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Draft Ramsar Technical Report on Global Guidelines for Peatland Rewetting and Restoration

Ramsar Global Guidelines for Peatland Rewetting and Restoration

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Citation

[To be completed by Secretariat]

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Foreword

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Executive summary

The Ramsar Convention and other national, regional and global policy frameworks promote the restoration of degraded peatlands. The Paris Agreement implies the rewetting of virtually all drained peatland (= some 50 million hectares) in the coming decades. 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 degradation forms, no specific guidance to ecosystem restoration exists. Therefore, it is wise to consult experiences from elsewhere, not to blindly imitate measures, but to develop solutions that fit the local circumstances.

- Whereas every peatland is in one way or another unique, peatlands worldwide share many characteristics. Too much emphasis on the ‘unique character’ of tropical (or other) peatlands carries the danger of distancing from 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.

- Important is the recognition that:

  - Peatland restoration cannot bring back all values lost by peatland degradation, which stresses the primacy of conservation.

  - Anything less than comprehensive rewetting will result in continued carbon emissions and peat subsidence.

  - All drained peatland is fire-prone and will by subsidence eventually fall victim to uncontrolled flooding or to complete oxidation of the peat, often leaving acid-sulphate or infertile land.

  - Insufficient consideration of hydrological coherence may lead to incorrect hydrological planning and management concepts.

Restoration goals

- Restoration goals can be formulated in terms of ‘ecosystem services’, i.e. the benefits that people/society may obtain from ecosystems. Restoration goals must be formulated as concretely as possible and in priority order to provide guidance in case goals conflict with eachother.

- In general, rewetting of drained peatlands is very positive for the climate compared to the drained situation, even if there are large initial methane emissions. Furthermore, management techniques exist to reduce these methane emissions substantially.

- Restoration for nature conservation should act as little as possible to limit the increase of ‘artificility’. 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-based farming and forestry. The global necessity to rewet 50 million hectares of degraded peatlands while simultaneously maintaining biomass harvest implies that drainage-based peatland use must largely be replaced by productive land use that does not require drainage (= ‘paludiculture’).

- As peatlands consist of 90-95% of water, contrasting land uses that necessitate different water tables (e.g., high water tables to promote climate change mitigation versus lower water tables required for drainage-based agriculture) cannot be combined sustainably within the same cohering peat body.

Restoring hydrology

- Water tables that are too low and unstable as a result of anthropogenic intervention are the central problem that peatland restoration has to address. Individual peatlands may, however, strongly differ with respect to their internal hydrologic functioning, to their dependence on water conditions outside the peatland, and thus to the restoration action to be taken.

- The presumption that in strongly degraded peatlands peat growth will eventually recover spontaneously is questionable. In most cases, the re-initiation of peat conserving conditions and renewed peat accumulation will require active intervention to restore the water table to around the peat surface, accompanied by recovery or restoration of the peat-forming vegetation.

- Effective blocking (damming) of drainage structures (ditches, canals, etc.) involves strategic planning of block location and spacing (to increase rewetting effectiveness), the use of local materials (to minimize costs), regular inspection/monitoring and timely 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 a 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 must re-establish, which might require the inoculation 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 spontaneous re-development of such structures will take decades, constructed mounds and ridges may support the hydrological function and facilitate the establishment of the right tree species.

- Half of the degraded peatland area worldwide has undergone severe changes in hydrology and vegetation as a result of conversion to agricultural use. A substantial part of these agricultural peatlands are (extremely) nutrient-rich as a result of peat mineralisation and fertilization. Three options exist with respect to rewetting/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;
- Topsoil 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 resuls 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 build to solve them.

Key findings/ messages

- The Ramsar Convention and many other policy frameworks promote the restoration of degraded peatlands. The Paris Agreement implies the rewetting of virtually all drained peatland (=some 50 million hectares wordlwide) in the coming decades.
- Whereas every peatland is unique, peatlands share many relevant characteristics. Experiences from elsewhere can therefore inspire solutions that fit local circumstances. Important is the recognition that peatland restoration cannot bring back all values lost; that without complete rewetting and vegetation regeneration, peat subsidence and carbon emissions will continue; and that eventually all drained peat will fall victim to uncontrolled flooding or complete oxidation, often leaving infertile soils. Conservation should therefore always prevail over restoration.
- Peatland restoration not only depends on scientific and technical capacities, but also on institutional, regulatory, economic, political and societal opportunities and constraints.

