Ramsar Technical Report 11

Convention on Wetlands

Global guidelines for peatland rewetting and restoration

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Foreword

Half of the world’s wetlands are peatlands, amounting to 3% of the Earth’s land surface. They provide many essential ecosystem services, regulating the water cycle, purifying water and supporting a wealth of biodiversity. Peatlands also store more carbon for longer periods than any other ecosystem worldwide. However, around 50 million hectares have been drained, causing an estimated 4% of global carbon dioxide emissions, and will continue to emit unless restored. Half of these drained peatlands need to be restored by 2030 if we are to achieve the objective of the Paris Agreement to keep global temperature rise below 1.5 – 2.0°C.

The 172 contracting parties to the Convention on Wetlands have recognized the need for peatland restoration, e.g. in Resolution XIII.13, *Restoration of degraded peatlands to mitigate and adapt to climate change and enhance biodiversity and disaster risk reduction*, as well as in the Convention’s Strategic Plan, which includes a Target on restoration of degraded wetlands with priority to wetlands that are relevant for biodiversity conservation, disaster risk reduction, livelihoods, and/or climate change mitigation and adaptation.

This technical report, prepared by the Scientific and Technical Review Panel of the Convention, summarizes the state of knowledge and identifies principles for restoring drained peatlands. The report is complemented by a Briefing Note (No. 11), which provides hands-on methodological guidance for restoring drained peatlands, and a Policy Brief (No. 5), which provides information and recommendations for policy makers.

Together, these products can help parties to the Convention as well as a broad range of other stakeholders identify and implement appropriate peatland restoration activities. They can support planning and informed decision making, enabling countries to, for example, include peatland restoration in Nationally Determined Contributions as well as other planning frameworks, while accelerating the implementation of the Convention on Wetlands.

Without ambitious action to protect and restore peatlands, it is unlikely that our shared climate change, sustainable development and biodiversity conservation goals can be reached. At the start of the UN Decade on Ecosystem Restoration 2021-2030, I hope that these products will inspire as well as empower action.

Lei Guangchun
STRP Chair

Summary

The Convention on Wetlands (The Convention) and other national, regional and global policy frameworks promote the restoration of degraded peatlands. Rewetting peatland to reduce greenhouse gas emissions is an important climate change mitigation strategy, and meeting the objectives of the Paris Agreement may require rewetting of virtually all drained peatland, a total of over 50 million hectares globally.

This Ramsar Technical Report provides comprehensive technical guidance and background information on peatland rewetting and restoration for regional planners, site managers and policy makers.

General principles

- For many geographical regions, peatland types and forms of degradation, no specific guidance to ecosystem restoration exists. Therefore, it is wise to draw lessons from experiences elsewhere, not to blindly imitate measures, but to develop solutions that fit the local circumstances.
- Whereas every peatland is unique, peatlands worldwide share many characteristics. Too much emphasis on the 'unique character' of tropical (or other) peatlands can result in a danger of ignoring global knowledge and common sense.
- Peatland restoration not only depends on scientific and technical capacities, but also on institutional, regulatory, economic, political and societal opportunities and constraints. Restoration requires public support and acceptance, including from the local community and local stakeholders. Goal setting should therefore always involve an iterative process of problem analysis and goal formulation with those affected.
- It is important to recognise that:
  - peatland restoration cannot bring back all values lost as a result of peatland degradation, which reinforces the primary importance of conservation,
  - anything less than comprehensive rewetting will result in continued carbon emissions and peat subsidence,
  - all drained peatland is fire-prone and will as a result of subsidence eventually fall victim to uncontrolled flooding or to complete oxidation of the peat, often leaving acid-sulphate or infertile land,
  - insufficient consideration of overall hydrological conditions may lead to poor planning and management.

Restoration goals

- Restoration goals can be formulated in terms of 'ecosystem services', i.e., the benefits that people and society obtain from ecosystems. Restoration goals must be formulated as concretely as possible and in priority order to provide guidance in case goals conflict with each other.
- In general, rewetting of drained peatlands has a net very positive impact for the climate, even if there are large initial methane emissions. Furthermore, management techniques exist to reduce these methane emissions substantially.
- Restoration for nature conservation should 'do' as little as possible, rely mainly on spontaneous development and, thereby, limit the increase of 'artificiality'. Management should, therefore, focus on veto-regulation (preventive/ forbidding/external management) and on once-off interventions. This also increases cost-effectiveness and decreases risks of losing investment, because perpetual active management continuously increases cumulative costs.
- Most peatland degradation results from drainage for farming and forestry. The global need to rewet 50 million hectares of degraded peatlands, while simultaneously maintaining biomass harvest, implies that use of drained peatland must largely be replaced by land use that does not require drainage (i.e., 'paludiculture', agriculture and forestry on wet peatlands).
- As peatlands consist of 90-95% water, land uses needing different water tables (e.g., high water tables to promote climate change mitigation versus lower water tables for drainage-based agriculture) cannot be combined sustainably within the same peatland.

Restoring hydrology

- Water tables that are too low and unstable as a result of anthropogenic changes are the central problem that peatland restoration has to address. Individual peatlands may, however, differ enormously with respect to their internal hydrologic functioning and their dependence on water conditions outside the peatland, and thus also differ in the types of restoration needed.
- The presumption that peat growth will eventually recover spontaneously in seriously degraded peatlands is questionable. In most cases, recovering optimal conditions for peat conservation and renewed peat accumulation will require active intervention to restore the water table to around the peat surface, accompanied by recovery or restoration of peat-forming vegetation.
- Effective blocking (damming) of drainage structures (ditches, canals, etc.) involves strategic planning of location and spacing of dams (to increase rewetting effectiveness), the use of local materials (to minimize costs), regular inspection, monitoring and maintenance, and the promotion of spontaneous re-filling of ditches (to eventually remove the need for dam maintenance). Great potential still exists for increasing effectiveness and reducing costs.
- Where continuously high and stable water tables cannot be secured by ditch blocking, the water table has to be raised *over* the surface. This should be done by creating or facilitating aboveground structures (bunds, hummocks, buttressed and stilt-rooted trees) that hamper wet-season surface run-off.
- Sites with concentrated downward seepage (e.g., ditches dug deep into the mineral subsoil) can be clogged with peat or other impermeable material (clay, bentonite). If downward seepage is diffuse, stabilisation of a high peatland water table will require raising the hydraulic head under the peatland, by raising the water table outside of the peatland.

Vegetation management

- Re-establishment of peat forming vegetation is the second main challenge of peatland restoration. The right vegetation not only allows renewed peat accumulation but may also be indispensable for regaining hydrologic self-regulation. Furthermore, vegetation may support important biodiversity as well as livelihoods of local populations.
- The principal mechanism of hydrologic self-regulation in raised bogs is the vegetation based 'acrotelm'. For *Sphagnum* raised bogs the 'right' peat-forming *Sphagnum* species are essential, which might require deliberate re-establishment of these species. For tropical peat domes, a forest cover should be re-established with tree species that develop hummocks and root structures that retain wet-season surplus water. While natural re-development of such structures will take decades, constructed mounds and ridges can support the hydrological function and speed up the establishment of the right tree species.
- Half of the degraded peatland area worldwide has undergone extreme changes in hydrology and vegetation as a result of conversion to agriculture. A substantial part of these agricultural peatlands are extremely nutrient rich as a result of peat mineralisation and fertilization. Three options exist for rewetting and restoration of these lands:
    - remove the extremely nutrient-rich top layer before rewetting ('top-soil removal');
    - remove nutrients by long-term phytoextraction after rewetting (*cf.* paludiculture); or
    - accept extremely nutrient-rich fens with low biodiversity for decades or longer.

Top-soil removal is very effective in reducing nutrient and pesticide availability, but costly.

- In case the desired species do not establish spontaneously, re-introduction can be considered, e.g., by direct seeding, hay transfer, transplanting sods, planting pre-grown seedlings, etc.

Monitoring, evaluation and knowledge gaps

- Restoration results should be systematically monitored and evaluated and the lessons learned incorporated in subsequent work and future planning.
- Important knowledge gaps for peatland restoration are:
    - the role of 'ecosystem engineer' and peat forming species in re-establishing peat formation;
    - the importance of hydrological self-regulation and spontaneous regeneration;
    - the return of ecosystem functions and services;
    - the effect of climate change on restoration perspectives; and
    - the lack of common monitoring concepts and protocols.
- To achieve peatland rewetting and restoration on the necessary scale, it is imperative that more awareness is raised on the problems and much more technical and institutional capacity is built to help solve them.

Key messages

- The Paris Agreement implies rewetting virtually all drained peatland (50 m ha globally).
- Without complete rewetting and vegetation regeneration, peat subsidence and carbon emissions continue; and all drained peat will eventually undergo uncontrolled flooding or complete oxidation, often leaving infertile soils.
- Peatland restoration cannot bring back all the values lost, so conservation comes first.
- Peatland restoration depends on societal opportunities and constraints. Goal setting must involve an iterative process of problem analysis and goal formulation.
- Restoration goals must be stated clearly and in priority in case different goals conflict.
- Restoration experiences should be monitored, evaluated and lessons incorporated in future work and planning.
- Low and unstable water tables are the central issue to be addressed by restoration, but the type of actions needed differs between peatlands.
- Effective blocking of drainage involves strategic planning of dam location and spacing, regular inspection, timely maintenance, and promotion of spontaneous ditch re-filling.
- When blocking ditches is not enough, bunds, hummocks, buttressed or stilt-rooted trees are needed to hamper wet-season surface run-off.
- Re-establishing peat forming vegetation is the second main restoration challenge. Re-introduction may be needed.
- In raised bogs, a key aim is to restore the acrotelm, a vegetation-based hydrologic self-regulation mechanism. Sphagnum raised bogs require the re-establishment of the right Sphagnum moss species; tropical peat domes trees that develop hummocks and buttressed and stilted roots.
- Peatlands under intensive agriculture are often nutrient-rich. Restoration means costly top-soil removal, phytoextraction of nutrients (paludiculture), or accepting long-term persistent, highly productive, low-biodiversity fens.
- Peatlands share many characteristics; one site can learn from experiences elsewhere.

1. Introduction

Peatlands are ecosystems in which – under permanently water-saturated, oxygen-poor soil conditions – dead plants do not completely decay. The semi-decomposed plant material accumulates as layers of 'peat' that over time may reach many metres in thickness.

Characteristics of peatlands

Typical characteristics of peatlands are:[1] [86]

- High soil organic matter and carbon content, permanent water saturation, a slow but continuous rising of the water table and the peatland surface, relative nutrient poverty and acidity, a cooler and more humid meso-climate compared to the surroundings, and the presence of noxious organic substances, toxic reduced elements, and black water. All these factors form the habitats of peatland-typical biota.
- A unique capacity for long-term carbon sequestration and storage, water retention, purification and control, and the accumulation and preservation of palaeo-environmental information and archaeological artefacts within the accumulating peat mass.
- A sophisticated interaction of plants, peat and water, which allows for the long-term development of self-regulation and self-organisation, making peatlands into enduring ecosystems, which often have fascinating surface patterning and unique ecosystem biodiversity.

More than 80% of global peatland, mainly situated in the inhospitable areas of Canada, Alaska and Siberia, is still in a largely natural state. However, a substantial area (~65 million ha,[86, 116] mainly in the temperate zone and the (sub)tropics, has been transformed and drained to be used for crops, grazing and forestry, or for peat extraction and infrastructure facilities. These degraded peatlands cause major environmental and socio-economic problems, including soil degradation, floods and fires, and create globally relevant greenhouse gas emissions. Other peatland ecosystem services and biodiversity values also deteriorate as a result of drainage and degradation.[13] An overview of these services and values is presented in Annex I.

The climate and health burden of degraded peatlands

Whereas natural peatlands have been cooling the climate for more than 10,000 years,[46] drained and degraded peatlands are significant sources of greenhouse gases (GHGs) and contribute to global warming. These GHGs mainly result from microbial oxidation of organic matter when air reaches the formerly water-saturated peat.[96] The drier conditions following drainage also increase the risk of fire.[69, 102, 170] Along with massive GHG emissions, smouldering peat fires cause widespread haze with deleterious effects on human health.[54, 123]

The emissions from peatland drainage, degradation and fires are currently responsible for some 2 Gt CO_2-eq, some 4% of global anthropogenic GHG emissions.[45, 63, 96, 116, 161, 184] Continuing emissions from drained peatlands until 2100 may consume 12–41% of the GHG emission budget that still remains to keep global warming below +1.5 to +2 °C.[116] Another projection indicates that the global land sector will be a net carbon source by 2100, unless all current intact peatlands remain intact and at least 60% of the currently degraded peatlands are rewetted in the coming decades.[79] This implies that by rewetting 'only' 60% of degraded peatlands (30 million ha), the entire carbon sink capacity of the remaining land sector (i.e., forest biomass and mineral soils) would be needed to compensate for the carbon losses from the remaining degraded peatlands (the remaining 40%) and will not contribute to the 'net carbon sinks' required to reach the Paris goals.[82]

1 Bibliographic references are available in the References section below in the text referred to with superscript bold italic numbers.

The climate issue in particular illustrates the magnitude of the challenge: Compliance with the 2015 Paris Agreement and reaching carbon and climate neutrality by mid-century[82, ch 2] implies that over the coming decades virtually all currently drained peatland (i.e., some 50 million hectares, half of this area being in agricultural use) needs to be rewetted and restored globally, almost **two million hectares *per year***.

Awareness of these issues brought the restoration of wetlands,[2] and peatlands in particular,[3] to the agenda of the Convention on Wetlands, the oldest of the modern global intergovernmental environmental agreements.[4] Other policy frameworks also emphasise the restoration of peatlands explicitly or implicitly. These frameworks include at the global level, *inter alia*, the UN Sustainable Development Goals,[5] the UNEA 2019 resolution on peatlands,[6] the Paris Agreement and its Nationally Determined Contributions (NDCs, UNFCCC),[7] the Aichi targets and the post 2020 Global Biodiversity Framework (CBD),[8] land degradation neutrality (UNCCD),[9] the Bonn Challenge,[10] and the UN Decade on Ecosystem Restoration,[11] along with many regional, national and local initiatives.

This Ramsar Technical Report includes general standards for ecological restoration,[47] but also deals with situations in which the former ecosystem *cannot* be fully restored or in which there is a wish to restore *only some* of the former ecosystem services. The Report is informed by and complements existing (regional) peatland restoration guidelines (*see* Chapter 6) and aims to provide an integrated global synopsis.

The wide variety of peatlands, the many causes and types of degradation, and the diversity of restoration goals do not allow all issues to be addressed in detail. Therefore, this Report focuses on the principles of peatland restoration and on understanding interrelations and problems. With this understanding, planners, practitioners and policy makers, can – with knowledge of local conditions and the information contained in this guidance, its references and the associated Ramsar Briefing Note No. 11 on practical peatland restoration[88] – identify and develop appropriate solutions. This Ramsar Technical Report, thus, presents:

- key principles that apply to peatland restoration efforts worldwide;
- restoration information for peatland types and aspects not yet covered by the Convention[12] and other guidance; and
- reference to practical guidelines and experiences.

Key terms and definitions used in this report[13]

Acrotelm: upper layer of a living raised bog, consisting of the vegetation and the uppermost peat, which through its distinct vertical gradient in hydraulic conductivity and large water storage capacity stabilizes the water level.

Anoxic: oxygen-free.

Bog: Peatland of which the upper peat layers are derived from vegetation that was only supplied with water and nutrients by precipitation. A raised bog is a bog of which the surface and water level are clearly raised above that of the surrounding fen or mineral soil.

2 https://www.ramsar.org/sites/default/files/documents/library/key_res_vii.17e.pdf. https://www.ramsar.org/sites/default/files/documents/pdf/res/key_res_viii_16_e.pdf. https://www.ramsar.org/sites/default/files/documents/library/cop11-res09-e.pdf. https://www.ramsar.org/sites/default/files/documents/library/bn10_restoration_climate_change_e.pdf. https://www.ramsar.org/sites/default/files/documents/library/bn4-en.pdf. https://www.ramsar.org/sites/default/files/documents/pdf/lib/hbk4-19.pdf.

3 https://www.ramsar.org/document/resolution-viii17-guidelines-for-global-action-on-peatlands.
https://www.ramsar.org/document/resolution-x24-climate-change-and-wetlands.
https://www.ramsar.org/document/resolution-xii11-peatlands-climate-change-and-wise-use-implications-for-the-ramsar.
https://www.ramsar.org/document/resolution-xiii13-restoration-of-degraded-peatlands-to-mitigate-and-adapt-to-climate-change.
https://www.ramsar.org/sites/default/files/documents/library/briefing_note_peatlands_vilm_workshop_sept_2016.pdf.

4 Peatlands are a cross cutting issue in the Convention and cover 20 types of the Ramsar Classification System for Wetland Types (https://www.ramsar.org/sites/default/files/documents/library/key_res_vii.11e.pdf).

5 https://sustainabledevelopment.un.org/?menu=1300.

6 https://wedocs.unep.org/handle/20.500.11822/30675.

7 https://unfccc.int/nationally-determined-contributions-ndcs.

8 https://www.cbd.int/sp/targets/ , https://www.cbd.int/conferences/post2020.

9 https://www.unccd.int/actions/achieving-land-degradation-neutrality.

10 https://www.bonnchallenge.org/content/challenge.

11 https://www.decadeonrestoration.org/ , UN General Assembly Resolution 73/284, 1 March 2019.

12 https://www.ramsar.org/document/resolution-xiii13-restoration-of-degraded-peatlands-to-mitigate-and-adapt-to-climate-change.

13 These definitions are for the purpose of this document only and have been kept as short and simple as possible. Extensive reviews of peatland terms are available in [89, 99].

Conservation: All deliberate actions that protect the environment and natural resources (including biodiversity).

Degraded: Lowered/altered in quality as compared to the original condition.

Ecosystem engineers: species that modify their environment to the extent that they determine the strategic functioning of the ecosystem.

Ecosystem services: Benefits that people obtain from ecosystems.

Fen: Peatland of which the uppermost peat layers are derived from vegetation that also received water that has been in contact with mineral soil or bedrock (*cf*. bog).

Flagship species: species that function as an ambassador, icon or symbol for a habitat.

GHG: greenhouse gas.

Horizontal mire: Mire in which the water table forms a horizontal plane leading to mainly vertical water movement (water level fluctuations).

Inclining mire: Mire in which the water table forms a sloping plane, leading to mainly horizontal water movement (water flow).

Mire: Peatland in which peat is being formed.

Organic matter: Carbon-hydrogen based material of plant, animal, fungal and microbial origin.

Organic soil: Soil with a substantial layer of organic matter at or near the surface.

Paludiculture: A farming and forestry system that targets the production of plant- or animal-based commodities on (wet) peatland while preserving the peat carbon stock and minimizing greenhouse gas emissions from the peat soil.

Peat: Substance largely consisting of dead organic matter, with macroscopic plant remains, which after its creation has not been relocated by water or ice or wind (*cf*. sediment).

Peatland: Area with a spontaneously accumulated layer of peat at the surface.

Recovery: The development of a degraded ecosystem to a former, better state or condition. When this state or condition has been reached, the ecosystem is (spontaneously) 'regenerated', (actively) 'restored' or (in general) 'recovered'.

Regeneration: The spontaneous recovery of a degraded ecosystem.

Rehabilitation: All deliberate actions that steer a degraded ecosystem to a more beneficial condition (e.g., in terms of delivery of ecosystem services), but unlike the one before degradation.

Restoration: All deliberate actions that contribute to the recovery of a degraded ecosystem. When this goal has been reached, the ecosystem is 'restored'.

Rewetting: All deliberate actions that aim to bring the water table of a drained peatland (i.e., the position relative to the surface) back to that of the original, peat-forming peatland. When this goal has been reached, the peatland is 'rewetted'.

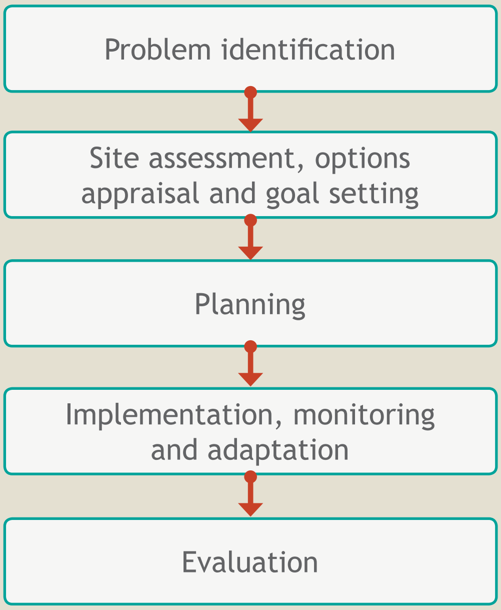
Transitional mire: Fen that receives acid and nutrient poor groundwater and functions like a fen, but with vegetation and hydrochemistry similar to that of a bog.

2. Problem identification

Every ecosystem restoration project starts with the awareness that something is wrong. Sometimes the issue is evident: the decline or loss of a species, a landscape view that has changed, a beneficial function that has been lost. In other cases, the problem is less obvious. Most people, for example, do not interpret a green meadow as being a heavily degraded peatland. The positive associations of rural income, milk, cheese and a familiar scenery hide the climate burden of drained peatland use. This common lack of awareness is understandable because peat is below ground and invisible. Furthermore, political awareness of the peatland – climate relationship is rather new[14] – and the urgency to *solve* this problem only emerged with the Paris Agreement (2015).

When you have formulated *what you have lost* and *what you would like to have back*, the next tasks are to:

- *analyse whether it is possible* to have these things back;
- *clarify whether active intervention is needed* (some problems solve themselves spontaneously…); and
- (informed by this knowledge) *choose and clearly formulate the targets* of the restoration action.



Every project starts with the awareness that there is a problem. This problem must be understood by examining the condition of the site (*what biodiversity or ecosystem services have been lost?*). Whether all losses can be regained will depend on the type of losses and the condition of the site (*which services can be restored?*). Using this knowledge, the goals can then be set within a coherent and logical context. After detailed planning of necessary actions, the measures are implemented, their results monitored and management actions are, if necessary, adapted. After the end of the project, an evaluation should take place to assess success to date, forecast future developments and plan further action.

Figure 1
Problem identification (source: Hans Joosten).

14 E.g., first awareness: Convention on Wetlands 2002: https://www.ramsar.org/document/resolution-viii3-climate-change-and-wetlands-impacts-adaptation-and-mitigation; Convention on Biological Diversity 2004: https://www.cbd.int/decisions/cop/7/15/1; Climate Convention 2008: http://unfccc.int/files/kyoto_protocol/application/pdf/iceland.pdf.

