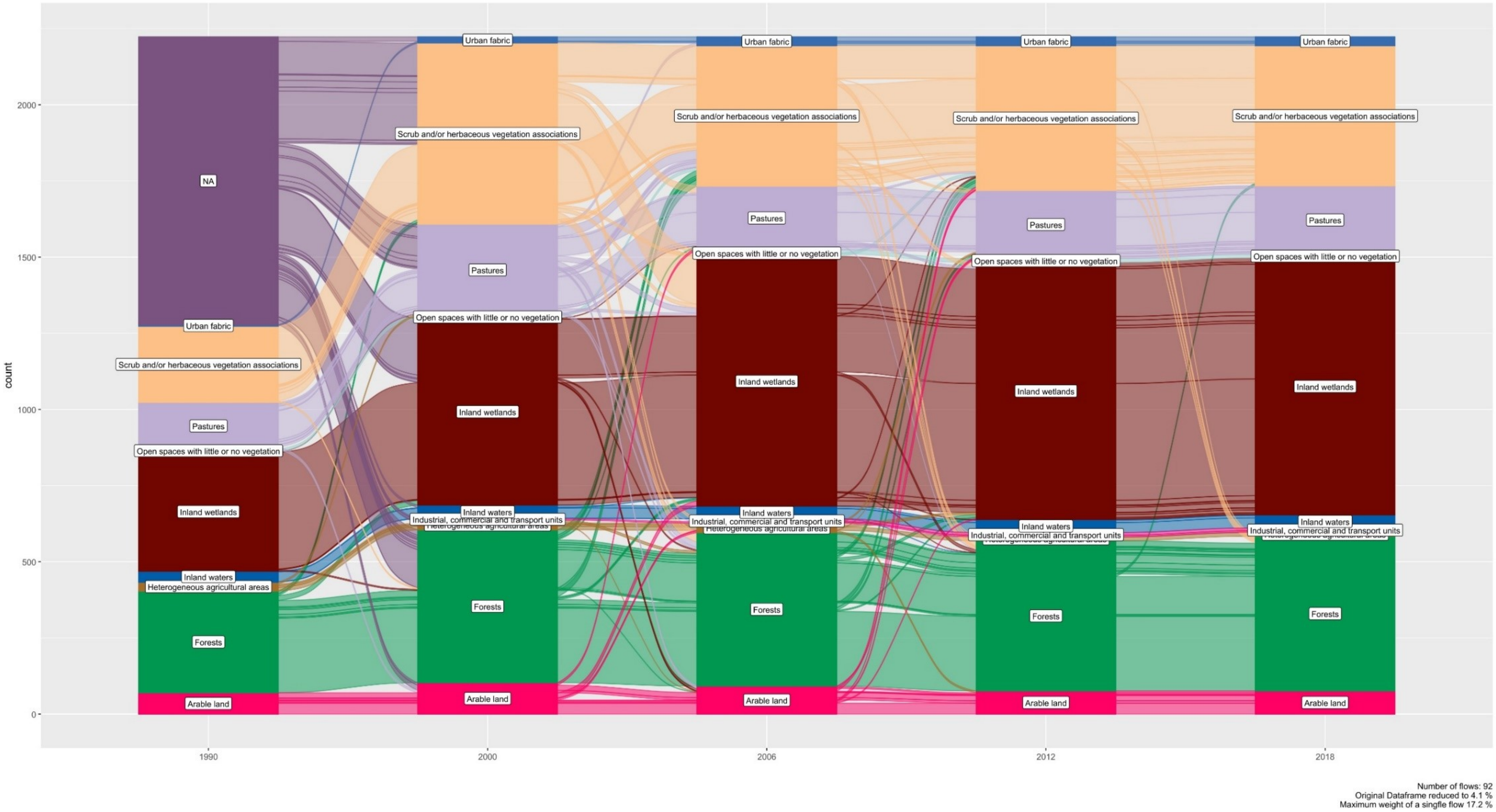

Figure 20. Alluvial plot of Corine Land Cover change in restored project sites, based on CLC classification level 2.