Goal setting will therefore involve an iterative process of problem analysis and goal formulation.

- Main goals of peatland restoration include climate change mitigation/adaptation, biodiversity conservation, securing productivity, and water regulation. Restoration goals must be formulated as concretely as possible and in priority order to provide guidance in case goals conflict with eachother. Land uses that necessitate different water tables (e.g., climate change mitigation versus drainage-based agriculture) cannot be combined sustainably on the same cohering peat body.

- Water tables that are too low and unstable are the central issue to be addressed by peatland restoration. Individual peatlands differ strongly with respect to their internal and external hydrologic functioning and the restoration action to be taken.

- Effective blocking of drainage structures involves strategic planning of block location and spacing, regular inspection and timely maintenance, and the promotion of spontaneous ditch re-filling. When 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/stilt-rooted trees) that hamper wet-season surface run-off. Concentrated downward seepage (as in deep ditches) may be stopped by clogging the leakage points, diffuse seepage by raising the water table outside the peatland.

- Re-establishing peat forming vegetation is the second main challenge of peatland restoration. In case desired species do not establish spontaneously, re-introduction can be considered. In raised bogs, the principal hydrologic mechanism to be restored is the vegetation based ‘acrotelm’. *Sphagnum* raised bogs require the re-establishment of the right *Sphagnum* species, tropical peat domes the re-establishment of trees that develop hummocks and buttressed and stilted roots.

- Peatlands under intensive agricultural use are often very nutrient-rich. Additional to rewetting, restoration options include top soil removal (costly), phytoextraction to remove nutrients (cf. paludiculture), or the acceptance of long-term persistent, highly productive, low-biodiversity fens.

- Restoration experiences should be systematically monitored, evaluated and 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 on the problems is raised and much more technical and institutional capacity is build to solve them.

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 thickness.

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

- the high soil organic matter and carbon content, the permanent water saturation, the slow but continuous rising of the water table and the surface, the relative nutrient poverty and acidity, the 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.

- The 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.

- The sophisticated interaction of plants and peat and water, which allows for the long-term development of self-regulation and self-organisation, making peatlands into persisting ecosystems with often fascinating surface patterning and a unique ecosystem biodiversity.

More than 80% of the global peatland area, 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 as cropland, grazing land and forestry land, or for peat extraction and infrastructure facilities. These degraded peatlands cause major environmental and socio-economic problems (such as through soil degradation, floods and fires), including 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 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, i.e. almost **two million hectares *per year***.

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 contributing to global warming. These greenhouse gases mainly result from microbial oxidation of organic matter when air penetrates the formerly water-saturated peat.[96] The drier conditions following drainage also increase the risk of fire.[69, 102, 170] Along with massive

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[1] Bibliographic references are available under URL xxxx and in the text refered to with superscript bold italic numbers.

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 will in the coming decades be rewetted.[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]

Awareness of these issues brought the restoration of wetlands[2], and peatlands in particular[3], to the agenda of the Ramsar 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 Diversity Framework (CBD[8]), land degradation neutrality (CCD[9]), the Bonn Challenge[10], and the UN Decade on Ecosystem Restoration[11], along with many regional, national and local initiatives.

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[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 Ramsar Convention and cover 20 types of the Ramsar Classification System for Wetland Type (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

This Ramsar Technical Report includes the 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 diverse 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 on Peatland Restoration[88] – identify and develop appropriate solutions. This Ramsar Technical Report thus presents:

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

Key terms and definitions used in this Note[13]

Organic matter: Carbon-hydrogen based material of botanical, faunal, fungal and microbial origin.

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

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

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

Mire: Peatland in which peat is being formed.

Bog: Peatland of which the upper peat layers are derived from vegetation that was only supplied with water and nutrients by precipitation.

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

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

Ecosystem services: Benefits that people obtain from ecosystems.

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[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]

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

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'.

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

Regeneration: The spontaneous recovery of a degraded ecosystem.

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'.

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.

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 stopped. 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.