3. Site assessment

To set clear goals, you must know *what is possible* and *what you want*. This chapter discusses: i) the major peatland functional types, ii) the ecological relations within a peatland and between a peatland and its surrounding and iii) the various intensities of degradation. All these aspects may constrain the perspectives of restoration, i.e., what can ultimately and realistically be achieved.

3.1. Peatland types

Just as horses, cars and airplanes are all a means of transport, but – if they malfunction - differ in the way they have to be cured or repaired, huge differences exist between peatlands. Failure to identify how the peatland in question functioned in a natural state may not only prevent effective restoration but may also risk attempts at restoration disrupting existing conservation values (figure 2).

The diversity of peatlands and peatland uses have given rise to dozens of peatland typologies.[98] Their classification principles often relate to how the peatland can be used, how it looks, or where it is situated. Such typologies, though commonly applied, give little information on how the peatland is or has been functioning and are, therefore, less useful from a restoration point of view.

Bogs and fens

A categorization that does have relevance to restoration is the classic division between **bogs** (peatlands that receive their water and nutrients solely from atmospheric precipitation) and **fens** (peatlands that also receive water that has been in contact with mineral soil or bedrock). Because of their water supply, bogs are strongly acidic and nutrient poor, while the water supply of fens is more nutrient rich and may vary from weakly acidic to alkaline. Some fens receive groundwater that is acid and nutrient poor. Based on their landscape positioning and water supply, such **transitional mires** function like a fen, but their vegetation and hydrochemistry are similar to that of a bog.

Figure. 2
Restoration plans in Sandaohaizi wetland (Xinjiang UAR, China) were stopped after recognition that the site was not a severely degraded peatland with remnant erosion hag tops, as assumed, but in fact China's only known palsa and lithalsa permafrost peatland complex with a natural build-up and degradation cycle. The levelling and flooding of the site that was initially planned would have destroyed this unique phenomenon. © Marc Foggin.

Figure 3
Bogs, fens and transitional mires (source: Hans Joosten).

Many problems encountered during peatland restoration relate to hydrology, meaning that insight into the hydrologic functioning of a mire[15] is of special relevance.[155] The **hydrogenetic mire typology** (*see* Annex II for more explanation and diagrams) specifically deals with this functioning and distinguishes basically between 'horizontal mires' and 'inclining mires'.

In **horizontal mires**, the peatland water table forms a horizontal plane and peat formation takes place by dead plant material filling up a pre-existing anoxic (oxygen-free) space under water. Water movement is largely vertical (water table fluctuations) and the water table of the mire generally follows the water table of the surrounding catchment.

In **inclining mires**, the peatland water table forms a sloping plane (often only slightly sloping), leading to mainly horizontal water movement. This lateral water flow is impeded by the growing vegetation and peat, thus causing a slow but continuous rise of the water table in the mire, creating new anoxic spaces for further peat accumulation. By hampering groundwater discharge, the accumulating peat also raises the water table in the catchment area, enabling further groundwater supply to the mire on a higher level.

Horizontal mires are widespread globally and may occur in all places where a long-term local water surplus creates a 'permanent' anoxic space. But as soon as this space has been filled with peat, these mires stop accumulating peat unless a new anoxic space is created by *externally induced rising water levels* or unless they change into inclining mires.

Inclining mires are more demanding with respect to the regularity of water supply, but inherently persist longer because they *raise their own water* level.[25] Because of the strong interrelationships between water, vegetation and peat, and the longer time involved, inclining mires may develop self-regulation mechanisms (often manifesting as surface patterns, perpendicular to the slope) that stabilize them and help them to persist, even under conditions where they could no longer originate. This also makes them more vulnerable when these mechanisms are damaged. The different hydrogenetic mire types (*see* Annex II for subtypes) therefore have different restoration challenges (Table 1).

The hydrogenetic mire typology describes the functioning of natural peatlands (mires) in terms of how water supply and water table fluctuations influence peat accumulation. As degraded peatlands have lost the relevant features to a greater or lesser extent (like original vegetation, water supply, and hydraulic peat properties), it might not be immediately clear how the degraded peatland originally has functioned. That insight may be derived from historical evidence (descriptions, oral history, taxonomic collections, maps, pictures), from comparison with pristine peatlands in climatically, geologically and biogeographically similar regions ('reference areas'), and from palaeo-ecological ('archive') information contained in the micro- and macrofossils of the remaining peat on site.

15 It makes sense to differentiate between 'land where peat is accumulating' (mire) and 'land where peat is present' (peatland). The latter category is much wider than the former and includes, along with 'mires', areas ranging from those where the vegetation is not accumulating peat any more, up to areas that have lost all characteristics of natural peatlands except for the presence of peat (e.g., bare peat extraction sites, arable fields with maize or sugar cane, and oil palm and pulpwood plantations). These are the 'non-mire peatlands' that are the focus of restoration.

3.2. Interconnections

Water is not only crucial for creating the necessary anoxic conditions for peat formation and conservation: most of what we call 'peat-*land*' actually is *water*. The fact that it is possible to walk over a peatland, conceals the fact that 90-95% of the peat body consists of water. And in the same way as it is impossible to extract half of the water from a lake without changing the entire lake, you cannot expect the rest of a peatland to remain the same when part of the peatland is substantially altered. Every single component within a mire must be regarded as a part of the total mire.

In Indonesia, the National Regulation for Protection and Management of Peatland Ecosystems (PP71/2014 amended to PP57/2016) requires peatlands to be managed as Peatland Hydrological Units (PHU), i.e., as coherent peat bodies between the bordering receiving waters (rivers, sea).

Not only must a peatland itself be considered in its entirety, it should also be viewed in its wider context. Most peatlands need external water supply and support, at least in their initial state. During their development, peatlands may develop self-regulation mechanisms and become less dependent on these external factors[23, 202], but in most cases, a dependency persists.

Main groups	Main hydrogenetic mire types	Typical hydrological restoration challenges
Mire with a horizontal water table and without lateral water flow or with water moving alternately in both directions along its slope → **Horizontal mire**	Mire developing in or over an open water body → **terrestrialisation mire**	Recreate open water habitats for early succession stages when the peat has filled the entire water basin
	Mire developing as result of a rising water table → **water rise mire**	Raise water table again to above the peat surface, to reinstall new anoxic spaces (and continue to maintain a raised water table)
	Mire developing by regular flooding by rivers (seasonal), lakes (wind) or seas (lunar tides) → **floodwater mire**	Restore regular flooding on continuously higher levels
Mire with an inclining water table and water flowing in one direction along its slope(s) → **Inclining mire**	Uppermost and deeper peat is porous, with water flowing *through* a major part of the peat body → **percolation mire**	Remove degraded (low-permeability) peat layers or re-install extremely regular and abundant water supply over the degraded peat to facilitate long term formation of new, highly permeable peat
	Uppermost peat compact, with water mainly flowing *over* the peat body. May have rather steep slopes → **surface flow mire**	Stop peat erosion by re-establishing protective vegetation cover and dispersing water flow
	Uppermost peat/vegetation with a conspicuous and effective vertical gradient in porosity. Water mainly flowing between the explicit V-notch shaped surface structures of the peatland or through the uppermost part of the coherent peatmoss vegetation/peat body → **acrotelm mire**	Support the development of a new V-notch-like structure, i.e., a surficial layer/zone with a significant vertical gradient in hydraulic conductivity combined with a large water storage capacity, both within the long-term average amplitude range of water table fluctuations

Table 1
The main groups of hydrogenetic mire types (source Hans Joosten). For a detailed description and subdivision see Annex II.

Peatlands may, thus, also degrade due to changes in land use and water management outside the peatland itself, if these alter the water supply to or the water discharge from the peatland. When planning restoration, it is therefore essential to bear in mind that *the factors causing the problems inside the peatland may lie outside*... (*see* section 6.3.4 below).

The relation of a peatland with its surroundings is not only relevant for the **water level**, but also for **water quality**. Precipitation water is generally poor in minerals and somewhat acid. Its chemical and physical properties change when it comes into contact with the mineral soil/ bedrock. Changes may take place in the concentration and type of dissolved minerals and gases, in acidity and in temperature. How much the water quality changes depends on the properties of the catchment (determined by climate, bedrock, soil, vegetation and land use) and the residence time of the water in the catchment (determined by its extent, permeability and relief). As a result, different peatlands may receive water of very different chemical composition, and within different parts of the same peatland, water of different origin and quality may be found.[113, 164, 204] Conversely, similar water quality conditions may be created by different hydrogeological settings.[60]

Cohesion and connectivity are not only important with respect to water. Peatlands may also degrade due to other problems that originate 'from the outside', including pollution, nutrient-enrichment (e.g., fertilizer run-off from agriculture), acidification by atmospheric deposition (e.g., of ammonium, NH_4, and nitrogen and sulphur oxides, NO_x, SO_x), lack of genetic exchange, loss of forage, migration and hibernation areas, noise, light and visual pollution. Most of these problems cannot be mitigated within the peatland itself but must be addressed by interventions in the wider surroundings.

The dependence of local mire conditions on the quality of the incoming ground- and surface water necessitates a thorough assessment of the hydrological relations of the peatland with its surroundings prior to determining peatland conservation and restoration activities.[18]

Interconnections and acidification

In fens, bicarbonate and mineral rich groundwater supply may create subneutral (pH 4.8 – 6.4) and calcareous (pH 6.4 – 8) conditions. Drainage of peatlands always leads to the production of H^+ (hydrogen ions) due to aerobic oxidation.[113] Whether or not this will lead to acidification depends on the acid neutralising capacity of the peat and the incoming water. A change in water quality – also independent from water level – may have important consequences for species diversity. In particular, peatland species of calcareous to subneutral, nutrient-poor and moderately nutrient-rich conditions have become globally rare, because they are threatened by both acidification and nutrient-enrichment.[105, 110, 113]

Are tropical peatlands different?

It is often said that tropical peatlands differ so much from those in the temperate and boreal zones that experiences from 'the north' have no relevance for 'the south'.

There are indeed many differences between northern *Sphagnum* bogs and Southeast Asian domed peat swamp forests. However, these peatland types are merely two examples of the wide variety of peatlands that exist, both inside and outside the tropics.

Sphagnum peatlands may function in at least five different hydrogenetic ways (*cf.* table 1).[185] Furthermore, they may be fed solely by rainwater, or – provided that the quality is right - also by near-surface soil water (interflow), or even by deep groundwater. Similarly, tropical peatlands may function in different ways. The already mentioned Southeast Asian forested peat domes have, for example, more hydrofunctional conformity with unforested temperate rainwater-fed *Sphagnum* raised bogs (both are 'acrotelm' mires, *see* section 3.1) than with temperate alder peat swamp forests (which are groundwater fed 'surface flow' mires), although these tropical peat swamp forests and temperate alder swamps share a similar vegetation and peat surface microrelief.[152] From a restoration point of view, it is more relevant to look at *functional* similarities and differences instead of classifying along simple geographical, taxonomic or physiognomic lines. Whereas every peatland is unique and needs to be dealt with on its individual merits, too much emphasis on the uniqueness of tropical peatlands creates a danger of isolating from global knowledge and common sense.

Differences between non-tropical and lowland tropical peatlands relevant to restoration relate to the permanently warmer conditions in the latter, which boosts all physical, chemical and biological processes. In tropical climates, peat accumulating vegetation must be structurally more robust (e.g., consisting of high reeds, like papyrus, and trees) and biochemically more recalcitrant (e.g., producing more lignin with lower carbohydrate and greater aromatic content[43, 75]). The warm, humid tropical climate also causes a faster deterioration of dams and weirs. An important social difference is that – compared to most northern peatlands – tropical peat landscapes may support larger numbers of people; thus, tropical peatland restoration often involves a stronger social dimension, by engaging essential community support and developing sustainable livelihoods options.[83, 156]

Individual peatlands may, thus, strongly differ with respect to:

- their internal hydrological functioning; and
- their dependence on water conditions outside the peatland itself.

A degraded peatland where the hydrological surroundings are still intact has good chances of recovery if the internal damage can be eliminated. In contrast, a peatland where the hydrological surroundings have been heavily affected, even though it may still appear 'from the inside' to be in a good state, will further degrade if the surrounding hydrology is not also restored in parallel.

3.3. Degradation intensity

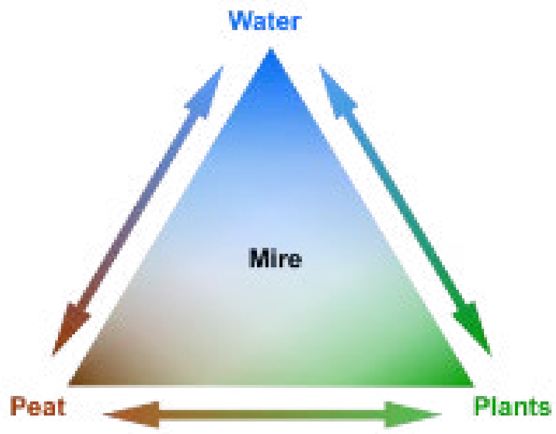


Figure 4
Interrelations between plants, water and peat in a mire (source: Hans Joosten).

In a living peatland (a 'mire') strong functional relationships exist between plants, peat and water (figure 4). If one of these components changes, ultimately the others will change too, resulting in changes in peat formation, biodiversity, GHG fluxes and other ecosystem services. The components, however, do not react with a similar speed. Generally, organisms are more easily affected than hydrology, and hydrology altered more easily than the peat. If a peatland is drained, wetland organisms may die rapidly, but it takes much more time before the drained peat has irreversibly changed or even completely gone. The different 'inertia' (slowness of reaction) of the various components enables the distinction of functionally different **degradation intensities** (figure 4).

Minimal and minor degradation

The least affected and most easily restorable (minimal and minor degradation intensity) peatlands are sites and massifs,[16] where populations of single peatland species have been greatly reduced or eradicated (e.g., by over-gathering, poaching, poisoning, or pollution), or where the vegetation has been damaged or removed, but not completely eradicated (e.g., by surficial fire, overgrazing, or the construction of pads, roads and seismic lines.[16]) If no other site conditions have been damaged, and particularly if hydrology is still intact, spontaneous development ('regeneration', e.g., from seeds/ spores or vegetative diaspores) may lead to an almost total recovery, provided that contaminants and possible disturbing cover material (e.g., temporary road surface material) are removed and further disturbance is prevented. Where spontaneous recolonisation has become impossible or is deemed to be too slow, restoration may involve facilitating the re-establishment of relevant species (e.g., by creating suitable site conditions) or their deliberate re-introduction. The choice of whether or not to re-introduce a species may depend on the aims of the restoration project and on whether the species in question is considered to be a functional species (ecosystem engineer) or a flagship species (high biodiversity value) (*see* section 4.3, Annex VII).

16 We differentiate between a 'mire *site*', which is a homogenous area within a mire, such as the mire expanse, the mire margin and the lagg in classical raised bogs[98] or the 'phasic communities' in tropical peat domes[4, 151], and a 'mire *massif*', which encompasses the entire cohering peat body, such as a raised bog, a string-flark fen, or a polygon mire. A mire massif mostly comprises various mire sites.[98]

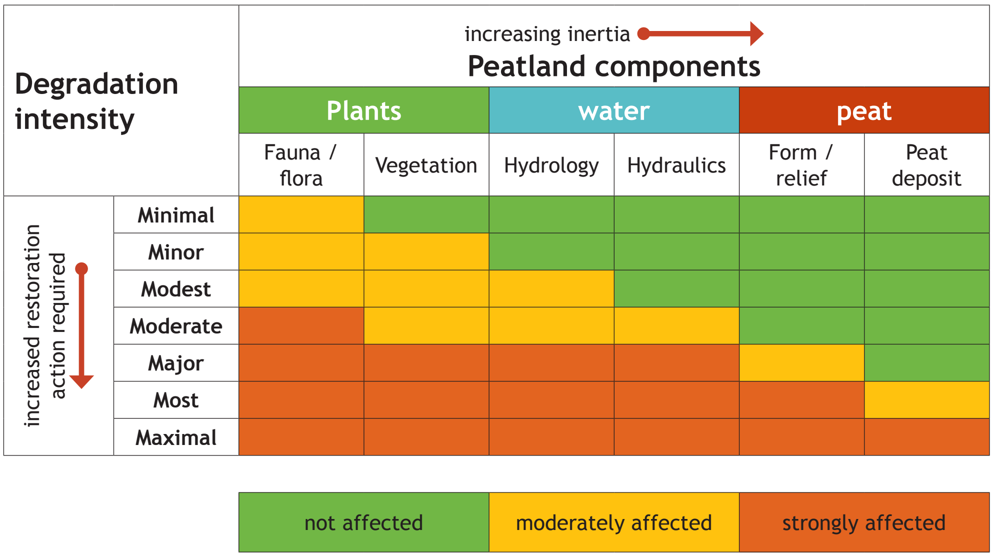


Figure 5
Peatland degradation intensities and restoration perspectives as a function of the impairment of increasingly more inert peatland components (source: Hans Joosten).

Modest degradation

If the peatland has only recently been drained or otherwise hydrologically impaired, e.g., by deforestation (modest degradation intensity) and hydraulic properties have not irreversibly changed[128, 150], restoration measures can be restricted to making the drainage infrastructure ineffective, e.g., by blocking canals, filling-in ditches or destroying subsurface drainage pipes[11], or – where the water losses are caused by activities outside the mire (e.g., groundwater extraction) - by halting or reducing these activities,[104] *see* section 6.3).

Most peatlands worldwide rely not only on rainwater, but also on surface- or groundwater. Therefore, water levels, water dynamics or water quality in the peatland itself may also be affected by interventions in the hydrology outside the peatland. The latter is clear in the case of pollution or nutrient-enrichment by incoming surface water. Less obvious, but often equally important, is decreased groundwater discharge into the mire or increased groundwater recharge from the mire as a result of drainage, water extraction, decreased groundwater recharge (e.g., by surface sealing) or increased evapotranspiration (e.g., by afforestation, increased agricultural production) in the hydrological catchment of the mire, even many kilometres from the peatland in question.

Alleged negative changes in the hydrological landscape setting must be explored by ecohydrological studies. If confirmed, they should be addressed by hydrological repair interventions outside the mire or – alternatively – by significant hydrological and hydrochemical engineering on-site.

Decreased groundwater discharge into a mire may lead to increasing rainwater influence and consequent acidification, nutrient-enrichment (because at lower pH, phosphates are released), vegetation change and a loss of rare species, even though the water levels in the mire may hardly have changed.[197]

Moderate degradation

Moderate degradation intensity concerns moderate changes in peat hydraulics, while peatland hydrology and vegetation still allow for peat accumulation. The changes in hydraulics are caused by superimposed loads (e.g., long-term low intensity mowing and grazing)[164, 204] or increased decomposition under the influence of oxidative atmospheric decomposition (NO_x, SO_x).[36] This may lead to a change of mire type from percolation or acrotelm mire to surface flow mire.[91]

A repair of the water regime of the original mire type requires long-lasting management (building up a new porous peat layer) or the removal of the uppermost compact peat layers (‘top-soil removal’) over large areas.

Major degradation

The degradation intensity 'major' refers to peatlands where substantial changes in hydraulics have taken place, mostly under influence of long-term drainage and where associated peat decomposition has led to a decrease in peat porosity, hydraulic conductivity and storativity[17] and an increase in bulk density[18] and soil water retention.[153, 163] Particularly in fen peatlands in warm climates, continuous shrinkage and swelling of the drained peat may lead to the formation of vertical and horizontal fissures, which impede upward (capillary) water flow and lead to a more frequent and deeper drying-out of the top-soil. Through increased activity of soil organisms, drained peat soils become loosened and fine-grained and may eventually become water-repellent.[144, 217] The associated changes in the hydraulic properties of the peat are largely irreversible. A similar situation occurs when slightly humified peat has been removed by peat extraction and only strongly decomposed peat with low porosity and storativity is left at the surface.

The destruction of hydrologically effective surface structures is a frequently overlooked impairment of peatland hydraulics. Especially in acrotelm mires, i.e., in *Sphagnum* raised bogs and tropical peat swamp domes, the combined hydraulic ('*acrotelm*') properties of vegetation, peat and surface relief are essential for regulating peatland hydrology, especially decreasing horizontal water discharge and providing water storage retention for drier periods, without which these mires cannot persist (figure 6 below).[33, 34] These structures, which mainly relate to spatially differentiated resistance to water flow, accompanied by a large storativity,[23] are destroyed by pressures such as peat extraction, compaction (e.g., by long-term grazing), fire, long-term drainage and decomposition, or deforestation in the case of forested peatlands.

Figure 6
The very first sketch (1891)[87] of a tropical peatland (on Kampar Peninsula, Sumatra) illustrates the buttressed bases of tree trunks and the stilt roots, which cause increasing resistance to water flow with lowering water levels. The inset picture from Sebangau National Park, Central Kalimantan, shows how in the wet monsoon stilt roots and hummocks reduce surface runoff and cause ponding of water as an above-ground storage for the dry season (source: Hans Joosten).[33]

Restoring the hydraulic conditions of degraded peat is virtually impossible.[155] In the case of degraded percolation fens (*see* Annex II), the largely irreversibly decomposed and compacted peat frustrates the inflow of groundwater, which formerly fed the surface layer, thereby ensuring typical stable water tables and low productivity.[110] The decreased storativity of the degraded peat leads to larger water table fluctuations, which again increase peat decomposition.[1]

Peatlands where relevant hydraulic peat properties have been irreversibly degraded cannot be restored to their former hydrological functioning unless the strongly degraded peat is removed. If the latter is impossible or undesirable, alternative restoration targets (involving a 'simpler' mire type, e.g., a water rise mire) may need to be formulated whereby new peat accumulation over time may again lead to better hydraulic conditions.[1]

17 Storativity is a measure of pore space and describes how much water is lost if the water table drops over a certain distance or how much water is needed to make it rise. There is an elastic component to storativity. Particularly in undisturbed peat soils, pore space increases with water content. Storativity is dimensionless.