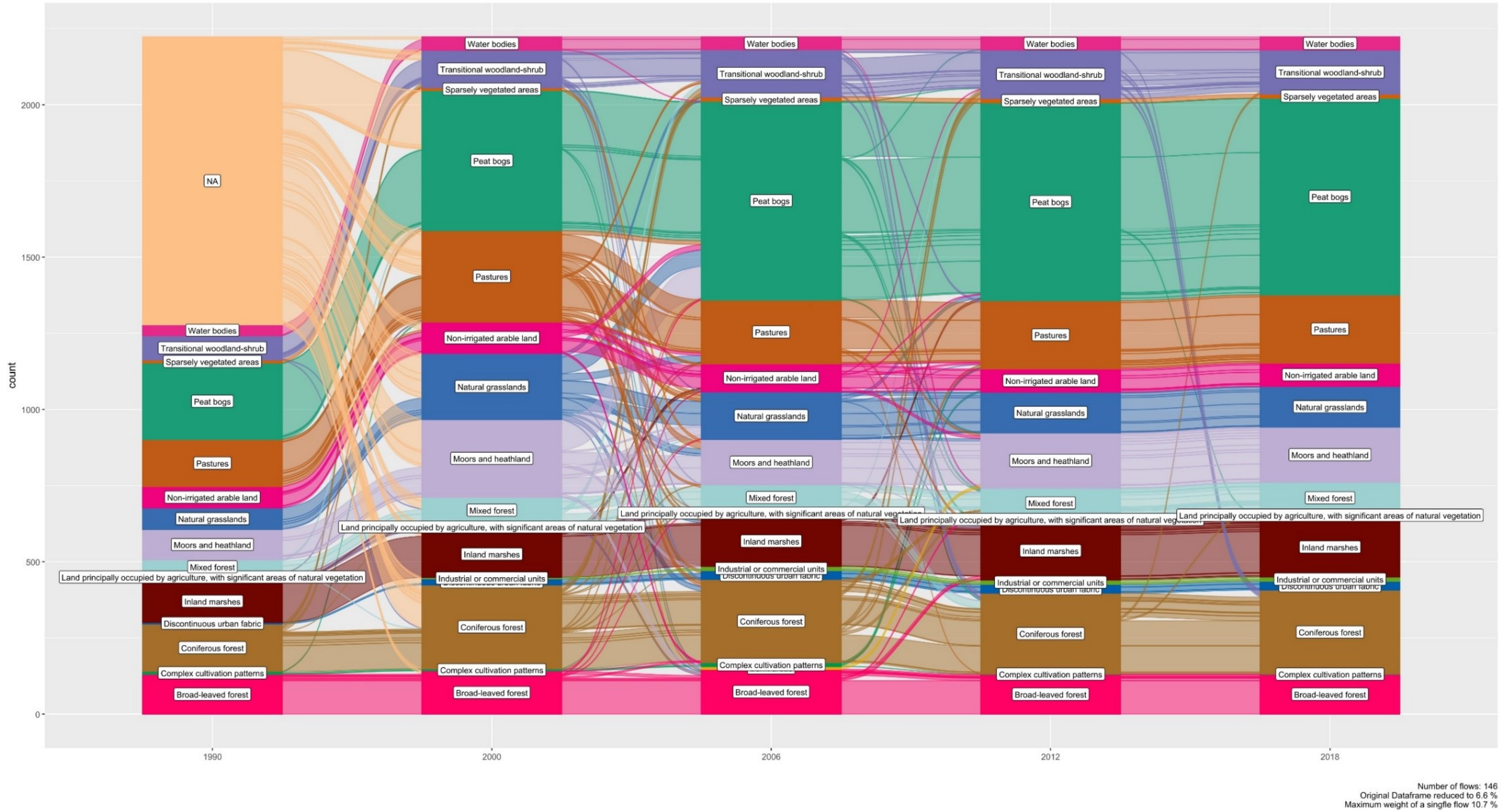

Figure 21. Alluvial plot of Corine Land Cover change in restored project sites, based on CLC classification level 3.

4.3 Discussion

4.3.1 A need for restoration

Despite covering less than 3% of the Earth's land surface (Xu *et al.*, 2018), peatlands have a large influence on global environmental health. They are the planet's most carbon-rich ecosystems per unit area, making them essential allies in addressing climate change. In addition to storing large amounts of carbon, peatlands help regulate hydrological systems, purify water, prevent flooding (Wilson *et al.*, 2011), and support a highly specialized flora and fauna (Rydin & Jeglum, 2013). However, when disturbed, their ability to provide these critical services is rapidly diminished.