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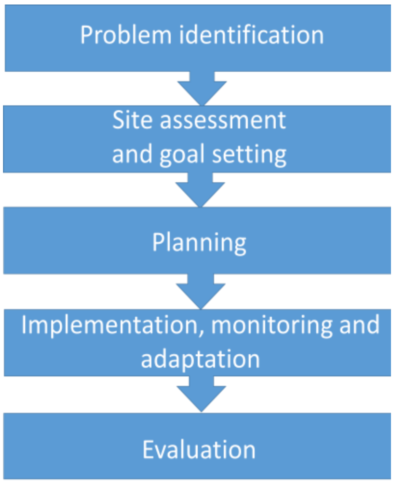
[14] E.g. first awareness Ramsar Convention 2002: https://www.ramsar.org/document/resolution-viii3-climate-change-and-wetlands-impacts-adaptation-and-mitigation; Convention on Biological Diversity 2004: https://www.cbd.int/decisions/cop/7/15/1; Climate Convention 2008: http://unfccc.int/files/kyoto_protocol/application/pdf/iceland.pdf.



Every project starts with the awareness that there is a problem. This problem must be established by examining the condition of the site (*which 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 logic context. After detailed planning of the necessary works, the measures are implemented, their results monitored and the measures, if necessary, adapted. After the end of the project an evaluation should take place to assess the success up to that point, to forecast future developments, and plan further action.

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 be realistically achieved.

3.1. Peatland types

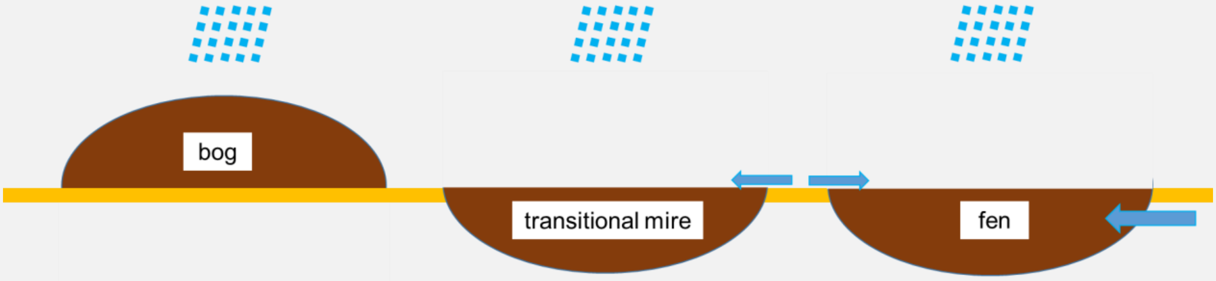
Just as horses, cars and airplanes are all a means of transport, but – if they malfunction - differ in the way they have to be cured or repaired, huge differences exist between peatlands. Failing to identify how the peatland in question functioned (in a natural state) may not only prevent effective restoration, but may also risk disrupting existing conservation values (fig. 1).

The diversity of and different interests in peatlands 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.

Fig. 1: Restoration plans in Sandaohaizi wetland (Xinjiang UAR, China) were stopped after timely recognition that the site was not a supposed severely degraded peatland with remnant erosion hag tops, but in fact China's only known palsa and lithalsa permafrost peatland complex with a natural build-up and degradation cycle. The initially planned levelling and flooding of the site would have destroyed this unique phenomenon

Bogs and fens

A categorization *with* restoration relevance is the classic division between **bogs** (i.e. peatlands that receive their water and nutrients solely from atmospheric precipitation) and **fens** (i.e. peatlands that also receive water that has been in contact with the 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 is similar to that of a bog.



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]* **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.

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[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' also areas where the vegetation is not peat accumulating anymore 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.

In **inclining mires**, the peatland water table forms a (often only slightly) sloping plane, leading to mainly horizontal water movement (water flow). This lateral flow is retarded by the growing vegetation and peat, which thus causes 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 globally widespread 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 up 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 availability, 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 makes them also 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 (like original vegetation, water supply, and hydraulic peat properties) to a greater or lesser extent, 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.

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.

Table 1: The main groups of hydrogenetic mire types. For a detailed description and subdivision see Annex II.

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 over the peat surface to reinstall new anoxic spaces (and continue to do that)
	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 porous and 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 on the long term the formation of new highly permeable peat
	Uppermost peat compact and 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

Peatlands may, thus, also degrade due to changes in land use and water management outside the peatland itself that 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 lay outside*... (see § 6.3.4).

Cohesion and connectivity are not only important with respect to water. Peatlands may also degrade via 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 NH_4, 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 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 also within different parts of the same peatland, water of different origin and quality may prevail.[113, 164, 204] Conversely, similar water quality conditions may be created by different hydrogeological settings.[60]

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 provide for 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]

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 perspectives for 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.

Are tropical peatlands different?

Regularly the remark is heared 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 § 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 incomparability of tropical peatlands carries the danger of being isolated from applying global knowledge and common sense.