18 Bulk density is the dry weight of soil divided by its volume. Bulk density is typically expressed in g/cm^3

It is important to understand that the restoration or regeneration of vegetation- and microrelief-based acrotelm structures that are effective in terms of hydrological regulation is a long-term process, involving at least several decades[90, 125, 178], if it is possible at all.[91]

Most degradation

As a natural peatland consists largely of water, a strict and delicate hydrological relationship exists between the shape of the peat body, the hydraulic conductivity of the peat and the amount of water that is transported through the peat body. The degradation intensity is particularly important in peatlands in which the peat body has become completely out of hydrological balance (e.g., by subsidence, peat extraction, erosion, fire or oxidation). In some cases, natural self-regulation processes (including subsidence) or anthropogenic modification of the peatland relief may restore the balance, but mostly the remaining imbalance results in further hydrological changes and continuous, progressive degradation.[22, 206]

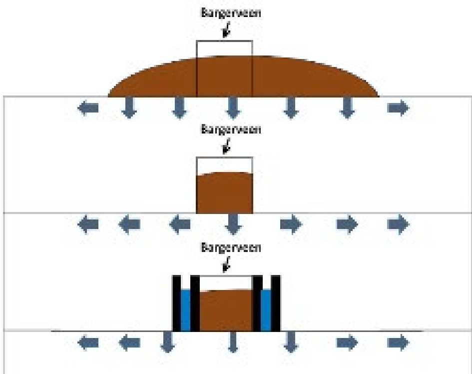


Figure 7
Left: Restoration of parts of the Bargerveen (Netherlands), compensating for the loss of large parts of the original bog dome by constructing huge dikes and water storage basins.61 Right: One of the storage basins with surrounding dikes (source: Hans Joosten).

Maximal degradation

The last and maximal intensity of peatland degradation refers to the situation that the peatland has virtually stopped being a peatland, i.e., when most or all of the peat has disappeared by extraction or oxidation, when the remaining peat layers have been turned upside-down and their stratigraphy disrupted by deep-ploughing and -digging, or when the entire catchment area has been turned upside down by open-cast mining. Here, any peatland restoration must start from scratch, re-creating conditions of permanent water supply and saturation to allow new peat to accumulate ('peatland re-creation').[101, 107, 154]

The **threshold beyond which it is impossible to restore** - within a human lifetime - a degraded inclining mire *massif* to its pre-degradation hydrogenetic functioning lies at the degradation stage 'moderate', i.e., when the relevant peat hydraulic properties start to become severely affected. Beyond this threshold, valuable biotic communities may still temporarily persist, and peatland *sites* may sometimes still *locally* be restored to their former peat formation strategy and vegetation, but the *massif* will continue degrading unless peat is removed or rearranged on a large-scale or infrastructure facilities (dikes, bunds, pumps) are perpetually maintained (*see* figure 7 and section 6.2). Beyond that threshold, it may be opportune to abandon the goal of restoring the original mire type and instead focus on rehabilitating 'easier' (e.g., 'horizontal') mire types with other, often less sophisticated, ecosystem services.

4. Goal setting

After having analysed the problems, the possible goals are identified in terms of the benefits that restored peatlands may provide. This step includes recognizing that specific benefits may be limited to specific degradation intensities, and that different goals may either conflict or be synergistic. A central conclusion is that restoration goals must be formulated *as concretely as possible* and *in priority order*.

Land use / Drainage status	Used for productivity	Managed for biodiversity	No management
Drained	Conventional use	Dryland landscape and biodiversity reserves	Abandoned land
Rewetted/ restored	Paludiculture	Wetland landscape and biodiversity reserves	Wet wilderness

Figure 8
Land use alternatives for currently drained peatlands (source: Hans Joosten).

4.1. Introduction

In order to set realistic objectives, it is essential to choose targets based on the *actual* potential for restoration.[113] General land use alternatives with respect to drained peatland use include (figure 8):

- continuation of current drainage-based land use or management (including abandoned land);
- abandonment of drained peatlands without deliberate rewetting;
- rewetting (both deliberate and spontaneous) without land use; and
- rewetting with biodiversity management or productive land use (paludiculture).

More concrete restoration targets can be formulated in terms of 'ecosystem services', i.e., the benefits (including biodiversity) that people and society obtain from ecosystems. Annex I gives a comprehensive overview of these services and differentiates between services from peat sequestering (natural or rewetted) and those from peat degrading (drained) peatlands. While some ecosystem services can be provided by both categories (e.g., scenery for tourism and outdoor activities) or some ecosystem services from both categories can be combined (e.g., renewed carbon sequestration while keeping historical patterns of exploitation visible, but not functional), in most cases ecosystem services from both categories are mutually exclusive. Schumann & Joosten[166] provide an overview of which services and targets are difficult to reconcile. Annex III presents major conflicts, trade-offs and synergies that may arise.

Whether it is *possible* to re-install the desired ecosystem services depends on:

- whether irreversible changes have taken place in the peatland itself (e.g., species loss, changed soil hydraulics) or in its wider surroundings (e.g., landscape hydrology, climate); which make restoration impossible; and
- whether it is possible to combine the identified targets.

What is possible to restore not only depends on scientific and technical capacities, but also on institutional, regulatory, economic, political and societal opportunities and constraints.[32] This means that the process of goal setting – along with scientific and technical knowledge – also requires good insight into the other stakeholders' interests and plans. Goal setting should therefore always involve an iterative process of goal formulation and problem analysis.

Compromises and incompatibility of aims: an example from Indonesia

'To promote long-term sustainability, rewetting and revegetation are required and promoted, but to meet the requirement of 'revitalisation', government agencies (agencies) often resort to compromises that lead to less sustainable solutions. Agencies often embark on programmes that promote the planting on rewetted peat of crops such as (Liberica) coffee, cocoa, pinang, coconut, bananas, cempedak, jengkol, maize, duku, durian, oranges, pepper, pineapple, red ginger, rubber and dragon fruit. However, these are all dryland crops that require at least 30 to 40 cm drainage, so the degree of rewetting is limited to accommodate these crops. At the same time, canals are kept open and canal blocks are equipped with spillways to facilitate the passage of small boats. This results in a range of issues and unsustainability in the long-term.'[50]

After all possible goals have been identified, the final goals must be chosen and formulated *as concretely as possible* and *in priority ranking* in order to:

- identify appropriate and effective restoration methods (different goals may require different methods);
- prioritise between possibly conflicting goals (too often irreconcilable goals are formulated); and
- enable effective monitoring and evaluation (the achievement of unspecified goals cannot be evaluated).

'Ecological restoration is a complicated, multi-faceted science, in which ecological, social, economic and political factors must all be considered. By simply planting seedlings or stopping fires, we do not address the issues that led to the initial degradation. If we do not seek to understand these "barriers" and develop solutions for them, restoration will be short-lived and superficial.'[145]

In the following chapters, we discuss some prevalent peatland rewetting/ restoration goals, i.e., respectively, climate change mitigation and adaptation; conservation of natural biodiversity; maintaining productivity and livelihoods (paludiculture); and water quality improvement, water supply and flood control.

4.2. Peatland restoration for climate change mitigation and adaptation

One of the most important reasons for peatland rewetting and restoration is climate change mitigation.[59] The huge emissions from drained and otherwise degrading peatlands can be significantly reduced by raising the long-term average water tables to near the surface and by restoring undrained degraded sites.

As long as the water table is below the surface, the relationship between mean water table and greenhouse gas emissions from microbial peat oxidation is largely linear: the deeper the water table, the larger the emissions.[26, 27, 73, 74, 214] This means that roughly half of these emissions can be reduced by raising the water table to half of the former depth below the surface.

As soon as the water table settles around the surface and above, part of the dead plant material is anaerobically decomposed, resulting in the emission of methane (CH_4), which is a greenhouse gas 28 times more potent than CO_2.[81] In general, rewetting of drained peatlands quickly leads to benefits because the overall greenhouse gas effect (expressed as the combined fluxes of CO_2, CH_4, N_2O and DOC) is very positive for the climate, compared to the former drained situation.[96, 214]

Rewetting will always lead to a reinstalment of methane emissions. But even in cases that rewetting leads to a disproportionally large initial methane peak (e.g., by anaerobic decomposition of dying-off dryland vegetation), the longer-term climate effects of rewetting are much better than maintaining the drained status quo. This is because CH_4 has a much shorter atmospheric lifetime lead compared to CO_2 and N_2O, which steadily accumulate in the atmosphere, whereas the atmospheric concentrations of CH_4 quickly reach a steady state (figure 9).

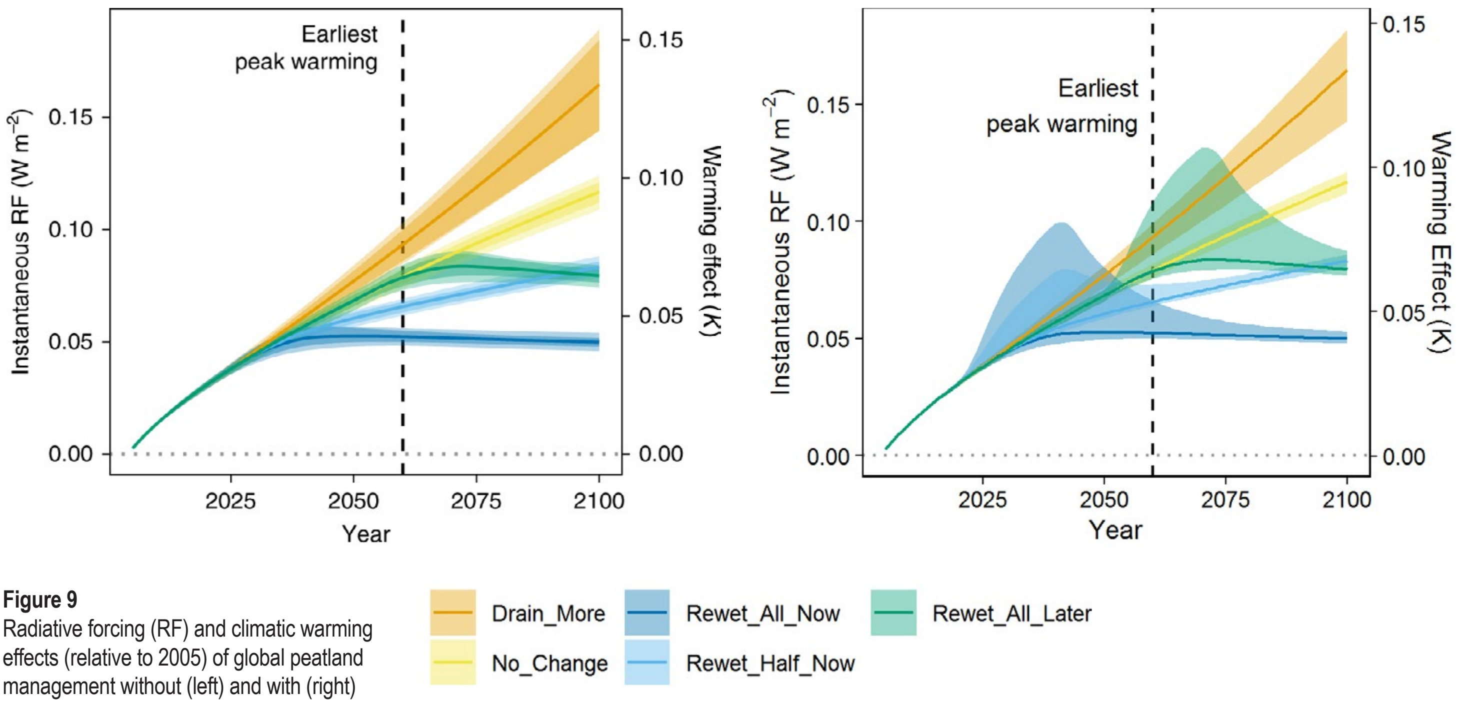


Figure 9
Radiative forcing (RF) and climatic warming effects (relative to 2005) of global peatland management without (left) and with (right) an initial 10 times larger methane peak for 5 years after rewetting. Drain_More: The area of drained peatland continues to increase from 2020 to 2100 at the same rate as between 1990 and 2017; No_Change: The area of drained peatland remains at the 2018 level; Rewet_All_Now: All drained peatlands are rewetted in the period 2020–2040; Rewet_Half_Now: Half of all drained peatlands are rewetted in the period 2020–2040; Rewet_All_Later: All drained peatlands are rewetted in the period 2050–2070.[63]

Because of the methane effect, it is opportune i) to rewet as fast as possible (i.e., between 2020 and 2040) to prevent the emissions from amplifying peak global warming,[63] and ii) to limit methane emissions as far as possible. The latter can be done by:

- avoiding prolonged summer inundation (without compromising long-term water tables to be around the surface);[35, 41]
- removing fresh biomass before rewetting;
- avoiding submerged water plants;
- regular flooding with sulphate-containing (e.g., slightly brackish) water;[199]
- sod and top-soil removal (5-10 cm thick layer);[66, 80, 199] and
- establishing decay-resistant, peat-forming species to reduce input of methanogenesis-prone material, but without introducing 'shunt species'.[19, 24]

Rewetting of tropical peatlands and agricultural peatlands outside the tropics always has a large and rapid effect for climate change mitigation. For boreal forestry-drained peatlands, the climate effect of rewetting may be comparatively much lower and slower,[142] and not so straightforward because of climate effects of changing albedos on the one hand[117] and, on the other, substantial CO_2 emissions following clear-cutting.[78, 106]

4.3. Conservation of natural biodiversity

One of the primary objectives of peatland restoration is to restore the quality of peatland habitats and biotopes, and thus slow or halt biodiversity loss.[169] This is certainly the primary objective for peatlands in protected areas, e.g., Ramsar Sites.

Although the number of species found on a peatland may in certain cases be relatively low, peatlands have a higher proportion of specialised, characteristic species than dryland ecosystems in the same biogeographic zone. As a result of habitat isolation and heterogeneity, peatlands play a special role in maintaining biodiversity at the genetic level.[131, 132, 133] Any introduction of species (*see* section 6.4.) must take careful consideration of this genetic diversity. Where possible, local stocks of propagules should be used for species re-introductions in order to protect against disrupting regional differences in genetic diversity.

19 Vascular plants stimulate CH_4 emissions by allowing the gas to bypass the oxygenated upper soil layer moving through the plant tissues. Plants that provide such a shortcut between the root zone and the atmosphere are referred to as 'shunt' species.

Rewetting, evaporative cooling and climate change adaptation

Peatland rewetting not only results in global, but also in direct local cooling.[215] This arises from the higher groundwater tables (including formation of water bodies), the change in vegetation and the increase in thermal conductivity of the soil/ peat because of higher soil moisture. As a result, more radiant solar energy is used for evaporation and less for warming.[100] The scale of the resulting climate cooling will depend on how the peatland is embedded into the landscape (largest in a dry environment) and is most effective in continental climates.[71, 93]

Peatlands may furthermore have a high ecosystem diversity[20], reflected in conspicuous surface patterns on various hierarchical and spatial scales, which express hundreds or thousands of years of sophisticated self-organisation and self-regulation.[23]

Peatlands also support biodiversity far beyond their borders by regulating the hydrology and meso-climate of adjacent areas. Peatlands are often the last remaining more or less natural areas in degraded landscapes. They, thus, provide with both refuge areas for endangered species with an originally much wider distribution (e.g., great apes in tropical Asia and Africa) and cool shelters for species displaced by climate change.[131, 132, 133]

Focusing restoration on the most threatened, vulnerable and rarest mire habitats and species (while protecting the more common but representative habitats and species) may increase the cost-effectiveness of restoration actions for global mire biodiversity conservation.[108]

Naturalness

Nature conservation is arguably the most difficult aim of peatland restoration, because of the inherent incompatibility of both concepts: restoration is about deliberate action, nature about spontaneous development. Nature conservation is not only interested in the results (e.g., the preservation of a species), but also about *how* these are achieved (i.e., in the most spontaneous way).[38] In nature conservation, the 'means' are an implicit part of the 'ends'. Every act of restoration decreases the spontaneity, the naturalness, of the result.

In principle, there are three basic levels of increasing artificiality (decreasing naturalness) associated with deliberate conservation action:

1. *not doing*: defensive measures to prevent injury (also called 'veto-regulation' or 'external management'), e.g., the instalment of hydrological buffer zones around the peatland;[196]
2. *doing once*: one-off activities to improve conditions, e.g., blocking ditches and building bunds; and
3. *doing continually*: regular measures (prescriptive regulation) to maintain favourable conditions ('internal management'), e.g., annual mowing or permanent grazing.

The big question in restoration for nature conservation is: Which means are justifiable to reach which ends? If all means are justified, the difference between a nature conservation area and a botanical garden or a zoo is lost. In contrast, restoration for nature conservation should restrict the intensity and frequency of the techniques employed to the necessary minimum. The following guidelines[85] may apply to restoration for nature conservation:

- Distinguish between aims and means. Species introduction is always a means (similar to using a device such as a mowing machine), never the aim of nature conservation. Introduction may result in more biodiversity but always at the expense of naturalness.
- Limit your activities to 'not doing' (defensive measures eliminating certain practices) and to 'doing once'.
- 'Doing continually' is only justifiable if long-term management is continued with the same or less intensity (e.g., mowing frequency, grazing intensity) and artificiality (e.g., replacing mowing by grazing, or water management by vegetation management).
- Exceptions may be made when otherwise, and as a result of human activities, natural phenomena would cease to exist globally.

Alongside conceptual reasons there are also practical reasons for limiting artificiality. The three levels of increasing artificiality also have a decreasing cost-effectiveness and an

20 In the sense of art. 2 of the Convention on Biological Diversity, https://www.cbd.int/doc/handbook/cbd-hb-01-en.pdf.

increasing risk of losing the investment. Whereas you only invest once in one-off measures, the cumulative costs of continuous management (i.e., resisting natural, spontaneous developments) are practically infinite, and any previous investment is lost once the management is stopped.

4.4. Securing productivity: paludiculture and livelihoods

Securing productivity relates to the central 'wise use' concept of the Convention. Most peatland degradation results from drainage-based agriculture and forestry, i.e., the peatlands have been drained to provide food, fodder, fibre and fuel. The necessity to rewet 50 million hectares of degraded peatlands worldwide by 2050/2070, and the worldwide increasing demand for biomass (for enhancing welfare of a growing world population and for replacing all carbon-based fossil resources) imply that these areas cannot all be abandoned after rewetting (figure 8). When restoration to a semi-natural peatland habitat is not feasible and productive use has to continue, existing drainage-based land use has to be replaced by land-use that does not need drainage[92, 97], i.e., by 'paludiculture'.[21] [147, 210]

Paludiculture does not *focus* on nature conservation but its practices may *contribute* to nature conservation by creating new wetlands, and as an intermediate stage between drainage-based agricultural use and nature conservation. Paludiculture may, for example, contribute to nutrient removal and vegetation management[175, 176] and act as a buffer surrounding, or acting as corridor between, wet conservation areas.[22]

What is paludiculture?

Paludiculture is a farming and forestry system that targets the production of plant- or animal-based commodities on peatland while preserving the peat carbon stock and minimizing greenhouse gas emissions from the peat soil. Whether these aims are reached is not only determined by which crops are cultivated but mostly by the conditions under which these crops are cultivated, permanently wet and without damaging the peat soil.[22]

4.5. Water quality improvement, water provision and flood control

The provision of good quality drinking water from peat-dominated catchments is generally limited to peatlands with little drainage and human use. More disturbed sites release substantial quantities of humic acids, nitrogen, sulphur, heavy metals and suspended solids,[138, 155] whereas drain-blocking generally leads to a substantial reduction in the outflow of such substances.[21, 127, 180, 203] Furthermore, simply re-vegetating bare peat can reduce loss of carbon particles dramatically.[182]

Denitrification as a nitrate removing process takes place when nitrate enriched water comes into contact with water-saturated, anoxic peat.[28, 70] Removal of organic matter, solids,

21 https://www.ramsar.org/document/resolution-xiii13-restoration-of-degraded-peatlands-to-mitigate-and-adapt-to-climate-change.

22 Concluding statement of the RRR2017 conference: http://www.imcg.net/modules/download_gallery/dlc.php?file=287&id=1552073692.

phosphorus, and nitrogen from incoming water is a function of wet peatland vegetation and therefore restricted to non-disturbed and little disturbed sites (including paludiculture).[93, 201] In some cases, restoration may result in a temporarily increased flush of nutrients into downstream water courses, but the release of nutrients decreases in the longer term.[126, 127]

Flood control

As peat accumulation requires high water tables, the available storage capacity in little disturbed mires is rapidly filled up and the surplus water drains quickly in times of abundant water supply.[155, 182] Minimally to moderately disturbed peatlands therefore generally show peak discharge, directly related to precipitation. However, surface flows in *Sphagnum*-dominated mires are lower than in mires dominated by other vegetation types or degraded mires, because the natural surface 'roughness' slows water flow.[53, 76] The loss of *Sphagnum* cover and increases in bare peat can increase peak flow, reduce runoff lag times, and may make runoff from blanket mires more irregular after peat drainage.[168, 182]

Only those mire types where the peat layer can shrink and swell with changing water supply ('mire surface oscillation') or that can store a large quantity of water at or over the surface (e.g., in hollows and pools) have a 'buffering' effect on catchment hydrology.

After drainage, peak discharge is strongly reduced because the peat layer is no longer completely saturated. Intensively drained peatlands and severely degraded peat soils, on the other hand, increase peak charge rates again, because of the development of water repellent peat and stagnating soil horizons.[217] Restoring the flood control function therefore requires critical awareness of the hydrological conditions.

Natural peatlands can in general withstand inundation for longer periods and peatlands may thus, in favourable settings, function as retention areas, also after rewetting. Flood mitigation is especially possible in peatlands that are unused or used for paludiculture and therefore less vulnerable to inundation.[93]

5. Planning

Peatland restoration measures must be carefully planned. As projects often involve large-scale activities with complex technical, operational, and administrative consequences, it is advisable to make:

- a **feasibility study** to provide the basis for choosing specific objectives and assessing the general feasibility of the restoration work required; then, when feasibility is confirmed,
- a more concrete **strategic plan** that describes conditions, objectives and measures in detail.[30, 67, 68, 114, 158, 167, 194, 195, 206]

A **strategic plan** could, *inter alia*, address:

- location and boundaries of the site, its general topography, landscape setting, geology and hydrology (within site and in relation to surroundings), soil (including peat types and depths), flora, fauna, archaeology and history;
- current land use, users, ownerships and tenancies, land availability, and infrastructure;
- the problem (why is restoration needed?), including the conditions and processes (in- and outside the area) that led to the problem and the effects of lack of action;
- the existing biodiversity, archaeological, historical and other values that should be secured;
- the goals and objectives, development routes, steering processes and interim targets;
- general plans, schedules and budgets (incl. available funding), and a strategy for making mid-course corrections (adaptation);
- appropriate materials, contractors, who must have experience in working with peatland and peat, performance standards, safety regulations, and the best time for access and execution of the work;
- the measures and indicators for monitoring, regular feedback, and evaluating progress,
- long-term protection and on-going maintenance and management; and
- handling of unforeseen circumstances (weather, practical constraints) and contingencies.

In this chapter we touch on some aspects relevant for planning restoration.