In Europe, peatlands span approximately 96 million hectares, accounting for around 20% of the continent's total land area (Lappalainen, 1997). Over time, human intervention has dramatically altered these ecosystems—an estimated 60% of Europe's natural peatlands (Joosten, 1997) have been transformed, primarily for agriculture (50%), forestry (30%), and peat extraction (10%) (Vasander *et al.*, 2003). These activities have led to widespread degradation, contributing to elevated greenhouse gas emissions, declining water tables and land subsidence (Holden *et al.*, 2004). The damage also threatens biodiversity, as many peatland-specialist species have lost their habitats or declined significantly in population (Janssen *et al.*, 2016). In fact, several peatland-related habitat types in Europe are now listed as endangered or in unfavourable conservation status under the EU Habitats Directive (Naumann *et al.*, 2020). Given both the ecological importance of peatlands and the scale of degradation, their restoration has become an urgent priority for climate mitigation (Loisel & Gallego-Sala, 2022). Also, disturbed and degraded peatlands do not provide the same ecological services and thus bear a significant cost to society (Andersen *et al.*, 2017). Restoration typically involves rewetting drained areas, ceasing harmful land uses like peat extraction or intensive agriculture, and re-establishing natural hydrological conditions. These interventions not only help reduce greenhouse gas emissions and enhance climate resilience, but also facilitate the recovery of native species while enhancing the overall ecological functionality and resilience of these ecosystems. Therefore, effective peatland restoration is essential for achieving global goals on climate change mitigation and halting biodiversity loss (Intergovernmental Panel on Climate Change (IPCC), 2023; Minasny *et al.*, 2023).

4.3.2 What is a successful restoration?

Recovery measures can be implemented in many forms. Allan et al. (2023) distinguished three levels of restoration intensity. The "passive**"** category includes sites with no reported intervention to encourage recovery, such as degraded control sites or those explicitly abandoned. Projects with reported interventions to remove stressors—like drainage blocking, rewetting, or tree felling—are classified as "basic**"** restoration. Finally, sites that report measures to actively reinstate peatland ecosystems by reintroducing vegetation are categorized as "active”**.**

Evaluating the outcomes of wetland restoration is challenging, since "success" can be viewed from different angles, e.g., from meeting contractual obligations (‘compliance’) to assessing if ecological functions have been restored. Assessing the effectiveness of peatland restoration requires a comprehensive, interdisciplinary approach that incorporates biophysical, socioeconomic indicators. Crucial to this process is the establishment of robust baselines and long-term monitoring, which enable practitioners to measure progress, identify trade-offs, and adapt management strategies over time. A clearly defined baseline or the use of intact reference sites provides not only a quantifiable "distance to target" but also a shared framework, a common language when talking about success (Andersen et al. 2017).

Biophysical indicators typically include water table levels, vegetation dynamics, greenhouse gas fluxes, and biodiversity metrics, while socioeconomic metrics such as stakeholder engagement, land-use compatibility, and local benefits are increasingly recognized as vital for long-term success and acceptance (Bhomia & Murdiyarso, 2021). Defining appropriate reference states is a practical tool for communication, evaluation, and policy alignment in peatland restoration efforts.
As demonstrated in the preceding analysis, the majority of the reviewed publications did not fulfil these requirements. In many cases, only a limited set of indicators—often biophysical—were monitored, and studies were frequently constrained by short timeframes, primarily due to limited funding. This narrow scope restricts the ability to evaluate long-term restoration outcomes and ecosystem resilience. In Western Europe, the absence of clearly defined baselines and reference sites remains a significant challenge (Andersen *et al.*, 2017), hindering the accurate measurement of restoration progress and the comparability of outcomes across projects.

4.3.3 Aiming at historical references?

Restoring functional conditions in peatlands can be particularly challenging in sites that have undergone extensive degradation or where environmental conditions have shifted significantly. In such cases, full recovery of the original ecosystem structure and function may not be feasible, and restoration efforts should focus on sites where there is a realistic potential for ecological recovery (Andersen *et al.*, 2017). The success of restoration is highly dependent on factors such as the duration and intensity of drainage, the degree of land-use alteration, and the duration between degradation and the onset of restoration (Laine *et al.*, 1995; Loisel & Gallego-Sala, 2022; Price *et al.*, 2003). In areas that have been drained only recently, restoration efforts have a higher likelihood of returning the ecosystem to its original habitat type. However, when the duration of drainage has been intensive and long, it becomes progressively more challenging to fully restore the site to its former ecological state (Vasander *et al.*, 2003). Moreover, physical changes to the peat substrate, such as compaction and oxidation, can result in a permanent reduction in specific yield[9]. A lower specific yield contributes to unstable water tables, which may prevent some functions returning fully. This underlines the need for landscape-scale hydrological interventions that restore high and stable water table levels (Loisel & Gallego-Sala, 2022).