Restoration relevant differences between non-tropical and lowland tropical peatlands 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 more rapid 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]

3.3. Degradation intensity

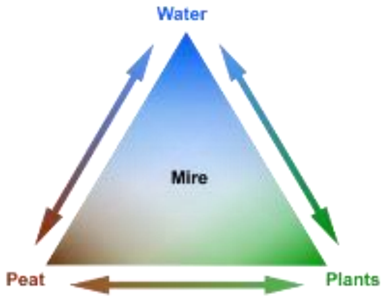

Fig. 2: Interrelations between plants and water and peat in a mire

In a living peatland (a 'mire') strong functional relationships exist between plants and peat and water (fig. 2): if one of these components changes, ultimately the others will change too, provoking 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 again 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** (fig. 3).

Minimal and minor degradation

Least affected and most easily restorable (minimal and minor degradation intensity) are peatland 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 with root and branch eradicated (e.g. by surficial fire, overgrazing, or the construction of pads, roads and seismic lines.***16***

If no other site conditions (esp. hydrology) have been damaged, 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 § 4.3, Annex VII).

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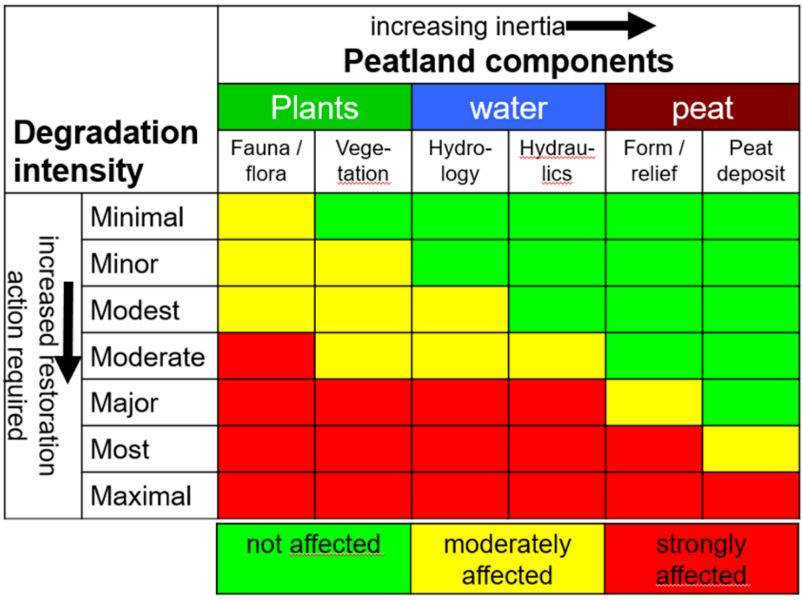
[16] We differentiate between a 'mire *site*', which is a homogenous area within a mire, such as the mire expanse, the mire margin and the lagg in classical raised bogs***98*** or the 'phasic communities' in tropical peat domes***4, 151***, and a 'mire *massif*', which encompasses the entire cohering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



increasing inertia →

Peatland components

Degradation intensity	Plants		water		peat	
	Fauna / flora	Vege-tation	Hydro-logy	Hydrau-lics	Form / relief	Peat deposit
Minimal	🟨	🟩	🟩	🟩	🟩	🟩
Minor	🟨	🟨	🟩	🟩	🟩	🟩
Modest	🟨	🟨	🟨	🟩	🟩	🟩
Moderate	🟥	🟨	🟨	🟨	🟩	🟩
Major	🟥	🟥	🟥	🟥	🟨	🟩
Most	🟥	🟥	🟥	🟥	🟥	🟨
Maximal	🟥	🟥	🟥	🟥	🟥	🟥

increased restoration action required ↓

🟩 not affected

🟨 moderately affected

🟥 strongly affected

Fig. 3: Peatland degradation intensities and restoration perspectives as a function of the impairment of increasingly more inert peatland components

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 § 6.3).

Most peatlands worldwide are not only dependent 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, i.e. even at many kilometres distance from the peatland in question.

Alleged negative changes in the hydrological landscape setting must be explored by ecohydrological studies. If these are 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] and 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 lead to a decrease in peat porosity, hydraulic conductivity and storativity and an increase in bulk density and soil water retention.[153, 163]

Particularly in fen peatlands in warm climates, continuous shrinkage and swelling of the drained peat may furthermore 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 sighly 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 an often 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 (fig. 4).[33, 34]

These structures (which mainly relate to spatially differented resistance to water flow, accompanied by a large storativity)[23] are destroyed by e.g. peat extraction, compaction (e.g. by long-term grazing), fire, long-term drainage and decomposition, or deforestation (in the case of forested peatlands).