5.1. Legal constraints

At an early stage, coordination should be sought with the responsible authorities on whether permits are required and possible, or whether restrictions apply. Relevant legislation and licensing depend very much on national circumstances and the type of activities planned. Legislation may pertain to, *inter alia*, physical planning, nature conservation, water management for changing drainage patterns and water levels, water extraction or discharge, water storage, mining for extraction of peat to build dams and fill drains, construction of water regulation devices, and waste disposal for importing filling or construction materials into the site.[210] In many countries and cases the restoration proposals may be subject to an Environmental Impact Assessment.

It is also important to consider rights, including common land, rights of way, turbary (the right to cut peat for fuel on common land), riparian, mineral, shooting and grazing rights, tenure, and the location of actual or planned public facilities such as pipelines, pylons, electricity lines, and roads.

Be aware that the hydrological requirements and effects of rewetting may well extend beyond the project area itself!

5.2. Public participation and stakeholder involvement

Successful implementation of a restoration project will often depend on public support and acceptance, not least from the local community and local stakeholders. Public participation is essential, certainly if substantial concerns over the planned project are likely. Relevant guidance can be found in the Convention's Programme on communication, capacity building, education, participation and awareness (CEPA)[23], the Convention of Biological Diversity CEPA Toolkit[24], Frogleaps[25], and Annex IV.

5.3. Costs, benefits and funding

In order to quantify the effect of peatland rewetting and restoration on public welfare, all costs and benefits need to be considered. This analysis must include:

- The direct costs of technical rewetting and restoration, which are heavily influenced by location, size, design, accessibility and distance to material sources. Average planning and construction costs in Germany are €2,363/ha,[162] while the costs of the Indonesian 2 million hectares rewetting programme are estimated at US$2,300/ha.[65] Similar orders of magnitude (with a wide range of values) are presented for the UK,[9, 136] Finland,[108, 169] EU-LIFE restoration projects,[3] Canada,[157] the Russian/German PeatRus project and Indonesia.[34, 50, 211]
- The marketable and non-marketable benefits (goods and services) that the restored area will provide (e.g., the climate effect or paludiculture income).
- The 'opportunity costs', i.e., the loss of goods and services that may no longer be provided (e.g., palm oil or Gouda cheese), the decrease in land value, and the loss of public support payments.
- The external effects, i.e., the positive and negative effects of restoration on the well-being of a third party.
- The costs of inaction.[9, 52, 162]

Whereas the social benefits of peatland restoration may widely outweigh the social costs, only the private costs and benefits determine the feasibility of restoration from the perspective of an individual land manager (owner or tenant).[135]

Many ecosystem services are difficult to valuate and for even fewer is there an existing 'market'. Furthermore, some values (e.g., human life, and fairness towards future generations) can and should not be measured in monetary terms. Monetary valuation can therefore capture only part of the total value.[14, 209] Monetary valuation remains, however, useful in order to:

- raise awareness about the societal costs of peatland degradation;
- improve decision making by displaying non-marketable services;
- optimise efficient allocation of financial resources; and
- justify payments to providers of services (payments for ecosystem services PES).

23 https://www.ramsar.org/activity/the-cepa-programme.

24 https://www.cbd.int/cepa/toolkit/2008/cepa/index.htm.

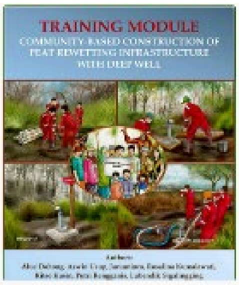
25 www.frogleaps.org.

A wide variety of funding mechanisms is available for peatland restoration, while foreseeable new mechanisms will emerge within the context of policy frameworks mentioned in chapter 1[194, 95, 208] Funding options may include:

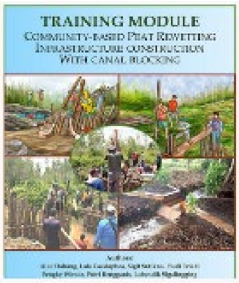
- government subsidies/ projects/ bi-/ multilateral international donor schemes;
- public-private co-sponsoring;
- post-exploitation (and exploration) restoration/rehabilitation funding by resource exploitation companies, voluntarily or to meet legal requirements;
- compensation activities/ offsets (habitat banking)/ insets;
- water purification projects by water supply and purification companies;
- payments for ecosystem services (PES) including carbon reduction credits,[12, 175, 200] and results-based finance; and
- paludiculture: 'earn money with cattail and get rewetting for free'.[216]

6. Restoration techniques

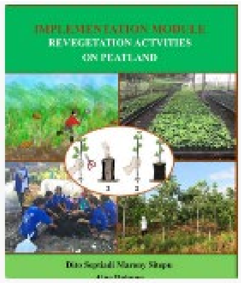
For many regions and situations, no guidance to restoration exists. Therefore, it is good to consult existing information from elsewhere, including various regional manuals [30, 44, 50, 62, 112, 114, 120, 147, 157, 169, 171, 173, 195, 206,183], not to blindly imitate the presented measures, but to get inspired to find solutions that fit the local circumstances.



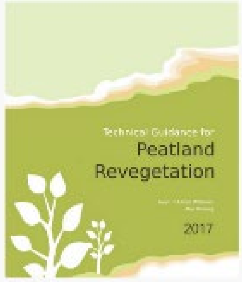
Training Module Deep Wells



Training Module Canal Blocking



Implementation Module Revegetation



Technical Guidance for Peatland Revegetation

A large number of practical handbooks produced by the Indonesian Peatland Restoration Agency BRG are available under http://brg.go.id/panduan/.

6.1. General principles

In the same way that all peatlands have important properties in common (chapter 1), some principles apply to all peatland restoration.[7, 40, 169]

- Ongoing peat formation requires slowly but continuously rising water levels and therefore peatland restoration must allow and enable such water level rise to happen. In the case of *horizontal* mires (section 3.1, Annex II), e.g., mangrove and floodplain mires, processes independent of the peatland itself (e.g., climate change, tectonics, sea level rise, deforestation of the catchment) are responsible for this (relative) water level rise. In the case of *inclining* mires, e.g., raised bogs and percolation fens, the growing vegetation and peat 'lifts up' the water level by obstructing the outflow of incoming rain- and groundwater, respectively.
- Peat formation requires a narrow range of water levels. Peat formation is hampered both by water levels that are too low and, thus, boost peat oxidation, or too high-water levels, which reduce plant production and increase water erosion.
- Peat soil wetness has to be almost permanent because peat decomposes 10 times faster when the peatland is drained than it builds up when the peatland is sufficiently wet.
- Peat is almost as light as water and therefore easily eroded by water, frost and wind action, if not protected by vegetation. Restoration must, therefore, disperse water flow over a large area, not concentrate it, and re-establish vegetation on bare peat surfaces.
- Peat is a soft material, necessitating the use of low-ground pressure machinery, adapted for this mode of action, and operated by experienced workers.
- Acid, nutrient-poor peats degrade more slowly than alkaline and nutrient-rich peats and therefore acid nutrient-poor peatlands are often easier to restore. Similarly, acid nutrient-poor peat is often more suitable for restoration construction.
- In warm tropical climates, all processes go faster than in colder climate such as the boreal: peatland degradation, degradation of dams, but also plant growth.
- Practical restoration must start with the ecosystem components with the strongest functional impact (i.e., the most inert ones, figure 4).
- Water flows from high to low. In order to keep access, rewetting activities (blocking) must start from the highest point of the peatland and work successively downwards. Distance between blocks should be minimised to allow more effective retention of water and to decrease the velocity and the water level difference at each dam/ block.

- To save costs, local materials are preferred (peat, wood, sods, sand). The use of foreign materials (hardwood, plastics, metal) may, however, be necessary to construct durable and optimally performing devices.
- Atmospheric pollution may constrain restoration, especially sulphur from industry and nitrogen from traffic, industry and animal husbandry. Atmospheric emission problems can only partly be reduced by removal of sources close to the site (nearer than 1km) and generally require reducing emissions over a larger area (30 and more km) around the site.
- Any dam will, over time, deteriorate, be destroyed (when dams frustrate local access) or its building materials may be stolen. Continuous intensive maintenance is not realistic. Blocking systems should, therefore, be constructed to be inherently robust and to remain effective over time with minimal maintenance. This can be achieved by:
  - reducing pressure and erosion risk for each dam by building a cascade of dams with water level differences less than 0.10 - 0.25 m;
  - not allowing water to run over a dam; and
  - infilling of canals (also partial) to allow the canals to overgrow, push up water levels, and reduce water steps over and pressure on dams.
- Let nature do the work: In the end, nature must restore itself – people can only help but not fully control.

In the following sections, we present the restoration measures to be taken, starting from the most severe degradation intensities and working towards the lightest (*see* section 3.3.).

6.2. Peatland relief and erosion

When the peat body is out of hydrological balance, restoration may require large-scale construction works and often permanent maintenance. This is, for example, the case when the margins of a bog have been steepened by subsidence, oxidation, erosion or peat removal resulting in more rapid water outflow.[120] In areas with regular ditch or canal spacing, subsidence may result in the formation of mini-domes (figure 10) and dams will have little effect beyond their immediate vicinity, leaving the centre of the mini-domes too dry.[32] Subsidence will continue there even after complete blocking of the canals, until a new equilibrium is reached.[50]

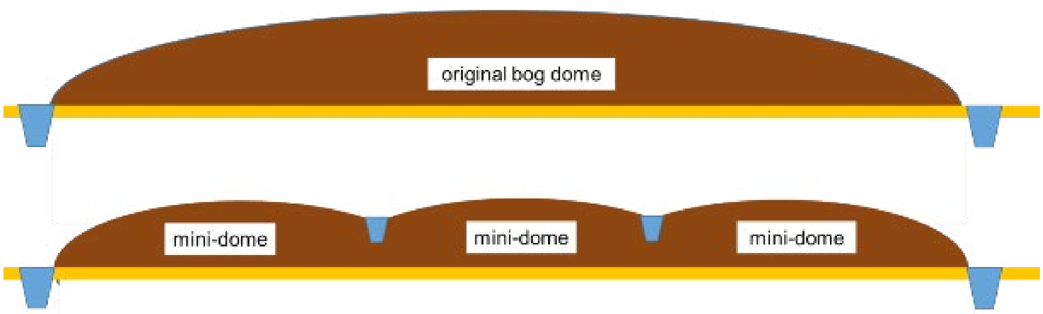


Figure 10
Formation of mini-domes between drainage ditches due to subsidence and oxidation.

A similar situation applies to milled peat extraction fields, which generally have a sloping surface to allow for effective drainage, and need to be flattened to allow even water distribution on the entire surface.[157]

Proposals to sculpt the peat surface in strongly mutilated bogs to the position of the perched water mound are based on a misunderstanding of dynamic peatland hydrology (*see* section 6.3.5).

In case of alternating lows and elevations as a result of varying peat extraction depths, the water level after rewetting should ensure rewetting of the elevated sections, implying flooding of the lows. These flooded sites may over time fill up with peat forming vegetation (especially when the water level is raised slowly), recreating a single mire with a smooth surface.[112] Often, however, open water will persist, requiring special action to stimulate vegetation establishment (*see* Annex V). Relief may only be levelled, when no important and irreplaceable values, e.g., palaeoecological and historical values, are present.

When peatlands are so severely eroded that deep gullies have established or only isolated peat hags have been spared, the bare peat needs to be stabilised and revegetated. Extensive guidance on erosion control and revegetation on eroding blanket bogs is provided in[148, 183] and in section 6.4.3.

6.3. Hydrological interventions

When planning hydrological interventions, the height differences within the peatland and the location of drainage structures can best be identified with a LiDAR-based high-resolution digital elevation model (DEM) or alternatively with aerial and satellite imagery.[42] Field verification can identify drains that are not easily visible by remote sensing. In the field the flow directions of ditches can be surveyed during wet periods. Discharge of groundwater is best observed during drier periods and may be evident from the presence of iron films and iron precipitation, by water temperatures strongly deviating from air temperature, chemical indicators (e.g., pH, EC, Ca, Mg, Na, K, HCO_3, SO_4, Cl)[149] and indicator plant species.

Many agricultural peatlands and peat extraction sites have been drained by subsurface (mole) drains. To ensure that rewetting activities are not compromised, functioning drainpipes should be disconnected by digging a trench across the draining system and removing a few meters of drainpipes. In some cases, mole drains will be effectively blocked by retention of water in the (blocked-up) main drains. The location of the mole drains can be derived from old drainage maps, from altered vegetation or from land managers.[30, 206]

6.3.1. Blocking and backfilling of ditches and canals

The main objectives of blocking and backfilling of ditches and canals are: (i) to raise the water tables, (ii) to re-establish surficial and overland flow, and (iii) to reduce the flow velocity to avoid erosion.[160] If drains are not maintained, they often tend to choke up with slumped peat and vegetation or may be closed by the activities of beavers (where present), but active blocking speeds up and improves the process.

- With respect to drain blocking, good general recommendations and practical guidelines exist.[7, 50, 62, 88, 114, 147]
- Be aware that canals may be used for navigation or transport by the local population. Therefore, consensus on blocking should be agreed with local people before starting.
- In cases where adjacent land use may be impaired, rewetting must be done gradually, and flooding of surrounding land must be avoided.

Dam location and spacing

Recommendations with respect to dam location and spacing[7, 50, 112, 147, 183] are:

- The most efficient approach to determining number and location of dams is to analyse the surface topography using LiDAR. Alternatively, traditional surveying techniques or a differential GPS system can be used.[112]
- The difference in water levels upstream and downstream of the dam should generally be limited to 20-30 cm to reduce pressure and increase effectiveness. The practical consequence is that a cascade of dams is often required. With too large distances (height differences) the water table in major parts of the peatland will remain too low.

A new method to position canal blocks by combining a hydrological model with heuristic optimization algorithms was applied to a 931 km^2 drained peatland in Sumatra, Indonesia. The algorithms performed systematically better than random or rule-based approaches. With only 10 blocks, they obtained the same amount of rewetted peat that random configurations achieved with 60 blocks. At their best, the algorithms found configurations that rewetted seven times more peat than the random and rule-based approaches with the same number of blocks; at their worst, they were still three times better than random.[191]

Damming and infilling material

- Where possible, local materials should be used to keep transport costs to a minimum. An obvious material is peat, given its local origin, low permeability, low weight (compared to sand, gravel and concrete), ready availability and minimal cost.
- Peat is less suitable i) in very wet, soft areas, ii) in dry areas, where peat easily fragments and oxidizes, iii) in steep drains, where peat easily erodes, iv) in sites too sensitive for machinery access, and v) in very wide drains where the large volumes of peat required may affect the visual appearance of the landscape.
- Bearing in mind the number of dams that may sometimes be needed, it is recommended that wood be used sparingly to avoid deforestation. Compacted peat dams are also significantly cheaper than wooden box dams.
- The size of the drain dictates the techniques and materials adopted, *see* the available ditch blocking decision trees.[7, 57, 114] There is, however, still great potential for experimentation to increase damming efficacy and reduce resource requirements.
- Other materials than peat that are used to construct dams include plastic piling, corrugated Perspex (poly(methyl 2-methylpropenoate)), plywood, stones and brash bales. Plastic plates are well suited for less accessible places because of their light weight.[30, 120] Structures made of concrete and steel are expensive, take a longer time to build, are heavy and tend to sink into soft peat.[32]
- Heather (or other brash) bales decrease flow velocities, trap sediment and eventually result in drain infilling.[7]
- For more solid constructions, rock can be used. However, be aware that rocks are heavy and may sink into the peat and that calcareous rocks may change the chemical properties of the peatland. Clay is extremely impermeable but is also generally basic and contains many minerals that may harm Sphagnum.[114]

Dam construction

General considerations with respect to dam construction[7, 30, 31, 32, 114, 157, 160, 169, 183, 206] are:

- All ditches should be blocked; also take account of old drains choked with vegetation which may still retain some drainage function. Low areas directly adjacent to the drains (e.g., a path or a trail) must be blocked if they could develop into preferential flow paths.
- Peat dams can be constructed by hand, but even in small ditches, machine-constructed dams are quicker to install.
- In most cases, peat dams will be adequate if they are built correctly, but they may need to have an impermeable core of plastic, metal sheeting, wood, etc.
- Resources have a significant bearing on the material or materials selected. A small peat dam is inexpensive if labour is in ready supply. Plywood dams are less expensive than plastic coated corrugated steel and both require similar labour resources. Large plastic dams are generally less expensive and quicker and easier to install than solid plank dams. Large dams and heather bale dams require the use of machinery and an experienced operator.

Dam design and maintenance

Various dam types can be distinguished depending on the size and function of the drain, *see*[7, 50, 63, 112, 114, 147, 183] and the associated peatland restoration Ramsar Briefing Note No.11.[88]

- If limited means are available, it is tempting to build fewer dams with larger head differences. However, the larger the head difference, the larger the water pressure and the higher the seepage flows through or around the dam. Head differences of more than half a meter prove difficult to maintain and may lead to rapid erosion and loss of the dam structure.
- The lifetime of dam blocks in the tropics is generally less than 10 years, too short for natural re-growth or sedimentation in the upstream canal to take over, and therefore dams need to be replaced on a regular basis. To promote vegetation re-growth, dam building may have to be combined with partial infilling of the upstream canal and planting of water tolerant woody species.

- Dams require regular inspection and a maintenance organisation capable of reacting quickly to repair any small damage before it becomes bigger.

'Two out of six dams built in Block C EMRP collapsed due to the fragility of the timber structures used to retain strong water current and high water debit within the dam. Similarly, a number of dams built in Block A North-West EMRP and in Sebangau National Park in Central Kalimantan experienced bending, leaning down and breakage owing to strong current, high water depth and excess water seepage, making them dysfunctional for retaining and raising nearby surface and ground water tables. Some dams built in the EMRP were also destroyed by illegal loggers, fishers and non-timber forest product collectors as the dams were perceived as hindering their transportation access to the interior forests.'[32]

Spillways and bypasses

Spillways and bypasses, especially in the tropics, exemplify the tension between the need to maintain high peatland water tables, the need to drain excess water, and the desire to keep the area accessible. The almost permanent water saturation that living peatlands require leads to the inevitable consequence that during times of water surplus – e.g., times of heavy rainfall - water has to be discharged effectively but diffusely to prevent erosion. On the other hand, in drained peatlands water tables have to be restored to natural conditions, implying the disruption of transport opportunities that ditches and canals may have been providing for local communities. It is therefore crucial to identify where water *has* to leave the area and where it would be better that it *should not*[34] in order to solve the respective conflicts.

- Involvement of the local people in planning, design and construction of blocks is important to gain their support but is no guarantee that the dams will be safe from human intervention. Small bypass channels could be considered for dams in canals that are frequently used for transportation of goods or people. Planks provided for pulling boats over a lower section of a dam have not proved to be very long-lasting.

Backfilling

Backfilling (i.e., completely filling up of ditches/canals) is the most effective method of restoring the water level of peatlands, especially in peatlands with a slope greater than 2% where the mere construction of dams will not be sufficient to achieve overall rewetting.[114] Backfilling requires a good quantity of peat or other material. Recommendations for backfilling (infilling)[18, 19, 50, 62, 114, 120, 160, 172, 183] include:

- An alternative to peat is sawdust. Sawdust is organic, low in nutrients, absorbent, easy to transport, cheap, locally available and load bearing.
- Filling with shredded fibre bales is a good option in wilderness areas or areas lacking peat or mineral soil fill because it is easily transported. Use other materials (e.g., bentonite or clay) may be necessary to reduce seepage.
- Care should be taken to seal ditches cut into highly permeable mineral soil.
- Infilling prevents ditches or canals being used as access, may be beneficial in conservation areas. Fish rearing in canal sections is then, however, no longer an option.

Gullies

Eroding peatlands may exhibit extensive areas of bare peat, often in deeply incised gullies. In the largest eroded areas, geotextiles and re-seeding have been used, in some cases involving fast growing grasses combined with lime and fertilizer application. For gully blocking *see*[7, 9, 18, 183].

- Gully blocking primarily aims to stop further erosion, to stabilise the peat and to allow progressive sediment deposition and revegetation of the gully floor.

6.3.2. Bunds and screens

Elongated embankments or barriers ('bunds', 'berms' and 'dikes')[88, 183, 206] can be used to restrict water loss or impound open water:

- Surface bunds in and over the peat raise water levels in the peat when peatland slopes have become too steep (following peat extraction, drainage and/or slumping).
- Peripheral bunds stop lateral water loss via surface drainage and subsurface seepage at the edge of an isolated peatland remnant (such as adjacent to peat extraction sites or ditches that cannot be blocked) and must often resist large water pressure. It should be noted that peripheral bunds set a permanent edge to the peatland and hinder its future expansion.
- Parapet bunds are installed when the water storage capacity of the peat is too low (because of peat extraction, degradation or compaction) and ditch blocking no longer suffices to reinstall high, stable water tables.[206] Bunds are then used to raise the water table *over* the surface as a storage to limit annual water table fluctuations.[30]
- Bale bunds consisting of heather or straw bales or coir logs are applied to reduce erosion and waterflows across bare peat areas.[20]

Considerations on the use of surface and parapet bunds are presented by[30, 88, 143, 157, 183, 188, 195, 206].

A foil screen can be used to prevent groundwater from flowing out of a reserve, or nutrient rich water from surrounding land flowing in. Foil screens may also be applied to prevent groundwater flow between adjacent compartments with different water levels. When the underside lies in a less permeable part of the peat profile, such screens may be highly effective.[195] If the screen completely seals off the underlying aquifer, it solves the problem of seepage losses in one go (*see* section 6.3.3), but this is only technically and financially practical when the underlaying aquifer is shallow.

6.3.3. Reducing leakage

Loss of water by vertical seepage into an underlying aquifer may happen in peatlands located over permeable substrata (porous bedrocks, sands and tills) when:

- the groundwater head has been lowered by regional agricultural drainage, groundwater abstraction, or quarrying (where de-watering is carried out to facilitate extraction);[120] and
- the resistance to downward seepage in the peatland has been decreased by canals and ditches and the removal of thick layers of peat.[165, 206]

By tapping into the more permeable underlying sandy soils, drainage ditches in the peatland itself can also lower the groundwater head and influence the water table over a much wider area than ditches that remain in the less permeable peat.[169]

Sites where downward seepage is concentrated can be clogged by bringing in peat or other impermeable material (clay, bentonite).

If downward seepage is a diffuse phenomenon as a result of widely reduced hydraulic resistance or strongly lowered regional hydraulic heads, elevating the water table in a residual peat massif will require raising the water level in the surrounding land (peat-workings, farmland etc.[206], *see* section 6.3.4).

6.3.4. Off-site hydrology and buffer zones

In many cases improving local hydrology by ditch blocking within the peatland is insufficient to restore hydrological conditions and additional measures have to be taken outside.