Alterations in the water storage properties of peat, along with the presence of a drainage ditch network, significantly affect the amount and nature of water storage on peatland sites. Although ditch blocking can significantly improve the summer water balance, the water storage processes of the residual peat do not replicate those of the previous state and a water deficit might occur in summer. To mitigate this, it is necessary to provide additional water during the growing season by retaining more

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[9] A ratio between 0 and 1 indicating the amount of water released due to drainage, from lowering the water table in an unconfined aquifer (https://www.dws.gov.za/Groundwater/GroundwaterDictionary.aspx).

winter rainfall or snowmelt water. Shallow basins into the peat, the use of companion species (e.g. *Eriophorum*) whose shading and shelter reduce evaporation losses or straw mulch can help to avoid excessive drying in summer (Price *et al.*, 2003; Vasander *et al.*, 2003). Additionally, attempts should be made to restore the hydrological aspects of the whole watershed, including adjacent mineral soil and peat-covered areas. However, such large-scale hydrological management is often constrained by fragmented land ownership (Vasander *et al.*, 2003).
Also, peat subsidence tends to be more severe near former ditches, causing water to remain concentrated in these areas even after blocking. This can lead to uneven rewetting, producing a patchy mosaic of wet and dry zones that diverges from the uniform moisture conditions typical of intact peatlands (Vasander *et al.*, 2003).
Intact peatlands typically support a mosaic of microhabitats—such as pools, hollows, hummocks, laggs, and patches of tree or shrub thickets—providing ecological niches for a wide range of plant species (Glaser, 1992). However, restoration activities often result in flattened landscapes with little structural diversity or topographic variation. Increasing the variety of micro-habitats is an important option for restoration (Price *et al.*, 2003). Small-scale depressions, or microtopographic minima, can act as initiation points for Sphagnum recolonization. Once established, Sphagnum further modifies its surroundings in ways that support continued expansion. Peatlands with a topography of alternating baulks and trenches do more readily recover than vacuum-harvested sites (Price *et al.*, 2003; Vasander *et al.*, 2003).

4.3.4 Side effects of restoration actions

While peatland restoration is essential for reversing ecological degradation, it is important to recognize that restoration actions, particularly rewetting, can also trigger unintended environmental side effects. For example, when previously drained peatlands are re-inundated, an increase in phosphorus (P) leaching can occur (Vasander *et al.*, 2003). The saturation of peat surfaces often mobilizes phosphorus, leading to elevated phosphorus concentrations, particularly in sites that had been fertilized during their drained phase. This nutrient flux poses risks to water and soil quality and can contribute to eutrophication. Consequently, restoration planning must carefully evaluate site history, hydrological dynamics, and nutrient loading to mitigate adverse effects (Vasander *et al.*, 2003).

4.3.5 Accelerating vegetation recovery

The successful restoration of peatlands and their associated ecosystem services depends critically on the reestablishment of characteristic, self-regulating, peat-forming vegetation, particularly Sphagnum mosses (Rochefort, 2000). In some cases, abandoned extracted peatlands are left to regenerate passively, relying on the spontaneous recolonization of species from nearby remnant vegetation under favourable conditions (Lavoie *et al.*, 2003). Vegetation recovery tends to be more successful when diaspores of peatland species are available nearby (Vasander *et al.*, 2003). However, this approach is often insufficient to reverse decades of degradation. Species may remain absent even after long periods, despite their presence in nearby areas, and restored sites frequently exhibit distinct species compositions for years or decades (Allan *et al.*, 2023; Vasander *et al.*, 2003). As such, active restoration is generally required to effectively recover peatland ecosystems.

Active seeding or planting may be constrained by limited availability of donor sites, dominance by competitive species (Gaffney *et al.*, 2020), or unfavourable abiotic conditions (Smolders *et al.*, 2003). Drainage (and the removal of the acrotelm if present) induces long-lasting changes to the hydraulic properties of the residual peat, including lower hydraulic conductivity and higher water retention. These conditions may restrict water availability for non-vascular plants such as Sphagnum, hindering their reestablishment. Additionally, deeper peat cutting can lead to the intrusion of minerotrophic water from regional groundwater flows, negatively impacting bog-specific flora (Price *et al.*, 2003; Vasander *et al.*, 2003).