Fig. 4: 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.*[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 storage coefficient[17] 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]

It is important to understand that the restoration/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.

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[17] With storage coefficient we mean the volume of water that can be easily removed from a volume of soil (l/l).

The degradation intensity ‘most’ concerns 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]

Fig. 5: Left: Restoration of parts of the Bargerveen (Netherlands) by 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.*

Maximal degradation

The last and maximal intensity of peatland degradation refers to the situation that the peatland has virtually stopped to be 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 put 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 fig. 5 and § 6.2). Beyond that threshold it may be opportune to abandon the goal to restore the original mire type and to focus on ‘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

Fig. 6: Land use alternatives for currently drained peatlands

4.1. Introduction

In order to set realistic objectives, it is essential to choose targets based on the *actual* potentials.[113] General land use alternatives with respect to drained peatland use include (fig. 6):

- continuation of current drainage-based land use or management (incl. 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 (incl. biodiversity) that people/society may 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) and 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

"In order to promote long-term sustainability, rewetting and revegetation are required and promoted, but in order to meet the requirement of 'revitalisation' 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 dragonfruit. However, these are all dryland crops that require at least 30-40 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 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 reinstallment 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 (fig. 7).

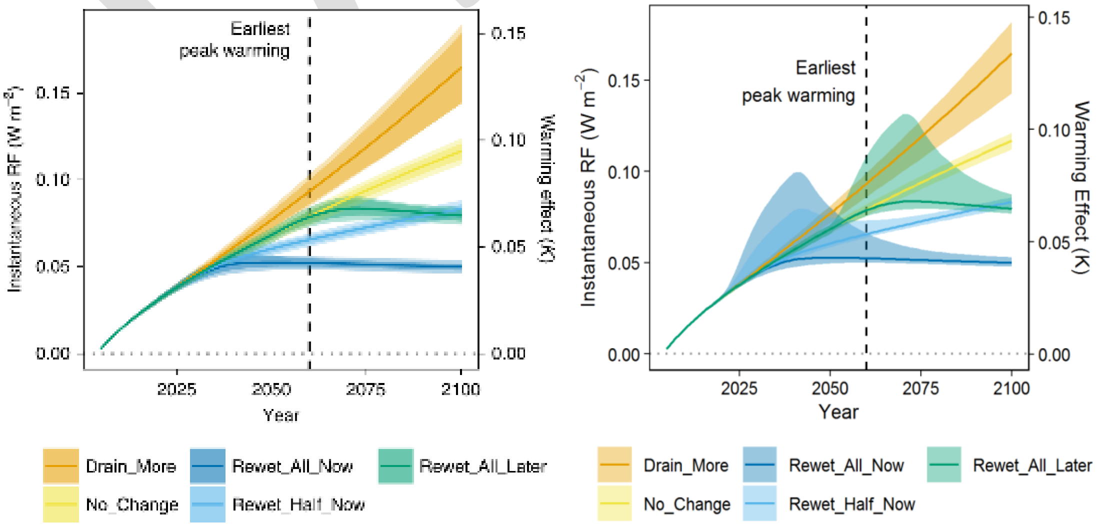

Fig. 7: Radiative forcings (RF) and climatic warming effects (relative to 2005) of global peatland management without (left) and with (right) an initial 10 times larger methane peak for 5 years after rewetting. Drain_More*: The area of drained peatland continues to increase from 2020 to 2100 at the same 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. beween 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 the fresh biomass before rewetting;
- avoiding submerged waterplants;
- regular flooding with sulfate-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’.[24]

Rewetting of tropical peatlands and agricultural peatlands outside the tropics has always a large and rapid effect for climate change mitigation. For boreal forestry-drained peatlands the climate effect of rewetting may be comparitively (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]

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]

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 (cf. § 6.4.) must be critically aware 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.