The effectiveness of buffer zones in reducing water losses from the project area depends on the size of that area, the geohydrological situation, the vertical resistance of the residual peat (which mainly depends on the residual peat thickness), and the difference in hydraulic head between the project area and the surrounding area.[195] The extent, constitution and nature of an external buffer zone can best be determined by three-dimensional, non-stationary hydrological modelling.[196]

If the discharge of regional groundwater into the peatland has to be restored, regional groundwater levels need to be raised by reducing drainage and groundwater extraction in the catchment area.[103] Examples of vegetation and floristic recovery after restoring artesian groundwater discharge by relocating groundwater extraction are given by[124, 197].

6.3.5. Peat wastage and removal

Perhaps the simplest approach suggested for peatland rewetting is the strategy of non-intervention, i.e., to permit subsidence to adjust the unbalanced shape of the peat body to the position of the water level in the peatland massif.

The presumption that the wasting peat surface will at some stage equilibrate at the zone of permanent saturation is, however, questionable in the case of raised bog remnants where acrotelm conditions no longer prevail. When the uppermost peat has wasted to the position of the pre-waste water level, the position of the water table will have sunk below the new peat surface in response to periods of dryness: as the peat surface subsides, the zone of permanent saturation will also sink beneath it. The eventual consequence of a 'natural wastage' scenario will be the loss of the entire ombrotrophic (rain-fed) peat deposit. Also, the option of removing peat to the predicted position of the perched water mound in a peat remnant is subject to the same problems.[206]

For fens in closed depressions, peat wastage may indeed lead to a re-establishment of wetland conditions. Peat formation will, however, be hampered because of the absence of a continuously rising water level (*see* section 6.1).

6.3.6. External water supply

An alternative approach to the problems of water retention is to irrigate peat massifs directly with water. This approach has had limited testing and should be avoided as being non-sustainable. However, artificially increased input of water ('pumping') may be considered:

- to provide an initial input of water in order to 'kick-start' the system;
- to keep areas wet as a temporary measure before full remedial action can be taken; and
- to preserve archaeological artefacts and palaeoecological values.[206]

Clearly, if this approach is applied, only water of the appropriate quality should be used. Using surface water from a surrounding agricultural area or river water may lead to serious water quality problems such as pollution and nutrient-enrichment,[198] which could be addressed by preceding biological or chemical purification.

6.3.7. Acrotelm restoration

The most important mechanism of hydrologic self-regulation in raised bogs (i.e., both the *Sphagnum* raised bogs of the Northern Hemisphere and Tierra del Fuego and the domed tropical peat swamp forests of Southeast Asia, the Congo Basin and Western Amazonia) is the 'acrotelm', the uppermost peat and vegetation layer with a special structure. The acrotelm is characterized by a horizontal permeability to water that decreases rapidly with depth. This strong differentiation implies that when the water tables rise, the water increasingly flows in layers with higher permeability. As a result, excess water flows off quickly but diffusely, i.e., without causing erosion. In the case of falling water tables, the horizontal water outflow becomes more and more concentrated in layers with a lower permeability. If the water table has dropped sufficiently, horizontal water discharge may even stop completely. At the same time, the acrotelm has a large storativity, meaning that losses of water by evapotranspiration only lead to a relatively small drop in water table.

In *Sphagnum* bogs of the boreal and temperate zones the acrotelm is composed of the upper layer of loose peatmoss biomass and the scarcely decomposed peat immediately underneath. In domed tropical peat swamps the acrotelm is formed by trees growing on hummocks of root material and litter. Particularly large hummocks (> 0.4 m high) are established around buttressed and stilted trees, whose buttresses and stilts are additional elements that restrict the movement of water across the forest floor. In this way runoff is retarded and water is stored in depressions between hummocks and behind buttresses (figure 4).[33]

For the restoration of 'acrotelm bogs' it is crucial that the relevant vegetational and micro-relief structures re-develop. For *Sphagnum* raised bogs this means that a vegetation must be restored with the 'right' *Sphagnum* species (only a handful *Sphagnum* species are able to build an effective acrotelm, see Annex V). For tropical peat domes a forest cover should be re-established with tree species that develop effective hummocks and buttressed or stilted roots[33], *see* section 6.4.1).

6.4. Plants and vegetation

Plants are the most important constituents of a peatland because they provide the organic material that forms the 'peat'. They are furthermore a main goal for biodiversity-focused restoration. After re-establishment of native 'ecosystem engineers' (the main regulators and peat formers), the rest of the biodiversity may in the course of time follow spontaneously. Restoration management should therefore first focus on these ecosystem engineers.

Re-establishment of wetland or peat-forming vegetation is - after restoration of hydrology (rewetting) - the second most important tenet of peatland restoration. A vegetation cover increases humidity in the soil and air and slows peat decomposition. Conversely, without vegetation cover the peat dries out rapidly and becomes more vulnerable to fires, especially in dry periods.[50]

In peatlands, drained bare surfaces caused by peat extraction, arable agriculture, peatland fires and other types of peat erosion are difficult to revegetate because bare peat is highly susceptible to frost, wind and rain erosion and is often unstable. Furthermore, surface temperatures in dry peatlands may rise very high in summer (to over 70°C in Central-Europe).[37] The remaining exposed old peat generally has no relevant seed bank, and furthermore, in the case of extensive bare surfaces, areas that may provide suitable diaspores (seeds, fruit or spores) may be far away.[183]

The approach to revegetating such areas depends on the type of peatland, the state of degradation, and the wider plans for the area. If remnants of the original vegetation remain, rewetting may be sufficient to allow natural regeneration. Revegetation of bare peat on slopes may require the application of lime, fertilizer and a nurse crop (e.g., composed of amenity grasses) to stabilise the peat surface rapidly and to provide the conditions for the re-establishment of native peatland plant species.[168]

6.4.1. Reforestation of tropical peat swamp forests

The reforestation of tropical peat swamp forest is not only necessary to provide a habitat for typical species and to re-establish a peat-forming vegetation (producing peat with its wooden roots), but also often for restoring peatland hydrology. Specifically, in rainwater-fed dome-shaped peatlands, such as in Southeast Asia, but also in Africa and South America, trees are indispensable to slow down water flow over the surface. This creates above-ground storage capacity for surplus water from the wet season, allowing the peat dome to be kept wet through the dry season.[33]

Restoring hydrology and stopping peatland degradation thus requires the re-establishment of forest. Location, density and species to be planted must be compatible with the local water flow intensities. In areas with high-profile discharge, flood-tolerant or floating species that form highly conducting vegetation are more promising. Areas with low-profile discharge are preferable sites for planting buttress- and mound-forming trees to increase surface roughness and depression storage (small hollows that store rainwater). While the development of such natural forest structures will take decades, artificially constructed mounds and ridges can mitigate the effects of an over-steepened slope by reducing runoff velocities in strongly subsided areas. Mounds also facilitate the establishment of tree seedlings in areas of large water table fluctuations. For rewetting and restoration to be successful, closing artificial drainage paths therefore has to be combined with the re-establishment of a tree cover.[34]

‘There is very little information available in literature on what happens post-planting, despite many projects having undertaken planting activities for over 10 years. Based on the authors’ knowledge, a large number of planted areas have been either lost to fire, or to flooding and drought and out-competition by ferns and sedges. Consequently, there are no data, as yet, illustrating how forest restoration successional pathways might develop.’[56]

Image from Mahyudi et al. 2017.[122]

Regeneration barriers

When disturbance in tropical peat swamp forests has been so extreme that most trees have disappeared, the landscape becomes dominated by ferns, sedges, and shrubs. Altered hydrological conditions and fire are in these conditions likely to be the primary ‘regeneration barriers’ for spontaneous forest recovery.[146] Other barriers include the lack of seed sources and dispersers, low soil nutrient availability, competition between tree seedlings and non-woody vegetation, increased light intensity, and seasonal flooding.[34, 51, 56, 145]

It is important to address these underlying causes and to decide whether reforestation will be undertaken through assisted natural regeneration or replanting or a combination of the two. In general, natural regeneration is preferable but may be slow and patchy (depending on site conditions) while replanting (enrichment planting) may generate faster results but is more expensive and in the long term may be less resilient.[88, 147] Species used will have to be able to cope with i) exposure to direct sunlight, ii) desiccation in dry months, and iii) some degree of flooding in the wet season. Many species of mature peat swamp forest will therefore not be suitable and the choice of species for the initial phase of planting should focus on those with a broad ecological tolerance, such as pioneer species.[147]

Revegetation requires the planting of mainly fast growing and hardy pioneer species that can tolerate flooding and exposure to drought, in combination with hardier, ecologically desirable species. The latter should include fruit species that are attractive for wildlife.[32] Giesen & van der Meer, 2009[51] provide lists of peat swamp forest species that are adapted to various flooding depths. In the most severely degraded areas that are flooded much of the year, focus should be on species that can float, retard water flow and cause infilling of canals and shallow depressions. Wibisono & Dohong, 2017[207] provide lists of species suited (and their means of propagation) for various levels of degradation for Indonesia. In spite of the large number of tree species that tropical peat swamp forests support,[55] most restoration projects use only a small number of species. Selection of a wider range of suitable species is now a high priority.[56]

Once pioneer species are well established, species with the capacity for hydrological regulation and peat formation can be planted or may establish spontaneously from natural seed dispersal; in other words, restoration needs to be in stages. To date, however, there is still limited information available on which species should be selected for particular locations and site conditions, and on how their establishment and growth can be enhanced. Beneficial species (i.e., those producing valuable timber or non-timber forest products) should be used when the restoration areas are located near villages, or belong to a particular community.[56, 147] Detailed guidance on replanting is given in[51, 122, 141, 147, 207].

6.4.2. Forest, tree and shrub removal

Some peatlands naturally support tree-cover such as peat swamp forest in the tropics, alder carrs in the temperate zone, and spruce and larch swamps in the boreal zone. However, in many instances, especially in the boreal and temperate zones, the presence of trees is due to direct planting, or invasion and expansion of trees following drainage of originally treeless or sparsely wooded peatlands. In these circumstances, peatland restoration may involve the removal of trees.[6] Clearance of trees on peatlands provides more light to the ground layer vegetation and decreases water losses by evapotranspiration and interception.[30] Thom *et al.* (2019)[183] provide very extensive and detailed guidance for tree and shrub removal. Further guidance is provided by[3, 5, 30, 169].

- To control scrub, it is necessary to establish the underlying cause of the problem. If trees have established in response to a lowered water table, efforts should be made to re-wet the site. Any clearance measures should be incorporated into a comprehensive site management programme.

6.4.3. Restoration of open vegetation

Many natural peatlands around the world do not support forest. In the boreal, temperate and subtropical climate zones only a limited number of tree species can cope with the permanent wetness and the continuous upward growth of the peat surface, which are characteristic features of peatlands. And some peatlands are simply too wet and unstable to carry a tree cover.

In this section we discuss the restoration of open fen vegetation, including starting from nutrient-enriched agricultural land. Subsequently we describe the restoration of *Sphagnum* dominated vegetation.

Rewetting of nutrient rich agricultural soils

About half of the degraded peatland area worldwide is formed by peatlands in agricultural use.[89] In terms of their extent and the efforts needed to rehabilitate them, these peatlands represent the largest restoration challenge. Most peatlands are extremely nutrient-rich as a result of peat mineralisation, application of fertilizer and manure, and the input of airborne ammonia and nitrogen oxides from cattle, traffic and power plants.[113] Rewetting may even increase this nutrient problem, e.g., by the mobilisation of hitherto bound phosphorus and nitrogen ('internal eutrophication').[66, 113, 193] After rewetting, the high nutrient availability favours the establishment of strongly competitive, fast-growing helophytes (emersed wetland plants), which take up the nutrients but rapidly release them again after dieback. Without further management it is unlikely that such fens will return to low nutrient levels within a human lifetime.[216]

The impact of nutrient-inputs from adjacent intensive farming often needs to be eliminated. In the Everglades of Florida, excess inputs of phosphorus from the northern agricultural areas constrain ecological restoration. The lowering of the phosphorus input in fen surface waters may require additional purification, by phosphate stripping using iron or aluminium salts applied to the water supply or *in situ*, or by constructed wetlands.[113]

Three options exist with respect to rewetting and restoration of these areas:

- remove the extremely nutrient-rich top layer before rewetting (top-soil removal);
- remove nutrients by long-term phytoextraction (*cf.* paludiculture); or
- accept extremely nutrient-rich conditions with low biodiversity for decades or longer.

Top-soil removal

Top-soil removal is a radical method of reducing availability of nutrients and agricultural pesticides. Removing a layer of degraded peat top-soil may also expose a more porous substrate, help to achieve wetter conditions and enhance the influence of groundwater in the upper soil layer. Additionally, it eliminates the existing vegetation, thus preventing rapid re-establishment of competitive, fast-growing species in nutrient rich areas.[66, 103, 113, 150]

The results of top-soil removal often depend on the depth to which it is removed, with deep removal (>20 cm) giving better results than shallow removal. For groundwater dependent plants it is only effective if groundwater seepage into the root zone is sufficient.[197]Top-soil removal is usually applied only on a small scale due to high costs.

Seeding and transplantation

If desired species do not establish spontaneously after hydrologic conditions have been restored (*see* section 6.3), re-introduction can be considered (*see* Annex V). Taylor *et al.*[179, 180, 181] present an overview of actions (and their effects) that complement planting, such as adding lime, fertilizer, organic fertilizer, or organic mulch.

Restoring traditional management

Many open fens in Europe and Eastern-Asia were traditionally mown and grazed for fodder and litter, and often drained to some extent, which resulted in compaction of the uppermost peat. As long as hay making and grazing persisted, the formation of rainwater lenses was prevented, whereas regular biomass removal suppressed competition and inhibited the establishment of trees and shrubs.[164] After use has been abandoned, the fens suffer heavy losses of their typical species diversity, a decrease in bryophyte cover, a dominance of some graminoid species, and tree and shrub encroachment.[111]

The former vegetation can be restored through intensive mowing[64, 130], which may, however, also lead to a loss of rare fen species by the destruction of microtopography[109] and enhanced acidification.[192] Restoration should therefore pursue the re-establishment of natural hydrological conditions, in which fens again become self-sustaining, and limit 'remedial mowing' to the necessary minimum.[111]

Taylor *et al.*[179, 180, 181] (www.conservationevidence.com) provide detailed information on the effects (what works and what doesn't work) of 125 different actions ('interventions') for managing and restoring peatland biodiversity (flora and vegetation) worldwide (with a focus on Europe and North-America), however without discussing causal relationships.

Sphagnum

Sphagnum mosses are arguably the most important peat-forming plants worldwide.[21] *Sphagnum* has, however, severe difficulties in re-establishing spontaneously, in natural,[15] drained[155] and rewetted peatlands[188] (Annex V). Thom *et al.*[183] provide detailed information on various methods to inoculate *Sphagnum* species. Except for the Moss Layer Transfer Technique (Annex V), these approaches are still in early stages of development, although initial trials are promising.

Open water colonisation

Peatlands with a slightly nutrient-rich character may easily revegetate and become peat accumulating after deep inundation.[134] In contrast, recolonisation of low-productive nutrient-poor, acid and humic rich deep open water is hampered by wave action and by lack of light and carbon gases for submerged mosses when the water is deeper than 30 cm.[195] Options to address this problem are i) to raise the water levels gradually to allow tussock vegetation to grow up with the rising water level, ii) to provide a framework for plant colonization by introducing brash or slightly humified peat, and iii) to minimize wave action by compartimentalisation.[84, 186, 187, 206]

6.4.4. Paludiculture

The central goal in paludiculture is biomass production. Paludiculture should be applied as a restoration option where peatlands constitute a major and indispensable part of the productive land.

Although paludiculture can build on many traditional methods and experiences, the required scale and intensity makes its effectiveness still largely unknown. Paludiculture requires regionally differentiated adaptation and innovation along the entire value chain, including crop breeding, cultivation, harvesting, transport and processing technologies, logistics, and markets. Extensive practical information on paludiculture is available in[48, 49, 50, 177, 210], in various special issues of the journal *Mires and Peat*,[26] and in the Database of Potential Paludiculture Plants (DPPP).[27]

Paludiculture options in Southeast Asia

Lowland Southeast Asian peat swamp forests hold 1,376 species of higher plants of which 534 species (39%) have a known use, 222 produce useful timber, 221 have a medicinal use, 165 are used for food (e.g., fruits, nuts and oils), and 165 have been assigned 'other' uses (e.g., latex, fuel and dyes). Many species have multiple uses, and 81 non-timber forest product species have a 'major economic use'.[49] Detailed information on cultivation options and economic potential of paludiculture is presented by[50, 147]. As rural communities are basically farming communities and paludiculture offers a sustainable way of continuing farming (albeit with modified techniques and alternative crops), paludiculture probably holds the greatest potential to contribute to maintaining and revitalising local livelihoods while rewetting peatlands.[34, 50]

26 http://www.mires-and-peat.net/.

27 https://greifswaldmoor.de/dppp-109.html.

6.5. Animals

Although various studies have monitored the effects of peatland restoration on fauna,[17, 29, 72, 139, 205] few restoration activities have focused on improving the habitat of animals. The latter include fen management for invertebrates,[124] the effects of forest removal on open-ground breeding birds in the Flow Country, Scotland,[212] and the proposal to reforest peat swamp forests with tree species whose fruits and nuts are favoured by wildlife.[50]

Compared with plants, the return of animal species in restored areas will more strongly depend on resulting heterogeneity in environmental conditions, because different animal species have different demands, and many species need a combination of conditions (*cf.* gradients). Dispersal ability of the species as well as the proximity of source populations (in remaining, undamaged peatlands) play important roles in recolonization.[29 ,28]

The Aquatic Warbler (*Acrocephalus paludicola*) is, with a global population of 11,000 singing males, the rarest terrestrial songbird in Europe. Its population has been declining due to deterioration of fens. Since 2014, the Aquatic Warbler breeds in only four countries: Belarus, Ukraine, Poland and Lithuania. The highly fragmented populations have a diminished genetic diversity, which increases the risk of extinction. In 2011, the species went extinct in Hungary, in 2014 in Germany. Tanneberger & Kubacka[174] present a detailed overview of management and restoration strategies for the species. Meanwhile a successful translocation process has started to strengthen the Lithuanian population.[27] (Image developed within the project Securing Sustainable Farming to Ensure Conservation of Globally Threatened Bird Species in Agrarian Landscape.)

6.6. Microbiota

The response of microbial communities to disturbance and restoration is far from fully understood.[159] After disturbance in a bog, specific communities were found to be replaced by more generalised species.[2] After rewetting non-mycorrhizal species increased and obligatory mycorrhizal species decreased, but the proportion of non-mycorrhizal species typical for natural mires was not reached.[104] In spite of substantial recovery, microbial communities in rewetted sites were only similar to those of undrained sites when soil organic matter was more than 70%, i.e., when the peat soil was not very degraded.[39]

The inoculation of mycorrhizae may be relevant for rehabilitating degraded tropical peat-swamp forests.[189] Wildlings (i.e., seedlings from the wild) should therefore be collected along with the peat surrounding the root ball, whereas cultivated seedlings could be inoculated at the nursery stage.[32]

6.7. Monitoring and adaptive management

During implementation, lessons will be learned as to what works and what does not, and these lessons should be incorporated into subsequent work and future planning. Planning and design should therefore integrate monitoring, assessment and adaptive management in a continuous process of 'learning by doing'.[147] Considerations with respect to monitoring can be found in Annex VI.

28 https://meldine.lt/wp-content/uploads/sites/2/2018/07/Meldine_factsheet_A4_ENG_preview.compressed.pdf.

7. Evaluation

Close, regular and systematic observation and documentation of changes in the project area are important steps in order to evaluate:

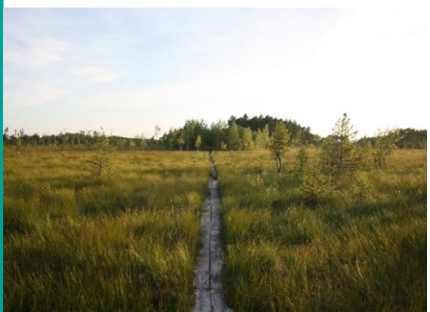
- whether the restoration targets have been met and which remain to be met;
- whether the money was spent effectively and efficiently; and
- what can or could have been improved (lessons learned for current and future projects).

The ultimate test of peatland restoration success is, obviously, whether the desired objectives are reached.[206] This means that these objectives should be formulated as concretely as possible (*see* chapter 4). Simply proclaiming an area as 'restored' prohibits any meaningful evaluation. What should be monitored and how it should be monitored is specified in Annex VII.

8. Outlook

8.1. Common pitfalls to rewetting and restoration

- In spite of claims to the contrary, peatland restoration cannot bring back all values that have been lost by peatland degradation, nor can it provide equivalent alternatives:
    - Whereas peatland restoration may rapidly restore carbon sequestration capacity, even to the extent that it may (temporarily) surpass that of pristine peatlands,[137, 140] it cannot within a foreseeable future (centuries or millennia) restore the carbon stock lost by pre-restoration degradation.
    - Losses in peat height caused by degradation mostly cannot be turned back. In fens, these height losses not only mean a huge water loss from the peat-filled basin itself, but also from the associated groundwater catchment, decreasing water storage in the overall landscape.[137]
    - A further important and unrestorable loss is the lost palaeoecological and paleoenvironmental archive. Whereas part of that archive is certainly redundant, every loss of peat implies a loss of potential information.[58]
    - Many peatlands have developed conspicuous surface patterns on various scales, which express hundreds or thousands of years of sophisticated self-organisation and –regulation.[23] Such coherent patterns cannot be replaced by mechanically remodelling of peat or restoration of the vegetation cover.
- This underlines the primacy of peatland conservation over peatland restoration.
- Many programmes involving peatland rewetting and restoration in reality involve only partial rewetting. It is often still not recognized that anything less than successful and comprehensive rewetting and re-establishment of a peat-forming vegetation cover will mean that peat subsidence and enhanced carbon emissions will continue.
- Related to the last point is a common failure to understand that drained peatlands cannot persist over time: they either fall victim to uncontrolled flooding (including by the sea in the case of coastal peatlands), as a consequence of ongoing subsidence, or their peat oxidizes completely, leaving a mineral ground that will often be acid-sulphate prone or infertile.
- 'Paludiculture' claims are often wrongfully attached to crops that need drainage and do not perform well on fully rewetted peat. Paludiculture is not defined by the selection of specific crops but by the conditions under which these crops are grown and managed (permanently wet and without damaging the peat soil).
- Insufficient recognition of the hydrological coherence of peatlands may lead to incorrect concepts being applied to hydrological planning and management. It is impossible to combine conservation or restoration sustainably with drainage-based agriculture on the same coherent peat body.
- The costs of revegetation are often underestimated. Revegetation is often much more expensive than rewetting and should therefore only be undertaken if the area is devoid of vegetation, if 'ecosystem engineers' have to be brought in, and if rewetting has already taken place, or is occurring simultaneously.
- Whereas 'peatland must be wet' applies as a general rule, rewetting is not 'always and everywhere good for everything' (*cf.* Annex III).