Where abiotic conditions are favourable but diaspores are lacking, targeted revegetation can facilitate recovery. Although restoring a near-pristine peat-forming vegetation cover is rarely achievable in the short term, more intensive interventions can significantly accelerate ecological recovery (Allan *et al.*, 2023).

4.3.6 Interaction with global change

Peatland ecosystems in recovery often lack the stability and resilience characteristics of fully recovered or undisturbed sites (Koebsch *et al.*, 2020). These recovering systems can remain more vulnerable to external stressors, such as extreme weather events, including flooding and fire. Drained and degraded peatlands are particularly prone to burning due to their lack of hydrological stability (Loisel & Gallego-Sala, 2022; Wilkinson *et al.*, 2018).
Sites in transition to be recovered might still be a net carbon source to the atmosphere. This can result from reduced net primary productivity (NPP) and altered litter quality, thereby limiting carbon input, or continued decomposition of previously accumulated peat due to site history (Loisel & Gallego-Sala, 2022). Therefore, restored sites should not be automatically assumed to act as long-term carbon sinks (Allan *et al.*, 2023).
Climate warming may be changing the current geographic extent of peatlands (Gallego-Sala & Prentice, 2013). Shifts in plant distribution are expected to be greatest in the transition between the Mediterranean and Euro-Siberian regions (Thuiller *et al.*, 2005). Identifying where peatlands are most likely to remain ecologically functional, or where disturbed systems are nearing irreversible thresholds, is vital for prioritizing restoration and management strategies that enhance ecological resilience (Gillson *et al.*, 2013). To effectively guide such actions, restoration planning should be embedded within a broader framework that incorporates climate modelling and future scenario analysis (Andersen *et al.*, 2017).

4.3.7 A monitoring framework

As demonstrated by our findings, the monitoring of peatland restoration outcomes is often significantly limited by resource constraints and short-term funding cycles. We have emphasized the need for standardized, well-funded, long-term monitoring programs that are fully integrated into restoration efforts. Trends observed to date may not persist under different or changing environmental conditions, highlighting the importance of sustained observation (Allan *et al.*, 2023).

Peatland restoration must be supported by monitoring frameworks that enable adaptive management. Such monitoring informs project design, site selection, restoration strategies, and ongoing management, allowing for iterative improvements based on observed outcomes. Protocols for assessing the trajectory of restored ecosystems are essential to objectively evaluate both successes and shortcomings. Particularly valuable are simple, clearly defined indicators that are easy to identify, measure and track over time. A scientifically robust, cost-effective and practical set of criteria and indicators can help key stakeholders to assess the progress and outcomes of restoration efforts, and determine whether restoration efforts are moving in the desired direction (Bhomia & Murdiyarso, 2021).

In addition, developing a reference library and identifying indicator thresholds across different peatland habitat types is essential. This will create a critical knowledge base to guide and optimize future restoration efforts (Kyrkjeeide *et al.*, 2024).

While vegetation is the most commonly monitored aspect of peatland restoration, other factors such as greenhouse gas emissions, peat properties, fauna, and hydrology, are assessed less frequently (Kentula, 2000). Ideally, monitoring indicators should be balanced across all dimensions of sustainability: environmental, social, economic, and governance. These include biophysical indicators that capture ecological, hydrological, and fire-related dynamics; social indicators reflecting networks, equity, trust, justice, and civic participation; economic indicators to track current incentives and emerging livelihood opportunities within peatland landscapes; and governance indicators that assess the effectiveness and appropriateness of policies at local, regional, and national levels (Bhomia & Murdiyarso, 2021).

Where necessary, peatland restoration practices and indicators should be adapted to local geographic conditions, taking into account specific biophysical challenges and social contexts (Bhomia & Murdiyarso, 2021).

4.3.8 Way forward

A single restoration technique is generally insufficient to deliver reliable improvements in the short term. Active revegetation is often additionally required. We would benefit from developing cost-effective methods and suitable proxies for monitoring large-scale restoration projects (Andersen *et al.*, 2017).