Peatlands may furthermore have a high ecosystem diversity[18], reflected in conspicuous surface patterns on various hierarchical and spatial scales, which express hundreds or thousands of years of sophisticated self-organisation and –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 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* that is done (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) of deliberate action:

1. *not doing*: defensive measures (veto-regulation) to prevent injury (= external management), e.g. the instalment of hydrological bufferzones around the peatland;[196]

2. *doing once*: one-off activitities to improve conditions, e.g. blocking ditches and building bunds and

3. *doing continually*: offensive 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 this: Which means are allowed to reach which ends? If all means are justified, the difference between a nature conservation area

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

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 (= a device like a mowing machine), never an aim of nature conservation. Introduction may result in larger biodiversity but always at the expense of naturalness.
- Limit your activities to 'not doing' (forbidding) and to 'doing once'.
- 'Doing contuinually' is only allowed 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 globally cease to exist.

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 increasing risk of losing the investment. Whereas you only invest once in one-off measures, the cumulative costs of continuous management (i.e. fighting against 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 Ramsar Convention. Most peatland degradation results from drainage-based agriculture and forestry, i.e. the peatlands have been drained to provide for food, fodder, fiber 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 (fig. 6). 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'[19].[147, 210]

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 most and for all by the conditions under which these crops are cultivated (permanently wet and without damaging the peat soil).[20]

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

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

Paludiculture does not *focus* on nature conservation but its practices may *contribute* to nature conservation by recreating 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.

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.[127, 180, 203, 21]. Furthermore, simply re-vegetating bare peat can reduce loss of carbon particles dramatically.[182]

Denitrification as a nitate removing process takes place when nitrate enriched water comes into contact with water-saturated (anoxic) peat.[28, 70] Removal of organic matter, solids, P, and N from incoming water is a function of wet peatland vegetation and therefore restricted to non- and little disturbed (incl. paludiculture) sites.[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 and

- 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 (incl. 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, archeological, 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), including a strategy for making mid-course corrections,
- appropriate materials, contractors (with peatland and peat experience!), 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,
- 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 (common land, rights of way, turbary, riparian, mineral, shooting and grazing rights), tenure, and the location of actual or planned public facilities (pipelines, pylons, electricity lines, 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 to be expected. Relevant guidance can be found in the Ramsar Communication, Education, and Public Awareness Programme (CEPA)[21], the Convention of Biological Diversity CEPA Toolkit[22], Frogleaps[23], 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 strongly depend on 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 $ 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, and

- 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]

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[21] http://www.ramsar.org/activity/the-ramsar-cepa-programme

[22] https://www.cbd.int/cepa/toolkit/2008/cepa/index.htm

[23] www.frogleaps.org

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 to and
- justify payments to providers of services (payments for ecosystem services PES).

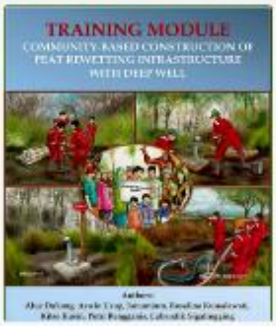
A wide variety of funding mechanisms is available for peatland restoration, while foreseeable new mechanisms will emerge within the context of policy frameworks mentioned in chapter.[194, 95, 208]

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) / carbon reduction credits,[12, 175, 200] results-based finance;
- paludiculture: 'earn money with cattail and get rewetting for free'.[216]

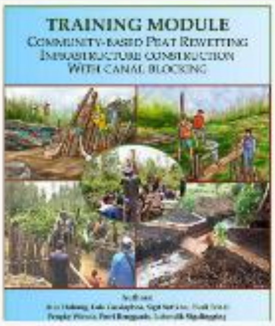
6. Restoration techniques

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.



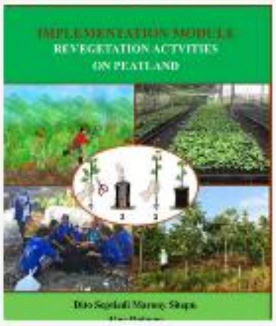
TRAINING MODULE
COMMUNITY-BASED CONSTRUCTION OF PEAT REWETTING INFRASTRUCTURE WITH DEEP WELL

Training Module Deep Wells



TRAINING MODULE
COMMUNITY-BASED PEAT REWETTING INFRASTRUCTURE CONSTRUCTION WITH CANAL BLOCKING

Training Module Canal Blocking



IMPLEMENTATION MODULE
REVEGETATION ACTIVITIES ON PEATLAND

Implementation Module Revegetation

Technical Guidance for
Peatland
Revegetation
2017

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 (§ 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, whereas 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 too low (boosting peat oxidation) and too high water levels (reducing plant production, increasing 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-groundpressure machinery, adapted for this mode of action, and operated by experienced workers.