8.2. Awareness and capacity building

The objectives of the 2015 Paris Agreement of the UN Framework Convention on Climate Change and the 2030 Agenda for Sustainable Development are unlikely to be met unless peatland degradation is halted, and peatland restoration is undertaken at a scale of 50 million hectares globally (*see* chapter 1). To achieve peatland rewetting and restoration on the necessary scale, it is imperative that more awareness is raised, and much more technical and institutional capacity is built.

Education and awareness programmes[29] are important not only to educate younger generations but also to inform and change attitudes among local communities, site managers and decision makers. Such activities may be spearheaded by education and research institutes, civil society organisations or networks, including particularly those specialising in peatlands.[147] A special role can be played by Wetlands of International Importance under the Convention, which have been established using the climate regulation function as an additional argument for designation. These sites may illustrate the importance of peatlands in providing locally and internationally relevant ecosystem services and act as on-the-ground examples of wise use and management.[10]

Only through effective collaboration and knowledge exchange between scientists, managers, entrepreneurs, practitioners and the policy community will we be able to develop sufficient capacity for peatland restoration and conservation.[118] Most current teaching and training strategies do not provide the breadth of cross-disciplinary knowledge required. Training, conceptual grounding and inspiration will not only be acquired in classrooms and workshops, but also by on-site, hands-on participation in restoration action.[8, 77]

8.3. Limitations and future research developments

Important limitations to and knowledge gaps in peatland restoration are:

- The ecosystem engineers: For various peatland types worldwide, insufficient knowledge exists about the choice of strategic species to kick-start peatland regeneration.
- Hydrological self-regulation, especially that of tropical peat swamp forests: understanding how species or phenological types (e.g., with stilt roots, buttresses, surface roots, etc.) and the forest floor structure contribute to water retention and regulation, and how these functions can be restored.
- Peat forming species: Whereas peat formation is generally attributed to a selected group of species of which macroremains are conserved in the peat, recent studies illustrate that charcoal[115] and microremains, including those of aboveground plant material of which no macroremains are conserved[129] may also contribute substantially to the peat matrix and to carbon sequestration. Related to this is the question of the chemical composition of these species (lignin, polyphenols, etc.) and the decay resistance of these components, which may play differential roles in peat accumulation.
- Return of ecosystem functions: Which ecosystem functions and services return, to what extent and when?
- The effect of climate change on restoration perspectives: The effects of higher temperatures, changing seasonality and weather extremes, and increased incidence of peatland fires and associated haze.
- The lack of common monitoring concepts and protocols: A common protocol for recording changes in ecosystem service delivery is required to enable a more robust evaluation of the cost-effectiveness of restoration projects.

29 See also https://www.ramsar.org/sites/default/files/documents/library/hbk4-06.pdf.

9. Conclusions

- The Convention on Wetlands and other policy frameworks promote the restoration of degraded peatlands. The target of rewetting of 50 million hectares of drained peatland to meet the Paris Agreement will require an enormous upscaling of restoration practice.
- Peatland restoration must consider ecological, social, economic and political factors. Public participation is essential, particularly if substantial concerns are anticipated. Without addressing all social and economic 'barriers', restoration will be short-lived and superficial.
- Restoration goals may not only include restoration of the full former ecosystem but may also aim at restoring selected ecosystem services. As different goals may conflict, goals must be formulated concretely and in priority order.
- In general, rewetting of drained peatlands is very positive for the climate. Restoration for nature conservation should restrict the intensity and frequency of the interventions. The increasing demand for biomass implies that drainage-based land use may have to be replaced by 'paludiculture'.
- Water levels that are too low are the central cause of peatland degradation. The presumption that without action peat growth will eventually recover spontaneously is questionable. In most cases, active intervention is required to raise the water table again to around or over the peat surface.
- Effective blocking of drainage structures involves strategic planning, regular inspection, timely maintenance, and the promotion of spontaneous re-filling. Great potential still exists to increase damming efficacy and reduce resource requirements.
- When blocking of drainage structures does not guarantee high and stable water tables, the water table has to be raised *over* the surface. Downward seepage can be reduced by clogging discharge points. If downward excess seepage is diffuse, the water level in the surrounding land has to be raised.
- Re-establishment of vegetation may not only protect the peat body, add to renewed peat accumulation and harbour important biodiversity, but may also be indispensable for hydrologic restoration.
- The most important mechanism of hydrologic self-regulation in raised bogs is the vegetation based 'acrotelm'. In *Sphagnum* raised bogs the 'right' *Sphagnum* species must be re-established, which might require the inoculation of these species. For tropical peat domes a forest cover with trees that develop effective hummocks (e.g., produced by buttressed and stilted roots) should be re-established. However, to date insufficient knowledge is available on which species to select and how to enhance their establishment and growth.
- Half of the degraded peatland worldwide is in agricultural use and most is extremely nutrient-rich. For these lands three options exist: i) top-soil removal, ii) nutrient removal by phytoextraction, or iii) accept (extremely) nutrient-rich fens with low biodiversity for decades or longer.
- If desired species do not establish spontaneously, re-introduction can be considered, e.g., by direct seeding, hay transfer, transplanting sods etc.
- Experiences gathered during restoration should be systematically evaluated and lessons-learned incorporated in subsequent work and future planning.
- Important knowledge gaps are the role of 'ecosystem engineer' and peat forming species, the importance of hydrological self-regulation and regeneration, the return of ecosystem functions and services, the effect of climate change on restoration perspectives, and the lack of common monitoring concepts and protocols.
- To achieve peatland rewetting and restoration on the necessary scale, it is imperative that more awareness is raised, and much more technical and institutional capacity is built.

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In 2019 and 2020, Chapter 4 was revised and republished in independent booklets;
Planning Restoration Projects (replace pp. 13 to 24 in the 2003 Guide)
Site Preparation and Rewetting (replace pp. 25 to 35 and pp. 60 to 62)
Plant Material Collecting and Donor Site Management (replace pp. 36 to 45)
Spreading of Plant Material, Mulch and Fertilizer (replace pp. 46 to 59)

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Annex I: Values, ecosystem services and restoration targets

The concrete targets of peatland restoration are chosen based on what is needed or wanted, and on what is possible. Restoration can aim for enhancing biodiversity, decreasing fire risk, reducing greenhouse gas emissions, improving water supply, increasing food security, enriching landscape experience, protecting archive values, etc., and these in all possible combinations. Restoration must choose, which targets to pursue, because not all targets can be combined.

Restoration targets can be formulated in terms of 'ecosystem services', i.e., the benefits that people/ society may obtain from ecosystems.[1] Ecosystem services do not only include marketable material products, but also a wide range of less tangible values. The table below provides an overview of these services. It is based on the Common International Classification for Ecosystem Services (CICES), which has been developed on behalf of the European Environment Agency, the United Nations Statistical Division and the World Bank, to systemize the monitoring, valuation and reporting of ecosystem services. The Standard uses three main categories (provisioning, regulating and cultural services) and divides these into subcategories (Bonn *et al*. 2016). While these three ecosystem service categories are directly used by human beings, supporting ecosystem services are not directly consumed or enjoyed by people and therefore excluded (Kahn, 2020). Examples of supporting ecosystem services include primary production, secondary production, biodiversity, genetic resources and nutrient cycling.

The term 'ecosystem services' may give the idea that the focus is merely on the 'material' benefits that peatlands may provide, varying from providing food, fodder, fiber and fuel, flood control and denitrification up to regulating climatic conditions. The concept of 'ecosystem services', however, includes a much wider range of values and includes all relationships relevant for humans and humanity.

Ecosystem services are sometimes confused with biodiversity. Biodiversity is not itself an ecosystem service but rather underpins the supply of ecosystem services. The value some people place on biodiversity for its own sake is captured under the cultural ecosystem services as spiritual, aesthetic or educational values. Other ecosystem services closely associated with biodiversity include food, genetic resources, timber, biomass fuel, recreation and ecotourism.

1 In the context of climate change politics, ecosystem services are also called 'nature's contributions to people' (Diaz *et al.* 2018, de Groot *et al.* 2018).

Table 1: Peatland ecosystem services according to the Common International Standard for Ecosystem Services (CICES), as adapted for peatlands (Joosten 2016).

Section	Division		Group	Subgroup	Examples of goods and services provided by peatlands	
					(Potentially) peat sequestering (undrained)	Peat degrading (drained or deeply flooded)
Provi-sioning services	Nutrition: Food and fodder		Natural		Wild game and fowl, fish, berries, mushrooms, sago, honey	
			Supported	Managed game	Meat of reindeer, deer or ptarmigan	Idem from high density populations that degrade peat by trampling, overgrazing or fire management
				In situ fodder	Fodder for livestock grazing wet peatlands (e.g. Water Buffalo)	Fodder for livestock grazing drained peatlands (e.g. high productivity dairy cattle)
				Ex situ fodder	Hay and silage from wet fen plant material	Hay and silage from drained and fertilised peatland
			Cultivated		Oil from *Shorea*-species, starch from sago	Carrots, potatoes, palm oil, maize and so on
	Water		Drinking, irrigation, indus-trial and cooling water		Outflowing (surplus) water	Withdrawn surface and groundwater
	Materials	Medicine and deli-cacy	Pharmaceuticals		Medicinal plants (and animals) e.g. *Drosera, Men-yanthes, Ledum*	Humic preparations, peat baths and poultices, peat based fungi- and bactericides, active coal from peat
			Flavours		Plants for flavouring drinks (e.g. *Menyanthes, Acorus, Hierochloe*)	Peat for flavouring whiskey
		Fibres	Construction materials		Plants (z.B. *Phragmites, Typha*) for thatching, insu-lation, building, wattling and veneer	Peat as foundation, building and insulation material; wood from drained peatland
			Clothing and textiles		Fur, leather, wool	Cottongrass peat fibre, hemp, wool from high intensity sheep grazing
			Pulp for paper and cellulose		Biomass from *Phragmites, Phalaris, Papyrus, Typha*	Wood from *Pinus, Picea, Acacia*
			Absorption, filter and bed-ding materials		Litter from biomass	Peat for litter in stables, filters, active coal, oil spill absorbent, diapers
			Growing media, potting soils		Peatmoss biomass, biomass compost	Peat as constituent of horticultural growing media
		Fertilisers	Nutrient enrichment		Compost of fen biomass	Peat ash as potassium fertiliser, fen peat as nitrogen fertiliser
			Improvement of soil structure		Biomass compost	Peat for improving soil structure
		Chemicals	Raw materials for chemistry		Refined plant sap, latex (jelutung)	Peat waxes and dyes, active coal made from peat

Section	Division	Group	Subgroup	Examples of goods and services provided by peatlands	
				(Potentially) peat sequestering (undrained)	Peat degrading (drained or deeply flooded)
Provi-sioning services (cont.)	Fuel	Fossil fuel		Marsh gas (methane)	Peat and peat-derived fuels
		Biomass based fuel		Reed, sedges, wood	Palm oil, maize for biogas production, wood, sugar cane for alcohol production
	Space	… for biomass provision		(See nutrition, materials and fuel)	(See nutrition, materials and fuel); fish ponds
		... for urban, industrial and infrastructural development		Space for some wind farms, some transport infra-structure	Space for settlements, harbours, airports, industry com-plexes, hydro-electricity reservoirs, landfills
		… for defence and isolation		Space for low intensity military training grounds	Space for high intensity military training grounds
				Little managed defence and border lines	Intensively managed defence and border lines
				Space for prisons and labour camps	Associated peatland drainage and reclamation
Regulating services	Regulation of waste	Bioremediation		Denitrification, nutrient retention and sequestration in plants and peat	Wastewater treatment, intensive denitrification
		Dilution and sedimentation tation		Clean water supply to dilute downstream pollution, filtering out of pollutants	-
	Regulation of flows	Regulation of water flow		Attenuation of run-off and discharge rates, mitigation of downstream floods	
				Maintenance of base flow, coastal protection	Rapid discharge and increased buffer capacity after drainage
		Regulation of mass flow		Erosion control	
	Regulation of the physi-cal environment	Global climate		Carbon sequestration and storage in peat	Idem in biomass and litter in some boreal peatland forests (temporarily)
		Local and regional climate		Evapotranspiration cooling	
		Water quality		Nutrient retention, denitrification	Waste treatment, denitrification
		Soil conditions		Peat accumulation, initiation and conservation of permafrost	Improved soil structure through secondary pedogen-esis, conservation of permafrost
	Regulation of the biotic environment	Life cycle maintenance and habitat protection		Pollination, seed dispersal	
				Wildfire control	
		Pest and disease control		Control of pathogens and invasive species	
		Gene pool protection		Rare and specialised mire and wetland species	Rare species of (slightly) drained fen meadows

Section	Division	Group	Subgroup	Examples of goods and services provided by peatlands	
				(Potentially) peat sequestering (undrained)	Peat degrading (drained or deeply flooded)
Cultural services	Symbolic	Aesthetic appreciation and inspiration		Areas of Outstanding Natural Beauty, mire patterning	Use of peat and fossil bog wood for artisan objects
				Themes for arts and literature	
		Heritage		Tradition, history and notions of cultural continuity, sense of place	Traditional peat extraction and land use, sense of place
		Symbols and mascots		Hunting trophies, Canadian beaver and Japanese crane as national symbols	
		Reflection and spiritual / religious enrichment		Wilderness, naturalness, quietness, solitude	Wide open spaces, wide horizon
				Notions of ecological and evolutionary connectedness, timelessness and naturalness	Sense of control over the landscape
				Sacred places and species	
	Intellectual and experiential	Recreation and community activities	Recreation and stress mitigation	Tranquility and scenery for tourism and outdoor activities, opportunity for hunting/angling and wildlife watching	
			Social amenity	Employment and volunteering in mire conservation and research	Employment in peat extraction and processing and in drainage-based agriculture and forestry
		Information and knowledge	Cognition and satisfaction of curiosity	Stratigraphical archives (palaeo record, preservation of archaeological artefacts)	
				Extreme habitat conditions and special adaptations of mire organisms, (reference for) self organisation – and regulation	Cultural land use history and sociology, behaviour of disturbed systems
			Indication	Palaeoecological record, indicator organisms	
			Education	Subject matter for educational literature, field excursions, presentations	Idem with respect to peat extraction, agriculture, forestry, water management and road building
	Transformation	Character development		Options for development of new tastes, moral and social skills, and growing awareness of evolutionary and ecological connectedness	
	Option and bequest	Continuous provision of ecosystem services		Benefits that still have to be discovered	Benefits that still have to be discovered

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Annex II: Hydrogenetic mire types

Hydrogenetic mire classification focusses on the processes that drive peat formation and peatland development. Special attention is paid to the interrelations and feedback mechanisms between i) water flow and fluctuations, ii) vegetation, and iii) peat formation, and to the role peatland development plays in landscape hydrology. The following text is largely based on Joosten *et al.* 2017, where also ample references can be found.

Hydrogenetic mire types consist of two major groups: the 'horizontal mires' and the 'inclining (sloping) mires' (Table 1).

HORIZONTAL MIRES occur in closed basins, where horizontal water movement is largely prevented by a flat relief and impervious substrates, and the water surface is therefore horizontal. Vertical (seasonal or inter-annual) water table fluctuations can be small to very large. Peat formation only occurs if the periods of waterlogging are much longer than the dry periods, so that oxidative losses are exceeded by the production of organic material. Horizontal mires have almost no influence on water flow in the landscape or on the water table of their surroundings. Their effect on landscape hydrology is merely that they diminish basin water storage as they fill the basins up with peat, which may lead to a larger near-surface peak flow elsewhere in the landscape.

Horizontal mires are subdivided into

- '**Terrestrialisation mires**', where peat formation takes place in or over 'open' water. Terrestrialisation mires are subdivided into:
  - '<u>Schwingmoor mires</u>' in which peat accumulates in a floating mat; and
  - '<u>Immersion mires</u>' in which peat accumulates on the bottom of the water body.

The peat deposited at the start of terrestrialisation is mostly weakly decomposed. As the basin fills up with continued terrestrialisation, the more recently deposited upper peat layers are subject to stronger decomposition because of increasing water table fluctuations. At the end of the terrestrialisation process, when the basin is completely filled, peat accumulation stops unless another peat formation strategy takes over.

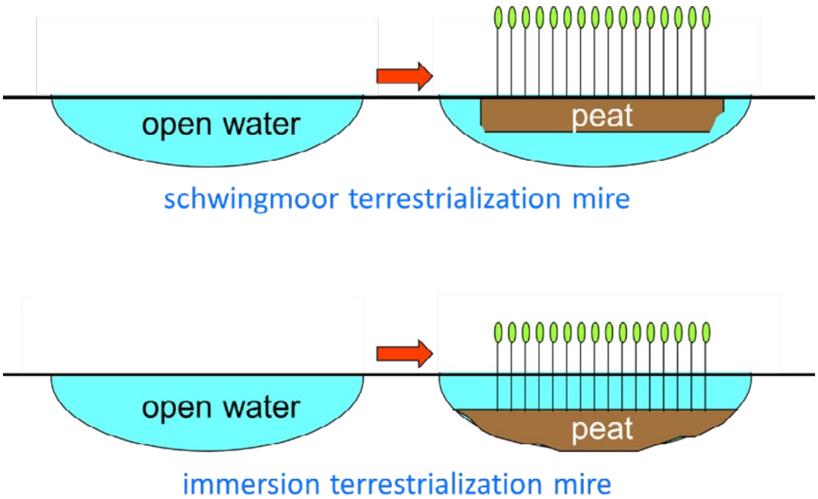

Figure 1

- '**Water rise mires**', where peat formation takes place following a rising water table (that is insufficient to create open water, see above). As water depth (above the surface) is mostly small and water table fluctuations are usually large, strongly decomposed peats are deposited that have a low hydraulic conductivity and only a small storativity, but high capillarity. Water rise mires are subdivided into
  - '<u>Groundwater rise mires</u>' in contact with and fed by the catchment groundwater;

- '<u>Backwater rise mires</u>' without groundwater contact, fed by interflow, and with allogenic sealing; and
- '<u>Self-sealing mires</u>' without groundwater contact, fed by interflow, and with autogenic sealing ("self-sealing").

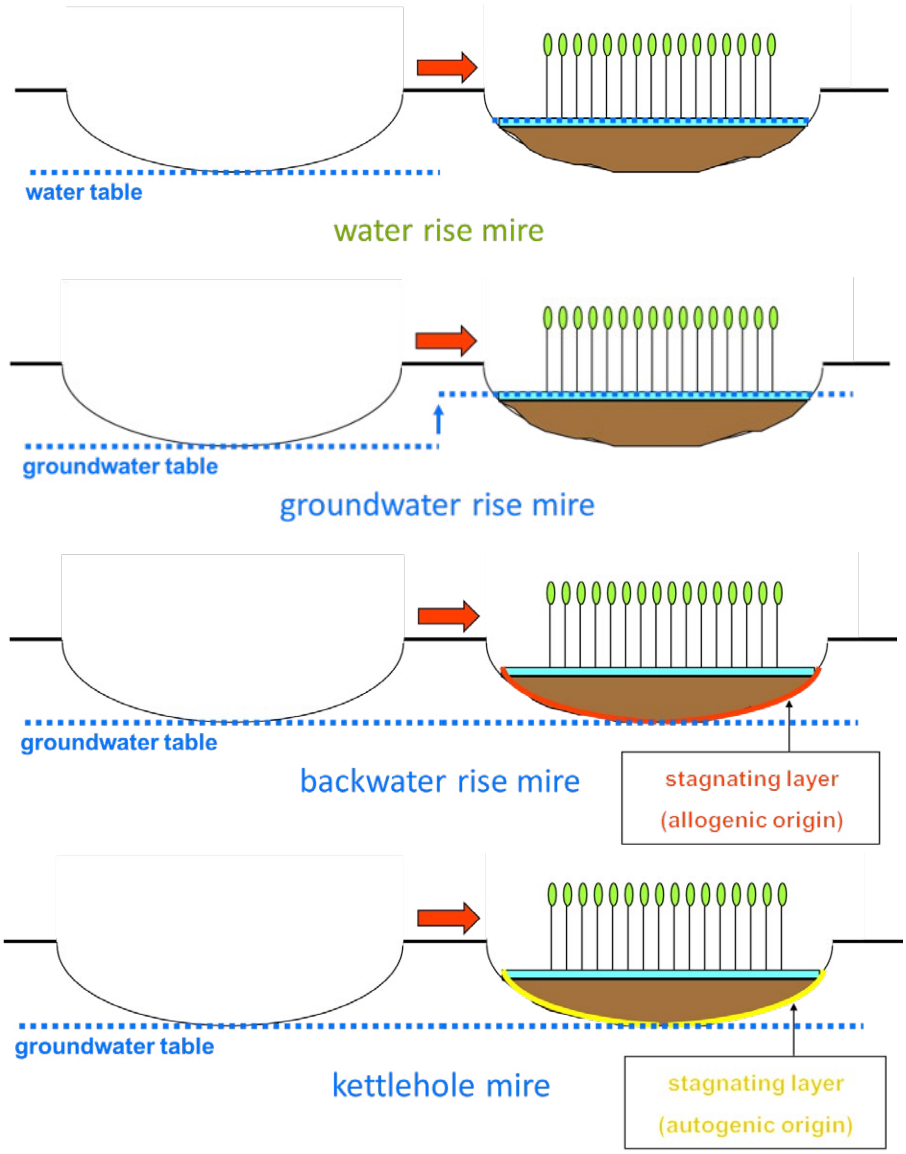

Figure 2

A rise in the groundwater level may occur regionally (e.g., because of sea level rise, a change in climate or land use, or because of peat formation in lower lying valleys). A relative rise in groundwater level may also result from tectonic or glacial isostatic (post-glacial earth movement) landfall or karst breaches.

In depressions without connection to the groundwater, the water table may rise locally because less water infiltrates due to sealing of the subsoil by mineral or organic particles (hardpan, B horizons of podsol soils), or because less water is lost laterally (for example due to beaver dams or mill weirs, or because more water flows into the depression (for example due to reclamation or soil compaction in the catchment).

A particular subtype of water rise mires is the 'self-sealing mire'. Self-sealing mires themselves form a stagnating layer in the previously more permeable mineral subsoil, usually in a kettle shaped basin. As water outflow is impeded to a higher and higher level, the mire internal water table rises. Although the sealing occurs under the influence of flowing water that transports the humus colloids responsible for the sealing from the mire to the mineral subsoil, the peat accumulation strategy is that of a mire without substantial lateral water flow.