Restoration depends heavily on social support, as the successful implementation of projects relies on broad public backing. Active social engagement is therefore important particularly through education and information sharing (Bhomia & Murdiyarso, 2021).

To accelerate the development and refinement of best practices, it is vital to create European and national platforms with practical knowledge, technological innovations, research and monitoring results that are openly accessible for all stakeholders (Andersen *et al.*, 2017).

Long-term commitment from all involved actors is critical—especially with regard to sustained financial investment. Ensuring the continuity of restoration programmes requires ongoing funding, which may be supported through existing market mechanisms, the creation of new markets for alternative livelihoods, consistent stakeholder contributions, or local actors taking financial responsibility for restoration activities (Bhomia & Murdiyarso, 2021).

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6 Annex [I] - [mire area estimates in Europe]

Table 1. Peatland estimates in Europe (EU countries). Definition of peatland based on peat depth and organic content differs between countries, and some estimates are rather rough. More details can be found in Joosten et al. (2017) and Tanneberger et al. (2017) . The percentage of peatland area expressed as a total fraction of the respective country, and the corresponding project sites in the database are also mentioned.

	Country	country area	peatland estimate		project database	
		(km²)	(km²)	% of country area		(km²)
European Union 27	Austria	83871	1200	1.43	1	0,15
	Azores	2333	160	6.86	0	0,00
	Belgium	30528	247.8	0.81	12	1,76
	Bulgaria	110900	208	0.19	0	0,00
	Croatia	56594	33.1	0.06	0	0,00
	Cyprus	9251	< 0.1	< 0.1	0	0,00
	Czech Republic	78866	285.4	0.36	26	3,82
	Denmark	43094	2029	4.71	33	4,85
	Estonia	45227	9150	20.23	9	1,32
	Finland	337010	90000	26.71	109	16,03
	France	551500	2875	0.52	37	5,44
	Germany	357137	12800	3.58	56	8,24
	Greece	131957	103	0.08	0	0,00
	Hungary	93026	300	0.32	1	0,15
	Ireland	69825	14664.7	21	86	12,65
	Italy	301339	750	0.25	0	0,00
	Latvia	64562	7514	11.64	15	2,21
	Lithuania	65300	6460	9.89	7	1,03
	Luxembourg	2586	3.5	0.14	0	0,00
	Malta	-	-	-	0	0,00
	Netherlands	37354	2733.4	7.32	9	1,32
	Poland	311888	14950	4.79	63	9,26
	Portugal	89879	271	0.29	0	0,00
	Romania	238391	7690	3.23	0	0,00
	Slovakia	49036	60	0.12	0	0,00
	Slovenia	20273	83.9	0.41	0	0,00
	Spain	505992	350	0.07	19	2,79
	Sweden	450295	66450	14.76	43	6,32

Table 2. Peatland estimates in Europe (non-EU countries). Definition of peatland based on peat depth and organic content differs between countries, and some estimates are rather rough. More details can be found in Joosten et al. (2017) and Tanneberger et al. (2017). The percentage of peatland area expressed as a total fraction of the respective country, and the corresponding project sites in the database are also mentioned.

	Country	**country area**	**peatland estimate**		**project database**	
		(km²)	(km²)	% of country area	project sites	% of sites
Europe (non-EU)	Albania	28748	44	0.15	0	0,00
	Andorra	468	5	1.07	0	0,00
	Armenia	29743	47	0.16	0	0,00
	Azerbaijan	86600	2.7	< 0.1	0	0,00
	Belarus	207600	25605	12.33	12	1,76
	Bosnia and Herzegovina	51209	180	0.35	0	0,00
	Faroe Islands	1393	17.6	1.26	0	0,00
	Georgia	69700	170	0.24	0	0,00
	Iceland	103000	5777	5.61	0	0,00
	Liechtenstein	160	2.6	1.63	0	0,00
	Republic of Macedonia	25713	281	1.09	0	0,00
	Republic of Moldova	33846	10	< 0.1	0	0,00
	Montenegro	13812	75	0.54	0	0,00
	Norway	323787	44700	13.81	0	0,00
	Russian Federation (European part)	4000000	680000	17	20	2,94
	Serbia	88361	100	0.11	0	0,00
	Svalbard	62422	3000	4.81	0	0,00
	Switzerland	41285	280	0.68	3	0,44
	Turkey	783562	220	< 0.1	0	0,00
	Ukraine	603500	10000	1.66	1	0,15
	United Kingdom	242495	26838.3	11.07	118	17,35