- Acid nutrient-poor peats degrade slower than alkaline and nutrient-rich peats and therefore acid nutrient-poor peatlands are often more easy to restore. Similarly, acid nutrient-poor peat often has a better suitability for restoration construction.

- In warm tropical climates, all processes go faster than in colder, e.g. boreal climates: 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, fig. 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 prefered (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 immission problems can only partly be reduced by removal of sources close to the site (< 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 'valuable' 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, departing from the most severe degradation intensities and working towards the lightest (see § 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 perpetual 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 (fig. 8) 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]

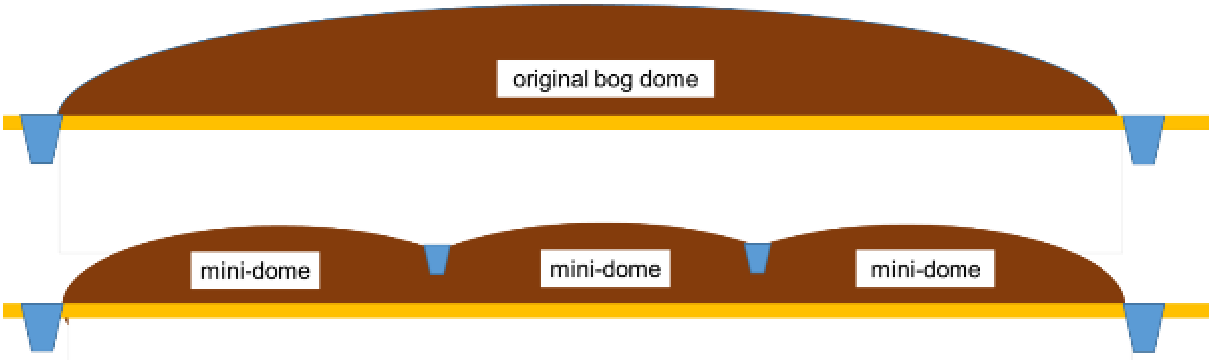


Fig. 8: Formation of mini-domes between drainage ditches due to subsidence and oxidation.

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 § 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 § 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/transport by the local population. Therefore, consensus on blocking should be reached with the local people.
- In cases that 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 determine 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 often a cascade of dams is 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 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 required large volumes of peat may affect the visual appearance of the landscape.

- Bearing in mind the number of dams that may sometimes be needed, it is recommended to use wood 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 low 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 may 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 Ramsar Briefing Note.[88]

- With limited means available, it is tempting to try to create fewer blocks 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, a time 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 small damage before such damage 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, embody the tension between the need to maintain high peatland water tables, the necessity 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 in times of water surplus – e.g. in 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 the recently emerged transport opportunities that ditches and canals may provide 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 (= completely filling up of ditches/canals) is the most effective method to restore 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 fiber bales is a good option in wilderness areas or areas lacking peat or mineral soil fill because it is easily transported. Other materials (e.g. bentonite, clay) may be necessary to reduce seepage.

- Care should be taken to seal ditches cut into highly permeable mineral soil.

- Infilling prevents ditches/canals being used as access, which may be beneficial in conservation areas. Fish rearing in canal sections is, 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’, ‘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 formalise the edge of the peatland and hinder its future expansion.

- Parapet bunds are installed when the water storage capacity of the peat is/has become 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 in the following references: [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 § 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 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 decreased by canals and ditches and the removal of thick layers of peat.[165, 206]

By tapping into the more permeable underlying sandy soils, also drainage ditches in the peatland itself can 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 the raising of the water level in the surrounding land (peat-workings, farmland etc.[206], § 6.3.4).

6.3.4. Off-site hydrology and bufferzones

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 **bufferzones** to reduce 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 and constitution/nature of an external bufferzone can best be determined by three-dimensional, non-stationary hydrological modelling.[196]

In case the discharge of regional groundwater in the peatland has to be restored, regional groundwater levels have 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 suggestion to remove peat to the predicted position of the perched water mound in a peat remnant is subject to the same misconception.[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 § 6.1).