- '**Floodwater mires**', which are bound to periodically flooded areas. The water surplus usually runs off fast. Floodwater mires are subdivided into

- ‘River floodwater mires’, where regular flooding is caused by (annual or subannual) water pulses from the catchment area;
- ‘Marine floodwater mires’, where regular flooding is caused by lunar tides (e.g., peat accumulating mangroves and saltmarshes); and
- ‘Lake floodwater mires’, where regular flooding is caused by wind tides (e.g., large lakes, Baltic Sea).

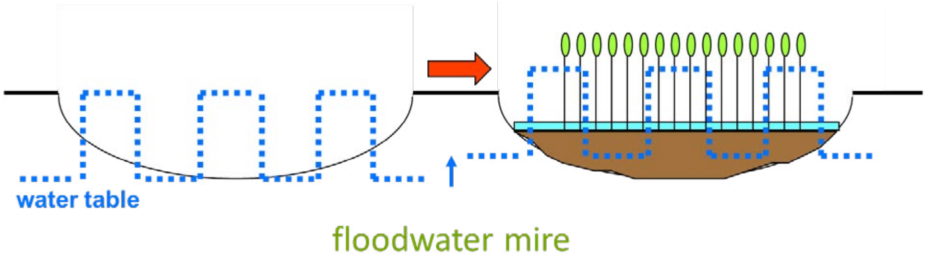

Figure 3

Usually, floodwater mires have strongly decomposed peats because of strong water table fluctuations. Floodwater mires with a substantial peat thickness can only occur if relative water tables are rising (rising sea water level, rising riverbeds, etc.). As such, they are related to water rise mires. The difference is the mechanical action of periodic lateral water flow and associated sedimentation of allogenic clastic materials (sand, clay). As a rule, mire surface oscillation does not occur, because of the high bulk density of the peat. As the hydraulic conductivity of the peat is low, surface run-off is high, although it is somewhat retarded by the vegetation. With this influence on lateral water flow, this type forms the transition to the group of inclining mire types.

Horizontal mires are ‘passive’: they lie horizontally in the landscape, water movement is largely vertical, and they have no (or only a very limited) hydrologic influence on the catchment area. Over time, as their basins gradually fill with peat, they reduce the water storage capacity of the landscape.

INCLINING MIRES are more 'active': the mire surface shows a slope and a significant amount of water is lost through lateral flow. The vegetation and the peat retard this flow and so vegetation growth and peat accumulation lead to an absolute rise in water table, in the mire and often also in the catchment, with continued accumulation of peat as a result. In contrast to horizontal mires, inclining mires enlarge the water retention of the landscape.

Inclining mires can regulate the water available to them to some extent. Most importantly, they retard its run-off, but they also discharge surplus water effectively over the surface because of their slope. In regulating water in- and outflow, the dynamic triangular relationship between water, vegetation, and peat plays an important role. Inclining mires are subdivided into:

- '**Percolation mires**', which are bound to landscapes where water supply is large and very evenly distributed over the year. As a result, the water table in the mire is almost constant relative to the surface. Dead plant material reaches the permanently waterlogged zone quickly and is subject to fast aerobic decay only for a short time. Consequently, the peat remains weakly decomposed and elastic. Because of the large pores and the related high hydraulic conductivity, a substantial water flow occurs over a substantial depth of the peat body. Whereas young percolation mires are susceptible to externally induced water table fluctuations, the growing peat thickness over time increasingly compensates for fluctuations in water supply and water losses by mire surface oscillation. The peat's ability to oscillate makes conditions for peat formation at the surface increasingly stable. Percolation mires are subdivided into
    - '<u>Percolation fens</u>', fed by groundwater (geogenous); and
    - '<u>Percolation bogs</u>', only fed by precipitation (ombrogenous).

Only large catchment areas can guarantee a large and continuous water supply in most climates. Therefore, percolation mires are normally only found as groundwater-fed mires (fens). In the Colchis area (Georgia); however, *Sphagnum*-dominated ombrogenous percolation mires (bogs) exist under conditions of almost 'constant' heavy rainfall.

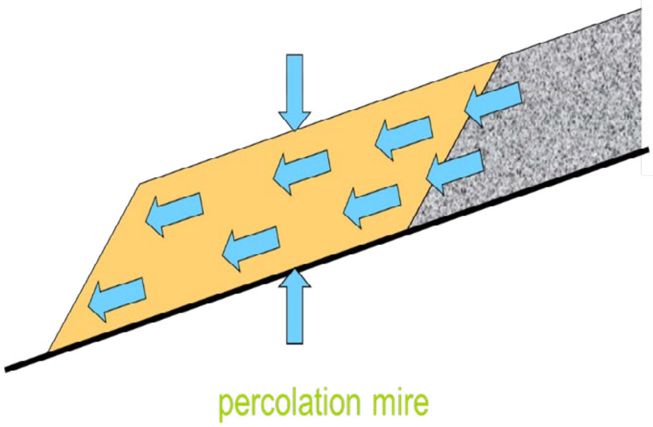

Figure 4

- '**Surface flow mires**', where strong peat decomposition forces the water to overflow the peat. Surface flow mires can only endure if oxidative losses are limited, i.e., if the water table drops only rarely. They are, therefore, limited to areas with almost constant water supply over the year and/ or with only little water losses (especially due to evapotranspiration). Because of the small storativity of the peat, any water shortages may still lead to rather large drops in the water table and resulting strong peat decomposition. Because of their low hydraulic conductivity and large water supply, surfaceflow mires may occur on and with steep slopes. Surface flow mires are subdivided into
    - '<u>Blanket bogs</u>', only fed by rainwater;
    - '<u>Hill slope mires</u>', also fed by surface run-off; and
    - '<u>Spring mires</u>', also fed by groundwater.

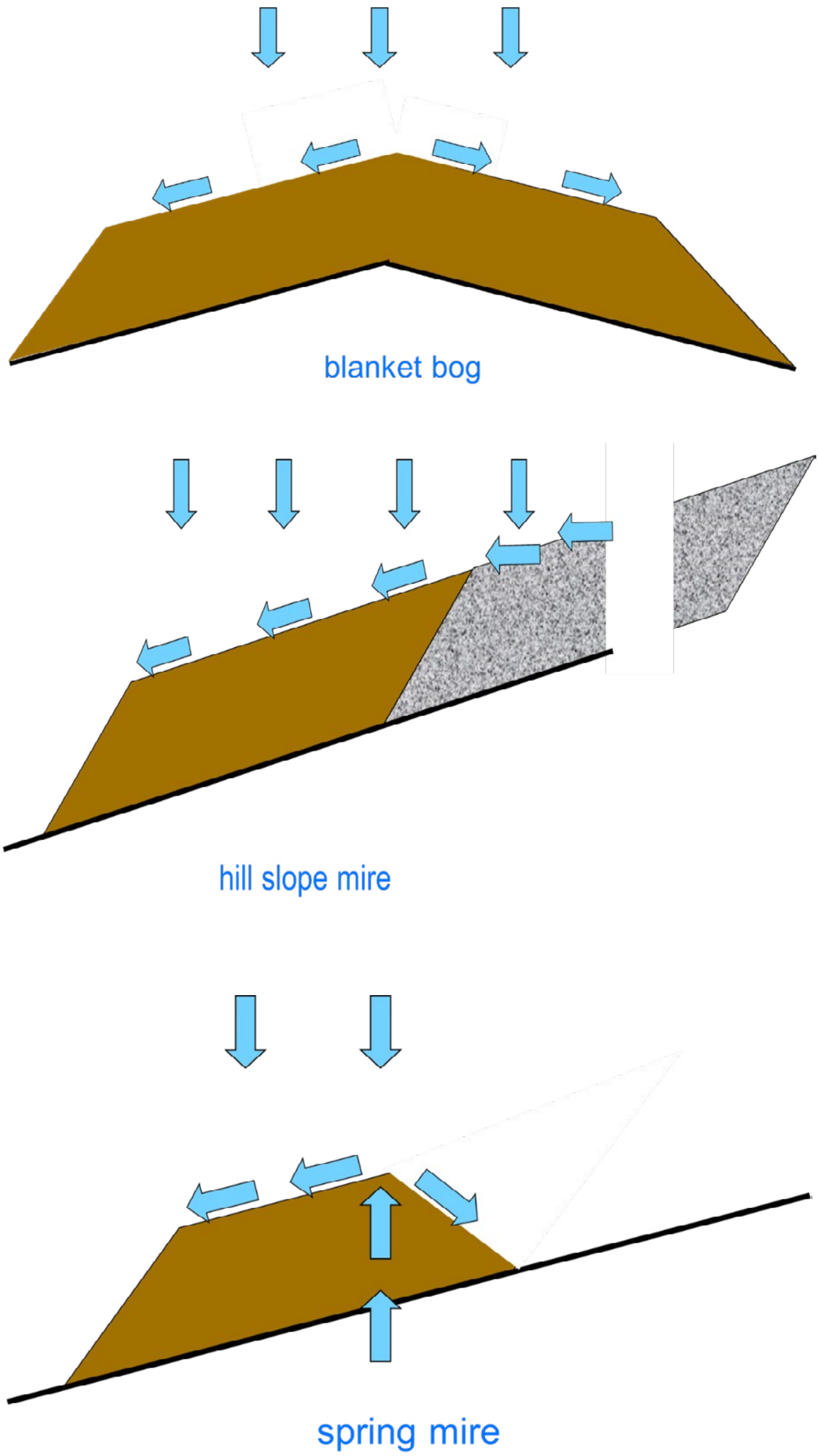

Figure 5

- ‘**Acrotelm mires**’, which show a distinct vertical gradient in hydraulic conductivity in their vegetation layer and near surface peat that allows them to regulate water flow and limit water losses. Acrotelm mires are only know as ombrotrophic ecosystems (i.e., only fed by rain) but theoretically also groundwater fed systems are imaginable (indicated with an interrogation symbol (?) in figure 6 below).
    - *Sphagnum* acrotelm mires (‘raised bogs’) are characterised by a continuous accumulation of fresh *Sphagnum* material that combines a high storativity (many and large pores) with a small decayability of the material. This limited decayability keeps the effect of water table fluctuations on pore space relatively small. Water losses by run-off and evapotranspiration cause only limited water table drop-downs because of the large pores and the large storativity of the peat. The distinct vertical gradient in pore space and hydraulic conductivity results

from the deeper, older peat material having longer been prone to oxidation and to pressure. If the water table does drop in times of water shortage, only little water can flow off through the less permeable part of the 'acrotelm'. In this way, the deeper peat layers (the 'catotelm') remain continuously waterlogged, even if water supply varies.

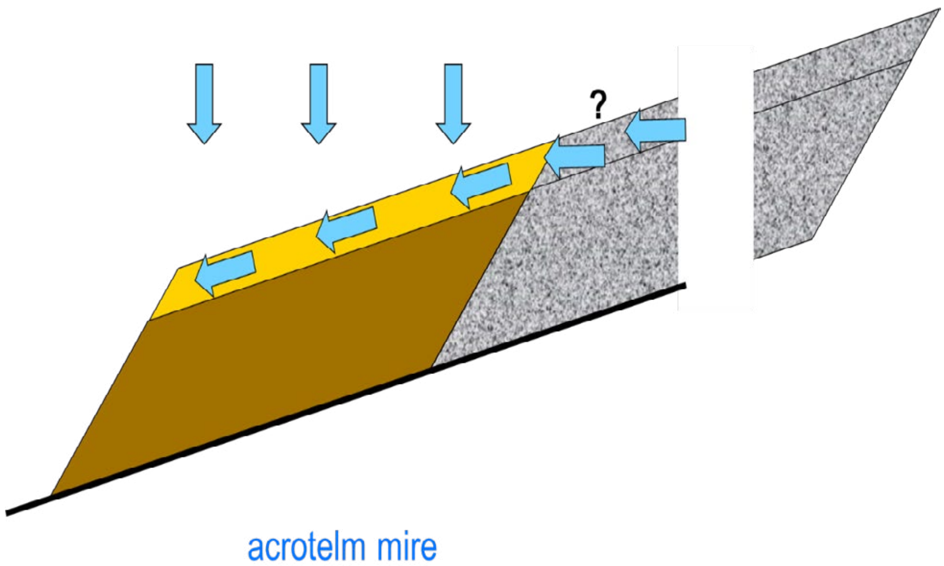

Figure 6

In the case of the *typus classicus* of acrotelm mires, the *Sphagnum* dominated raised bog, the contrasting requirements of a large storativity (to prevent large water table drops by evapotranspiration losses), and a small hydraulic conductivity are only fulfilled by a handful of *Sphagnum* species, first and foremost *Sphagnum austinii*, *S. fuscum*, *S. magellanicum/medium/divinum*, *S. papillosum*, and *S. rubellum/capillifolium*. These species combine a limited decayability with favourable nutrient poor and acidic conditions, inherent to ombrotrophic conditions. The surprisingly wide distribution of the *Sphagnum* acrotelm mire type shows the effectiveness of this strategy.

- Also, the tropical domed peat swamp forests in SE Asia (and probably also elsewhere in the Tropics) are acrotelm mires. Here, the lowermost part of the forest vegetation, the litter layer and the ground surface structure realizes the typical conductivity gradient that keeps the wet season water longer in the mire.

The hydrogenetic peat formation types can be combined with other variables, e.g., with:

- the origin of the water
- water quality
- vegetation, etc.

As an example, we present a combination with the origin of the water (see table 1):

- ombrogenous: stemming solely from precipitation water
- soligenous: also stemming from surficial run-off
- lithogenous: also stemming from deep groundwater
- thallasogenous: also stemming from seawater

Table 1: Hydrogenetic mire types (columns) combined with their hydrological properties and the origin of the water (rows), with examples in *italics*. Grey fields denote combinations that are probably not existing (Joosten *et al.* 2017).

	Horizontal mires				Inclining mires		
Water regime	**Terrestrialisation**		**Water rise**	**Floodwater**	**Surface flow**	**Acrotelm**	**Percolation**
	Schwingmoor	**Immersion**					
Water supply	Continuous	Mostly continuous	Small	Periodic	Frequent	Frequent	Continuous
Mire surface slope	None	None	None	None / small	Small / large	Small	Small
Internal water storage	Large	Mostly large	None	Small / large	Very small	Rather large	Large
Effect on landscape water storage	Storage decreasing	Storage decreasing	Storage decreasing	Storage decreasing (maybe increasing?)	Storage increasing	Storage increasing	Storage increasing
Origin of the water: **Ombrogenous** *bog*	Ombrogenous schwingmoor mire *schwingmoor in bog*	Ombrogenous immersion mire *terrestrialisation in bog*	Ombrogenous water rise mire *water rise in bog complex*	Ombrogenous floodwater mire *floodwater mire along large bog lake*	Ombrogenous surface flow mire *blanket bog*	Ombrogenous acrotelm mire *typical raised bog*	Ombrogenous percolation mire *percolation bog*
Origin of the water: **Geogenous** *fen* – **Soligenous**	Soligenous schwingmoor mire *floating mat in moorpool*	Soligenous immersion mire *terrestrialisation in moorpool*	Soligenous water rise mire *Self-sealing mire (Kesselmoor)*	Soligenous floodwater mire *Self-sealing mire (Kessel-standmoor)*	Soligenous surface flow mires *sloping fen, Hangmoor*	Soligenous acrotelm mire	Soligenous percolation mire *some sloping fens*
Origin of the water: **Geogenous** *fen* – **Lithogenous**	Lithogenous schwingmoor mire *floating mat on lake*	Lithogenous immersion mire *lake terrestrialisation mire*	Lithogenous water rise mire *groundwater rise mire*	Lithogenous floodwater mire *river floodplain mire*	Lithogenous surface flow mire *most spring mires*	Lithogenous acrotelm mire	Lithogenous percolation mire *typical percolation mire*
Origin of the water: **Geogenous** *fen* – **Thalassogenous**	Thalassogenous schwingmoor mire	Thalassogenous immersion mire *coastal terrestrialisation mire*	Thalassogenous water rise mire *coastal floodwater mire, mangrove*	Thalassogenous floodwater mire	Thalassogenous surface flow mire	Thalassogenous acrotelm mire	Thalassogenous percolation mires

As a result of interactions of vegetation, water, and peat ('self-organisation'), mires develop various morphological types. These consist of a characteristic landform (cross-sectional profile, Grossform) combined with characteristic configurations of microtopographic surface-elements (Kleinform). Classical examples are kermi bogs (an acrotelm mire) and aapa mires (a surface flow mire).

In inclining mires, ice development leads to a stronger differentiation between, and a more explicit arrangement of, positive and negative microrelief elements (hummock and hollows, strings and flarks etc.). This results in the development of 'concentric' and 'eccentric bogs' and of 'ribbed fens'/aapa mires.

Next to internal processes, also external processes, such as fluvial and frost activity, may be important in the configuration of peatland macro- and micro-structures. Frost activity may lead to features that also exist in mineral soils but which, in case of peat-covered areas, give rise to specific morphologic peatland types, such as 'palsa', 'peat plateau' and 'polygon' mires.

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Annex III: Conflicts, trade-offs and synergies

Peatland rewetting and restoration aim at multiple ecological, social and economic functions and a range of ecosystem goods and services for multiple stakeholder groups. Some services are synergistic and reinforcing, others are potentially conflicting (Acreman *et al.* 2011). This annex considers the main conflicts and synergies.

Most important conflicts are:

- Waterborne diseases: rewetting may increase the incidence of vectors of waterborne diseases, both for livestock and humans (Cromie *et al.* 2012).
- Nuisances to surroundings: loss of familiar landscape, flooded cellars, biting midges, mosquitos (Becker *et al.* 2010, Verdonschot & Besse-Lototskaya, 2014, Hawkes *et al.* 2020).
- Internal and external eutrophication: rewetting with surface water may lead to nutrient input and sulphate-induced phosphate mobilisation (Lamers *et al.* 2002). Rewetting, especially of nutrient-rich, former agricultural land, may lead to the temporary mobilisation of nutrients (Haapalehto *et al.* 2014, Kotowski *et al.* 2016), particularly phosphate, which can eutrophicate the site itself as well as downstream waters (Sallantaus 2014, Harpenslager *et al.* 2015, Zak *et al.* 2018). Risks and mitigation options are discussed in Zak *et al.* (2010). The leaching of nutrients and suspended solids can be reduced by diverting water from the drainage ditches to be blocked onto the surrounding peatland (Rehell *et al.* 2014).
- Methane emissions: rewetting not only stops the emissions of CO_2 and N_2O (Wilson *et al.* 2016), but also re-installs the generation and emission of the potent greenhouse gas methane (see section 4.2).
- Destruction of historical, archaeological and palaeoecological values (Joosten, 1987, Similä *et a*l. 2014, Waylen *et al.* 2016). Conflicts can be minimized by prior inventory (*cf.* Coles 1995, Coles *et al.* 2001, Greiser & Joosten, 2018), by involving specialists in management planning and regular monitoring (Thom *et al.* 2019), and by providing information to the executing personnel about valuable sites and how they should be considered during restoration work.
- Impairment of existing species conservation values. Mitigation options include minimising damage to remnants and refugia by redistributing the risks through timing, modifying restoration techniques and creating alternative (and functional) habitats for the species involved (Remm *et al.* 2019).
- The fundamental conflict between 'making' and 'becoming': design annihilates spontaneity - "creation destroys nature" (see section 4.3).

Synergies:

- Diseases: Felling conifer forest to restore peatlands may produce a dramatic decline in tick abundance with implications for reduced disease risk (Gilbert, 2013).
- Archaeology/ archive value: Generally, the protection of palaeo-values is favoured by measures that stabilise peat and reduce erosion, halt the physical removal of peat, maintain high water tables, and promote active peat formation[1] (Brunning *et al.* 2000, 2012, Gearey & Fyfe, 2016).

Goal-setting should weigh the desired outcomes against the risks of failure, specifically if a 'degraded' ecosystem already contains high-value components. Where there is large uncertainty, it may be wiser to retain present values, even if restoration *might* achieve greater benefits over the longer term. Joosten & Van Noorden,1992 present a valuation system for all kinds of natural and cultural elements by combining spatial diversity (how rare is the element locally, nationally, globally) and temporal development (does development take years,

1 https://www.ramsar.org/document/resolution-viii19-guiding-principles-for-taking-into-account-the-cultural-values-of.

centuries or millennia). Based on this integrated valuation, they provide guidelines for deciding between actual and potential elements. When actual and potential elements are of the same value, actual values should prevail over potential ones ("one bird in the hand is better than ten birds on the tree"). If the potential values are of a higher category than the actual ones, choices about the way forward become more of a gamble. If you consider a 50% probability for a jump between two successive categories acceptable (i.e., from 8 to 7, or from 5 to 4), you could jump from a category 8 value to a category 3 value with a realisation probability of 0.5 x 0.5 x 0.5 x 0.5 x 0.5 = 0.03 (3%).

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Annex IV: Public participation and stakeholder involvement

Successful implementation of a restoration project will often depend on public support and acceptance, not in the least from the local community and local stakeholders. Public participation is essential, particularly if the planned project is expected to be met with scepticism or resistance. The Aarhus Convention requires that opportunity is given for public participation in decisions about developments that may have a significant effect on the environment.[1]

> "For restoration measures to succeed on tropical peatlands, they must be conducted in collaboration with local communities. This is because communities who currently depend upon peatlands for meeting their livelihood needs may destroy restoration efforts that they perceive not to be in their interests. Examples of how they may do this include illegal forest felling, the use of fire to promote agriculture in degraded forests, or the destruction of dams designed to slow peatland drainage. Significant and appropriate incentives are, therefore, needed to persuade local communities to substitute peat degradation-based income earning strategies with alternative livelihood opportunities that have limited impacts on tropical peat ecology and hydrology." (Jewitt, 2008)

Increasing intensities of public participation include:

- **providing information**, e.g., using leaflets, brochures, posters, stickers, calendars, newsletters, unstaffed exhibits, advertisements, articles in public newspapers, radio or television comments, videos/ DVDs, social media, organised site visits (also for journalists);
- **collecting feedback**, e.g., via responding staff at public exhibitions, social media, staffed telephone lines, regularly updated websites and blogs, telephone/ online conferences, project presentations and public meetings …
- **involving in decision making (consultation)**, e.g., via workshops, forums, open houses (also in the field and on the internet, e.g., with bulletin boards, mailing lists, discussion forums); and
- **enabling stakeholders to decide**, e.g., via community advisory committees, 'planning for real' or 'citizens' juries' with local groups or representative jurors participating in project planning, Free and Prior Informed Consent (FPIC).[2]

> In 2017, the USAID-funded LESTARI project supported a **Free, Prior and Informed Consent** (FPIC) process for developing canal blocks in five villages within the C-2 block (55,733 hectares) of the former Mega-rice Project Area in Central Kalimantan, Indonesia. The work involved local governments and communities, the Peatland Restoration Agency (BRG) and the Water Management Centre. Of the five villages engaged, one village declined to have canals blocked while four villages agreed to build canal blocks with BRG funding. FPIC facilitation ensured that communities were well informed about canal blocking, had an opportunity to provide inputs, and gave their willing consent to construct, maintain, and protect the dams. Notably, local communities were able to influence the design of dams so that their small boats could pass through spillways in order to maintain their livelihoods.
>
> In total, 178 canal blocks were successfully constructed between 2017 and 2018. After the construction of the blocks, the number of fire hotspots within the C-2 area decreased from 944 hotspots in 2015 to one hotspot in 2018. The construction of the canal blocks provided increased production of fish in canals that were blocked,

1 UNECE Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (Aarhus Convention) https://www.unece.org/env/pp/treatytext.html.