7 Annex [II] - [stress categories]

livestock	overgrazing
	lack of grazing
	inappropriate grazing regime
	livestock pressure
	grazing
	undergrazing
other	poldering
	dam (hydropower)
	vegetation removal
	habitat loss
	invasive species
	management
	recreational pressure
	urban sprawl
	LU change
	industrialisation
	subsidence
	scrap yard
	invasive species
	fragmentation
	coal mining
	abandonment of management
	cement factory
	sand & pebble quarry
	steep slope

agriculture	agriculture
	agricultural intensification
	ploughing
	cultivation
drainage	drainage
	ditching
	breaching of sealing layer
Peat extraction	peat extraction
	hand cutting of peat
	domestic fuel
	peat fuel
	peat removal
	cut over
	fuel cutting
	mining
	excavation
	large scale peat extraction
	domestic peat extraction
	drainage, peat removal, change in groundwater flow
	industrial scale peat cutting
	peat mining
	peat cutting
	cutover peatland

erosion	peat erosion
	erosion
fire	fire
	burning
	wildfire
	illegal burning
	extensive burning
forestry	afforestation
	forestry
	tree planting
	forestry plantations
overgrowing	overgrowing
	spread of trees
	tree invasion
enrichment	atmospheric pollution
	nutrient enrichment
	nutrient rich effluent
	eutrophication

8 Annex [III] - [CLC change tables]

Table 3. CLC Change for hierarchical level 1

CLC Level	CLC label	Reference year				
LEVEL1	LABEL2	1990	2000	2006	2012	2018
1	Artificial surfaces	5	25	43	43	43
2	Agricultural areas	253	435	332	313	313
3	Forest and semi-natural areas	593	1106	987	981	981
4	Wetlands	391	613	819	843	843
5	Water bodies	36	44	42	43	43
9	NA	18	NA	NA	NA	NA
NA	NA	927	NA	NA	NA	NA

Table 4. CLC Change for hierarchical level 2

CLC Level		CLC label	Reference year				
LEVEL1	LEVEL2	LABEL2	1990	2000	2006	2012	2018
1	1	Urban fabric	5	20	29	29	29
2	1	Arable land	70	103	92	76	76
2	3	Pastures	154	300	209	224	224
2	4	Heterogeneous agricultural areas	29	32	31	13	13
3	1	Forests	334	502	504	493	508
3	2	Scrub and/or herbaceous vegetation associations	250	595	461	475	460
3	3	Open spaces with little or no vegetation	9	9	22	13	13
4	1	Inland wetlands	391	613	819	843	843
5	1	Inland waters	36	44	42	43	43
9	9	NA	18	NA	NA	NA	NA
NA	NA	NA	927	NA	NA	NA	NA
1	2	Industrial, commercial and transport units	NA	5	14	14	14

Table 5. CLC Change for hierarchical level 3

CLC Level			CLC label	Reference year				
LEVEL1	LEVEL2	LEVEL3	LABEL3	1990	2000	2006	2012	2018
1	1	2	Discontinuous urban fabric	5	20	29	29	29
2	1	1	Non-irrigated arable land	70	103	92	76	76
2	3	1	Pastures	154	300	209	224	224
2	4	2	Complex cultivation patterns	9	7	13	1	1
2	4	3	Land principally occupied by agriculture, with significant areas of natural vegetation	20	25	18	12	12
3	1	1	Broad-leaved forest	131	142	147	131	131
3	1	2	Coniferous forest	156	275	273	265	275
3	1	3	Mixed forest	47	85	84	97	102
3	2	1	Natural grasslands	71	217	157	134	134
3	2	2	Moors and heathland	99	255	148	181	181
3	2	4	Transitional woodland-shrub	80	123	156	160	145
3	3	3	Sparsely vegetated areas	9	9	13	13	13
4	1	1	Inland marshes	139	153	166	193	197
4	1	2	Peat bogs	252	460	653	650	646
5	1	2	Water bodies	36	44	42	43	43
9	9	9	*NA*	18	*NA*	*NA*	*NA*	*NA*
NA	*NA*	*NA*	*NA*	927	*NA*	*NA*	*NA*	*NA*
1	2	1	Industrial or commercial units	*NA*	5	14	14	14
3	3	4	Burnt areas	*NA*	*NA*	9	*NA*	*NA*