6.3.6. External water supply

An alternative approach to the problems of water retention is to directly irrigate peat massifs 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 (pollution, nutrient-enrichment) problems[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 acrotelm is characterized by a horizontal permeability for water that from the top of the acrotelm rapidly decreases with depth. This strong differentiation implies that when the water tables rise, the water increasingly flows in layers with an increasingly 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 storage coefficient, 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 thereunder. 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 (fig. 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, Joosten 1993). 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 § 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. Without a vegetation cover peat dries out rapidly and becomes more vulnerable to fires, especially in dry months.[50]

In peatlands, drained bare surfaces that originated from 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 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, whereas - in the case of extensive bare surfaces - areas that may provide suitable diaspores may be far away.[183]

The approach to revegetate such areas depends on the type of peatland, the state of degradation, and the plans for the area. If remnants of the original vegetation remain, rewetting may be sufficient for the vegetation to regenerate naturally. Revegetation of bare peat on slopes may require the application of lime, fertilizer and a nurse crop (e.g. composed of amenity grasses) to rapidly stabilise the peat surface and 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 biodiversity 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. The above-ground storage capacity for surplus water from the wet season they create in this away, allows the peat dome to be kept wet also in 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.

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 in strongly subsided areas by reducing runoff velocities. 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]

Regeneration barriers

When disturbance in tropical peat swamp forests has been extreme to the extent that most trees have disappeared, the landscape becomes dominated by ferns, sedges, and shrubs. Altered hydrological conditions and fire are 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] If pioneer species are well established, then species with the capacity for hydrological regulation and peat formation can be planted or may establish from natural seed dispersal.

To date, however, there is limited information available on which species should be selected for particular locations and specific 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].

“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]

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. Inspite 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]. Picture left from[12]

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 tree.[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 in the world do not support a forest cover. 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 paragraph 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 effort to rehabilitate, these peatlands represent the largest restoration challenge. Most of these 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 life-time.[216]

Three options exist with respect to rewetting/restoration of these lands:

- 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.

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

Top soil removal

Topsoil removal is a radical method to reduce availability of nutrients and agricultural pesticides. Removing a layer of degraded peat topsoil 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.[66, 103, 113, 150]

The results of topsoil removal often depend on the removal depth, 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]

Topsoil 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 § 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 slightly drained), 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 currently 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 become again 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 to re-establish spontaneously both 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 indispensible part of the productive land.

Although paludiculture can build on many traditional methods and experiences, the required scale and intensity makes paludiculture largely ‘unknown land’. 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[24], and in the Database of Potential Paludiculture Plants (DPPP)[25].

Paludiculture options in Southeast Asia

Lowland Southeast Asian peat swamp forests hold 1376 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, oils), and 165 have been assigned “other” uses (e.g. latex, fuel, 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 (be it with modified techniques and other crops), paludiculture probably holds the greatest potential to contribute to maintaining and revitalising local livelihoods while rewetting peatlands.[34, 50]

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]

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[24] http://www.mires-and-peat.net/

[25] https://greifswaldmoor.de/dppp-109.html

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, Aquatic Warbler breeds in only 4 countries: Belarus, Ukraine, Poland and Lithuania. The strongly 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: https://meldine.lt/wp-content/uploads/sites/2/2018/07/Meldine_factsheet_A4_ENG_preview.compressed.pdf

6.6. Microbiota

The response of microbial communities to disturbance and restoration is far from fully understood.[159] After disturbance in a bog, the specific communities were found to be replaced by more ubiquitous 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.

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 have been reached.[206] 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. 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 can not 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/millenia) 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 palaeoenvironmental 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 still insufficiently 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 the failure to understand that drained peatlands cannot persist over time: they either fall victim to uncontrolled flooding (incl. by the sea in 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 hydrological planning and management concepts. It is impossible to sustainably combine conservation/restoration 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 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[26] 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. They may be facilitated by education or research centres developed in or specialising in peatlands.[147] A special role can be played by Wetlands of International Importance under the Ramsar Convention that 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] Current teaching and training strategies may not yet 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.

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

- Hydrological self-regulation, especially 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 towards 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 also charcoal[115] and microremains, including those of aboveground plant material of which no macroremains are conserved[129] may 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, including 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.

9. Conclusions

- The Ramsar Convention 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 ‘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 only 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 re-establish, 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 largely (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.

Bibliographic references

All references are available under URL xxxx

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Fig. 1: Marc Foggin, Fig. 4: Hans Joosten, Fig. 5: Hans Joosten

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Annexes

Annex I: Values and ecosystem services
Annex II: Hydrogenetic mire types
Annex III: Conflicts, trade-offs and synergies
Annex IV: Public participation and stakeholder involvement
Annex V: Notes on vegetation management
Annex VI: Monitoring and adaptive management
Annex VII: Evaluation