2 http://www.fao.org/indigenous-peoples/our-pillars/fpic/en/.

providing economic benefits. Community involvement at the site level has resulted in well maintained canal blocks (compared to adjacent areas where communities were not engaged and many blocks have failed). Given the social and economic complexity of peatland restoration, canal blocking engaging communities through the FPIC method and in construction is advocated (Parish *et al.* 2019).

Promote participation:

- meet people at regularly visited places
- involve different communities
- spread information by different media (social media, newspapers, television, radio, internet)
- distribute materials in local language(s)
- engage interpreters and moderators
- train staff in cultural awareness, anti-racism and equal opportunity
- create a community atmosphere (guided field trips, action days, exhibitions and presentations)
- offer refreshments, tea and biscuits, fruits
- provide encouragements (e.g., prizes or gifts)

Relevant guidance can be found in

- The Convention's Programme on communication, capacity building, education, participation and awareness (CEPA) [3]
- the Convention on Biological Diversity CEPA Toolkit[4]:
- Frogleaps[5]

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3 https://www.ramsar.org/activity/the-cepa-programme.

4 https://www.cbd.int/cepa/toolkit/2008/cepa/index.htm.

5 www.frogleaps.org.

Annex V Notes on vegetation management

Seeding and transplantation

After the hydrologic conditions have been restored (see section 6.3), the chance that characteristic fen communities will spontaneously re-establish depends on:

- the length of time the fen has been drained (which next to the quality of the seed bank also determines how degraded the top-soil is and whether top-soil removal should be considered);
- the plant species present within the re-wetted area; and
- the proximity of extant fen habitat with the desired species.

The seed bank of characteristic fen species is only short-lived and will not have survived long-term drainage, ploughing or top-soil removal. Seed dispersal of relevant species is generally bad, so that colonisation from nearby fens is unlikely, unless vegetative fragments and seeds can float into the receptor site. Only wetland plants with effective dispersal by wind or waders and ducks immigrate rapidly (Pfadenhauer & Grootjans, 1999, Mälson *et al*. 2008, McBride *et al*. 2011, Hedberg *et al*. 2012, Lamers *et al*. 2015, Klimkowska *et al*. 2019).

In case the desired species do not establish spontaneously, re-introduction can be considered (Hedberg *et al*. 2012), e.g., by direct seeding, hay transfer, planting pre-grown seedlings, transplanting sods from nearby donor fens, planting pre-grown plugs or species grown on geotextile matting, or even by actively transporting a complete fen (Mälson *et al*. 2008, Ramseier *et al*. 2009, McBride *et al*. 2011, Kiehl *et al*. 2014, Lamers *et al*. 2015, Wilhelm *et al*. 2015, Chimner *et al*. 2017, Pedrini & Dixon, 2020).

Hay transfer is cheap and effective for both vascular plants and bryophytes, whereas local hay guarantees adaptation to the local climate (Pfadenhauer & Grootjans, 1999, Patzelt *et al*. 2001). Turf replanting uses the feature that most fen plant species spread vegetatively by rhizomes. Fen mosses may well regenerate from fragments (Malson & Rydin, 2007). For most species, a closed vegetation mat of highly competitive species is a major constraint to establishment (Van Dijk *et al*. 2007).

Taylor *et al*. (2018) present an overview of actions (and their effects) that complement planting, such as adding of lime, fertilizer, organic fertilizer, or organic mulch.

> The aim of many restoration projects in Europe is to re-establish 'fen meadows'. Fen meadows are slightly drained, groundwater-dependent fen ecosystems, which have usually lost the ability to accumulate peat, but because of the long-term, low-intensity agricultural management, have acquired a high biodiversity density of typical fen species. Fen meadows are restored by (i) raising water levels by closing drainage ditches, (ii) removing excess nutrients by long-term mowing or top-soil removal, (iii) re-introducing target species and (iv) restoring traditional management (Klimkowska *et al*. 2014). In contrast, fen restoration in North America focusses more on the peatland's natural state.

Restoring traditional management

Traditionally, many of the naturally open fens in Western-Europe and Eastern-Asia were mown and grazed for fodder and litter (and often slightly drained), which in spite of its low-intensity resulted in compaction of the uppermost peat. As long as hay making and grazing persisted, the formation of rainwater lenses was prevented because the tread of humans and animals regularly pushed the peatland surface down into the buffering groundwater. Furthermore, regular biomass removal suppressed competition and inhibited the establishment of trees and shrubs that would result from the stronger fluctuating water levels (Schipper *et al*. 2007). After use has been abandoned, the fens currently suffer under heavy losses in typical species diversity, a decrease in bryophyte cover, a dominance of some graminoid species, and tree and shrub encroachment (Kozub *et al.* 2018).

The former vegetation can be restored through intensive mowing (Middleton et al. 2006, Hájková *et al.* 2009). This may, however, also lead by the destruction of microtopography to a loss of rare fen species (Kotowski *et al.* 2013) and enhance acidification (van Diggelen *et al.* 2015). Nature managers should, therefore, try to restore altered ecosystem properties to their natural (including natural hydrological) conditions, in which fens become again self-sustaining, and limit 'remedial mowing' to the necessary minimum (Kozub *et al.* 2018).

Additionally, grazing with domesticated animals has been part of the traditional use of fens for millennia, both in lowland fens (Middleton *et al.* 2006) and in mountain areas (Maldonado Fonkén, 2014), and has had a significant influence on the historical development of peatland habitats (Thom *et al.* 2019). In Tibet, grazing with yaks has even changed the hydrogenetic character of many peatlands, making them more susceptible to overgrazing and erosion (Zhang *et al.* 2016). Whereas grazing promotes structural diversity, it may also lead to local over- and undergrazing (Middleton *et al.* 2006, McBride *et al.* 2011).

> Taylor *et al.* (2018a, b, 2019, www.conservationevidence.com) provide detailed information on the effects (what works and what does not work) of 125 different actions ('interventions') for managing and restoring peatland biodiversity (flora and vegetation) worldwide (with a focus on Europe and NorthAmerica), however, without discussing causal relationships.

Sphagnum

Sphagnum mosses are arguably the most important peat-forming plants worldwide (Clymo & Hayward, 1982). Furthermore, only a handful of lawn and hummock *Sphagnum* species worldwide are able to build an acrotelm that can raise the surface of a peatland above the influence of groundwater to become a 'raised bog' landscape (Joosten, 1993). *Sphagnum* has, however, severe difficulties in re-establishing spontaneously both in natural (Campbell & Corson, 2014), drained (Price *et al.* 2016) and rewetted peatlands (Thomassen *et al.* 2012).

> A study of 71 rewetted peatlands in Germany revealed that after 30 years only a few hollow species (*Sphagnum cuspidatum* and *S. fallax*) had re-established, whereas lawn and hummock species were absent (Andersen *et al.* 2017).

The failing or retarded recolonization may be due to the rareness of diaspore sources (as in Western-Europe) but will mostly relate to properties inherent to the plant. The large pores and loose structure of *Sphagnum* cannot generate a strong capillary rise to the capitula (the 'heads' of the plant), where growth takes place (Gauthier *et al.* 2018). For the capitula to remain humid, water levels should therefore not drop too deep under the capitula. Under natural conditions, this is secured by the 'acrotelm conditions' of the surface layer, i.e., limited horizontal permeability combined with a high storitivity (Joosten, 1993) and the gradual transition of older peat to younger biomass. After long-term drainage or peat extraction, the low storativity of the remaining peat easily leads to deep water levels in dry periods (Schouwenaars, 1993). Restoring a constant high water level is then only possible by raising the water level substantially *over* the compacted peat surface. This, however, favours the growth of hollow species, which outcompete the slower growing hummock species (Robroek *et al.* 2009). It may take many decades before the former have accumulated sufficient peat to make the environment so much drier that hummock species can win the competition (Joosten, 1995, Van Duinen *et al.* 2011, Lindsay & Clough, 2016).

Water availability in the capitula can furthermore be improved by limiting evapotranspiration, e.g., by providing some shelter against light and wind by herbs or trees, or by covering the re-introduced peatmoss with straw, as is done in the Canadian Moss Layer Transfer Technique (*see* below).

Various methods have been developed to inoculate *Sphagnum* species, including:

- collecting and spreading of *Sphagnum* fragments (the Moss Layer Transfer Technique (MLTT), see box);
- collecting and planting whole *Sphagnum* clumps;
- spreading of *Sphagnum* grown using micropropagation techniques (in e.g., gel beads);

- planting *Sphagnum* grown into plugs or as hummock from micropropagated *Sphagnum*.

Thom *et al.* (2019) provide detailed information on these methods. Except for the MLTT, these approaches are still in early stages of development. In general, the transplantation of larger volumes is more successful than spreading less and smaller fragments (Robroek *et al.* 2009).

> The MLTT developed by the Canadian Peatland Ecology Research Group (PERG) for the restoration of peatlands (bogs, poor fens and moderate-rich fens), especially after peat extraction, is based on active reintroduction of peatland plant species, especially peatmosses, combined with rewetting. The method has been used in over one hundred restoration projects in Canada as well as in many other countries. It allows establishment over 80 % of the species present in the plant material collected from the donor site, shows a progressive decrease in atypical species as the moss carpet develops, and may allow a restored peatland again to capture and sequester carbon 15 years after restoration (Nugent *et al.* 2018, Hugron *et al.* 2020, Quinty *et al.* 2020). The first MLTT restoration guide was published in 1997; a second edition in 2003 (Quinty & Rochefort, 2003). In 2019 and 2020, the chapter dealing with restoration was revised and republished in independent booklets dealing with planning restoration projects, site preparation and rewetting, plant material collecting and donor site management, and spreading of plant material, mulch and fertilizer.

Once established, *Sphagnum* cushions somewhat stabilise soil moisture variations, more so in larger cushions (Robroek *et al.* 2009, Price *et al.* 2016). A vital *Sphagnum* layer also immobilises large amounts of nutrients and prevents nitrophilous vascular species from becoming dominant (Tomassen *et al.* 2012, Temmink *et al.* 2017). A nurse crop may help to stabilize the peat, prevent erosion and provide physical shelter to newly establishing mosses (Sliva & Pfadenhauer, 1999, Groeneveld *et al.* 2007, Dinesen & Hahn, 2019).

Re-establishing light grazing on raised bogs may reduce shrubs and scrub and favour *Sphagnum* (Thom *et al.* 2019).

Open water colonisation

Peatlands with a meso- and slightly eutrophic character may easily revegetate and become peat accumulating after deep inundation (Minke *et al.* 2016). In contrast, recolonisation of low-productive oligotrophic, acid and humic rich deep open water is hampered by wave action and by lack of light and carbon gases for submerged mosses when the water is deeper than 30 cm (Van Duinen *et al.* 2017). Options for addressing this problem are i) to raise the water levels gradually to allow tussock vegetation to grow up with the rising water level), ii) to provide a framework for plant colonization by introducing brash or slightly humified peat and iii) to minimize wave action by compartmentalisation (Joosten, 1992, Wheeler & Shaw, 1995, Tomassen *et al.* 2003, 2004).

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In 2019 and 2020, Chapter 4 was revised and republished in independent booklets:

Planning Restoration Projects (replace p. 13 to 24 in the 2003 Guide)
Site Preparation and Rewetting (replace p. 25 to 35 and pp. 60 to 62)
Plant Material Collecting and Donor Site Management (replace p. 36 to 45)
Spreading of Plant Material, Mulch and Fertilizer (replace p. 46 to 59)

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Annex VI: Monitoring and adaptive management

It is neither possible nor desirable to provide a complete "blue-print" for the implementation of restoration plans. During implementation, lessons will be learned as to what works and what does not, and these lessons should be incorporated in subsequent work and future planning. Planning and design should therefore integrate monitoring, assessment and adaptive management in a continuous process of "learning by doing" (Parish *et al.* 2019).

> Many stakeholders are concerned about the external effects of peatland restoration and are apt to interpret simultaneous or consecutive phenomena as a causal effect of rewetting, be it the flooding of cellars or the nuisance of midges and mosquitos. Monitoring can effectively demonstrate the true effects of restoration measures. The inclusion of a monitoring programme as an integral part of any restoration plan provides a means of demonstrating to stakeholders that their concerns are taken seriously.

Objectives, performance standards, and protocols for monitoring and data assessment should be incorporated into restoration plans prior to the start of a project. The monitoring strategy should consider that the final goals of restoration may only be attained after a long and unplannable period (Bonnett *et al.* 2009). This may require the formulation of indicators for the appropriate trajectory of ecosystem development towards the intended goal. Joosten (1992), for example, proposed calling 'bog restoration' a success, not when an autonomously functioning bog landscape has re-established (this would take a very long time) but when a 'permanent' establishment has taken place of those key species and communities that are able to rebuild such a bog landscape under current climatic conditions (Wheeler & Shaw, 1995).

Monitoring within the project period should mainly focus on the 'input' parameters, i.e., are the planned measures adequately implemented? With respect to peatland rewetting and adaptive management, this will especially concern the execution and after-care of water control structures, leading to the following recommendations (Wheeler & Shaw, 1995, Similä *et al.* 2014):

- Monitor the condition of all water control structures.
- Check dams and bunds regularly, particularly following heavy rain events. Check also for erosion channels around dams and for scouring of the ditch base caused by strong overflows.
- Correct any damage as soon as possible. In case measures are not urgent, they may be postponed to a period with better access to machinery (e.g., a dry summer).
- Check for shrinking and cracking of dams during dry weather and take action to prevent water loss due to preferential flow though these cracks.
- As rewetting progresses, it may be necessary to increase the height of dams and bunds periodically, if the adjacent peat swells.
- Maintenance of 'internal' bunds is less important than of 'external' bunds. Vegetation growth may help to bind the surface peat together, but tree growth may increase drying and cracking.
- Mowing of vegetation may be beneficial if bunds have to be used for access.

In addition to addressing the input parameters, it is necessary to monitor output parameters related to the targets. Indicators for the climate effect would be peat accumulation/ loss and green house gas fluxes, and their proxies: high and stable water levels, vegetation and absence of subsidence. For various other ecosystem services and for biodiversity, vegetation could be a good indicator.

Thom *et al.* (2019) present extensive information on **monitoring methods and techniques** for:

- general site conditions (using field assessment, satellite-, UAV- and fixed-point photography);
- topography (using levelling frame, plane tables, hand levels, quick-set and similar levels, tacheometric surveying, theodolites, Electronic Distance Measurers EDM and Global Positioning Systems GPS, aerial photogrammetry, LiDAR);
- hydrology: water levels (using ground wetness, dipwells, water level range gauges, capacitance probes, chemical tracing techniques, data loggers, multispectral remote sensing, SMAP satellite-based soil moisture content radar, modelling), seepage/ discharge (using V-notch weirs, tipping bucket flow gauges, piezometers), evapotranspiration (using lysimeters) and rainfall (collecting and recoding gauges);
- chemistry: pH, electrical conductivity (EC), and redox potential (using manual devices) and various ions/ elements/ substances (using laboratory techniques);
- peat depth (using coring and Ground Penetrating Radar) and peat properties, including degree of decomposition, texture, fibre content, bulk density, water, ash, soil organic Matter (SOM) and carbon content;
- surface level changes (using peat anchors, accumulation plates, LiDAR, photogrammetry;
- peat erosion (using reference markers, erosion pattern mapping, high resolution satellite imagery, LIDAR and aerial photography derived Digital Elevation Models DEMs, sediment trapping);
- vegetation (using permanent or random area, point or line quadrats, field, aerial photography or satellite-based mapping);
- fauna (using breeding bird surveys, transect counts, lek counts, mist netting, malaise traps, pitfall traps, water traps, light traps, suction traps, aerial attractant traps, emergence traps, and direct counting techniques such as transect walking, netting, hand searching, use of quadrats).

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Annex VII: Evaluation

Closely, regularly and systematically observing and documenting changes in the project area are all important steps in order to evaluate:

- whether the targets have been met and remain being met;
- whether the money was spent effectively and efficiently; and
- what can or could have been improved (lessons learned for the current and future projects).

The ultimate test of success of peatland restoration is, obviously, whether the desired objectives have been reached (Wheeler & Shaw, 1995). This means that these objectives should have been formulated as concretely as possible (*see* chapter 4). Simply proclaiming an area as “restored” prohibits any meaningful evaluation.

> “Success is a nebulous part of the lexicon of restoration; target criteria can vary widely in both ambition and rationale, even among stakeholders within the same project. Ecological outcomes also differ from success related to economics, aesthetics, recreation, or education. Setting evaluation standards requires consensus among scientists, funding agencies and citizen groups.” (González & Rochefort, 2019)

However, the long time that full recovery is likely to require necessitates the formulation of intermediate targets against which progress can be assessed and necessary management adjustments can be identified. In general, the most immediate response is hydrological, followed by biological changes and ultimately regeneration of peat growth.

Long-term monitoring

The eventual “success” of practical restoration is hardly ever assessed in a systematic way. Degraded ecosystems usually recover slowly, whereas the costs of long-term monitoring and evaluation are often difficult to fund because schemes are too short (<5 years) and too restrictive (i.e., supporting implementation but not monitoring and evaluation (Andersen *et al.* 2017, Strobl, 2019). As a result, most studies only cover a short time, whereas long-term studies are rare. This creates a risk of drawing premature conclusions on the efficiency of restoration (Klimkovska *et al.* 2014, Haapalehto *et al.* 2017). Furthermore, general long-term monitoring standards do not exist (Andersen et al. 2017, Artz *et al* 2018). Here, remote sensing should be developed as a near real-time and cost-effective method for monitoring large-scale restoration projects (*cf.* Sirin *et al.* 2020).

Monitoring what?

The success of a restoration project is ultimately determined by whether the desired objectives have been achieved, but in view of the long timescales over which recovery is likely to take place, it is important that a series of intermediate targets be identified so that progress towards the goal can be assessed and adjustments to management operations can be made (Wheeler & Shaw, 1995).

Monitoring of ***water*** levels and regular checks on the condition of water control structures allows the following questions to be answered:

- Are water levels consistently higher than previously?
- Have water levels stabilised and fluctuations been reduced sufficiently?
- Are water levels maintained at the required levels?

Note that assessment must be made with due regard to the actual and prevailing weather conditions.

Vegetation often concerns an operational tool (e.g., the establishment of 'ecosystem engineers'), a method of monitoring (bio-indication) and a goal of restoration (biodiversity conservation). The selection of species for monitoring could focus on all these aspects.

Certainly, the bio-indication aspect may be important to assess the short-term response on restoration activities and to indicate these activities have been appropriate for reaching the ultimate objectives. In this respect it is good to realise that it is easier to eradicate (unwanted) species than to regain target species (Haapalehto *et al.* 2017), so that 'absence' of species is also an important observation.

> It is difficult and costly to monitor entire species assemblages, so a few species groups have to be chosen. These could include:
>
> - Ecosystem engineers, i.e., species that determine the strategic functioning of the ecosystem, e.g., specific *Sphagnum* species for bog habitats;
> - Indicator species, i.e., species that reflect particular aspects of the habitat quality, e.g., water regime and quality, nutrient supply, disturbance, and may indicate specific drivers of change (Strobl, 2019);
> - Characteristic species, i.e., species that are typical for (consistently found in) a habitat, including flagship species which act as an ambassador, icon or symbol for the habitat;
> - Dominant species, i.e., species that dominate communities.

Peat growth is more difficult to assess, because increasing water retention within a formerly drained peat may cause a physical 'swelling' of the peat mass, which results in an increase in the relative height of the peat surface. The latter should not be interpreted as a sign of renewed peat accumulation.

Peat accumulation is a subtle process with large annual variation. Therefore it is – without direct long-term carbon flux studies (Nugent *et al.* 2018) or extensive palaeoecological analysis and dating (Joosten 1995, Mrotzek *et al.* 2020) – difficult to determine whether a peatland is actually peat accumulating. Indicators of peat formation are the prevalence of plants whose remains are also found in the uppermost peat, together with almost permanently waterlogged conditions (Joosten *et al.* 2017) and direct vegetation indication using specifically elaborated vegetation types (Couwenberg *et al.* 2011).

> Restoration ecologists have traditionally focused on abiotic and vegetation-based properties as goals and as monitoring criteria, while animals have generally been less studied (birds being the exception). This is related to the assumption that if habitat quality and vegetation structure recover, the fauna will spontaneously follow. At the same time, vascular plants are easier to assess, show less seasonal variation, and integrate site conditions over long time periods.
>
> However, it has been shown that insect communities do not recover to the same extent as plant communities. Animals are a significant part of ecosystem recovery, given their role as decomposers, herbivores and predators strongly affecting plant diversity and ecosystem functioning (Strobl, 2019).

The Society of Ecological Restoration (SER 2004) lists nine attributes for determining when ecological restoration has been accomplished. Gann *et al.* (2019) present a system of 'stars' to summarize recovery outcome. Bonnett *et al.* (2009) present an extensive review of techniques for monitoring the success of peatland restoration. Extensive information is also found in McBride *et al.* (2011). Useful also is the Ramsar Handbook No. 13 on Inventory, Assessment and Monitoring.[1]

> Peatland ecosystems have often been developing for many thousands of years. In peatland restoration, however, time is often seen as a luxury because funding bodies demand evidence of value for money and proof of success within relatively short funding cycles.

1 https://www.ramsar.org/sites/default/files/documents/pdf/lib/hbk4-13.pdf.

This attitude highlights a marked imbalance between forest and peatland management: if a forest is being established, funding bodies tend to recognise that trees require decades to become established. Curiously, the same recognition is not afforded to peatland restoration although most peatlands typically have lifespans significantly longer than forests.

Some peatland responses can be surprisingly rapid and therefore fit within short funding timescales, but the majority are not and must be given time to stabilise and establish. This is a fundamental rule of peatland restoration management and evaluation – a rule that should be recognised by policy makers, academic researchers and practitioners alike. (modified after Lindsay et al. 2016).

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