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Effectiveness of conservation interventions globally for degraded peatlands in cool-climate regions

Running title: Effectiveness of peatland conservation

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Abstract

Peatlands support unique biodiversity and essential ecosystem services, such as regulating climate and providing freshwater and food. However, land-use change, resource extraction and changing climates are threatening peatlands globally. Restoring degraded peatlands requires re-establishing the key features that drive these ecosystems – the hydrology, chemical properties and characteristic biota. Using the best-available evidence to identify interventions that will effectively abate threats and restore ecological processes can facilitate successful conservation. 'Rapid evidence reviews' have emerged in healthcare as a method of delivering key research findings to policymakers and decision-makers in a timely manner. Here, we used a rapid-review approach to identify, appraise and synthesise scientific evidence on the effectiveness of interventions intended to restore the hydrology, chemical properties and/or characteristic biota of degraded boreal, montane, alpine and temperate peatlands globally. We found consistent evidence that rewetting, shading or mulching, reprofiling, mowing, controlling grazers and active revegetation can improve the condition of degraded peatlands. Taking a whole-system approach was reported as essential to successful conservation because the hydrology, chemical properties and biota are intrinsically linked. There is consistent evidence that restoring peatlands can enhance the ecosystem service of carbon storage. We demonstrate that applying the rapid-review approach to a conservation problem: 1) proved efficient for synthesizing evidence from 453 individual studies collected through 23 reviews, and 2) yielded a valuable synthesis of the common interventions to support effective, evidence-based conservation and recovery of peatlands globally. This can enable policymakers and practitioners to apply the best-available research knowledge when addressing this important challenge.

Keywords: bog, fen, ecosystem management, conservation, restoration, evidence-based decision making

Introduction

Peatlands are globally important ecosystems for biodiversity and ecosystem services (Finlayson et al. 2005). Peatlands are palustrine wetlands made up of partially decomposed organic matter (peat) (Page & Baird 2016). Unique environmental conditions in peatlands promote species adapted to these environments (e.g., *Sphagnum* mosses) and support adjacent ecosystems, such as by providing water for rivers and support existence of permafrost (Minayeva & Sirin 2012). Peatlands provide vital regulatory ecosystem services, including regulating local and global climates via carbon storage and protecting against erosion (Page & Baird 2016). Peatlands cover approximately 3% of the world's land area (4.23 million km^2) (Figure 1; Xu et al. 2018) yet contain 21% (644 gigatons) of the world's soil carbon (Leifeld & Menichetti 2018), making them the most important terrestrial ecosystems for carbon storage. Peatlands deliver provisioning services to millions of people, such as freshwater, food (e.g., fish, mushrooms, berries), and energy sources (e.g., wood, moss, peat) (Page & Baird 2016). Yet unsustainable use and modification of peatlands is threatening long-term carbon stores, biodiversity and human wellbeing (Parish et al. 2008).

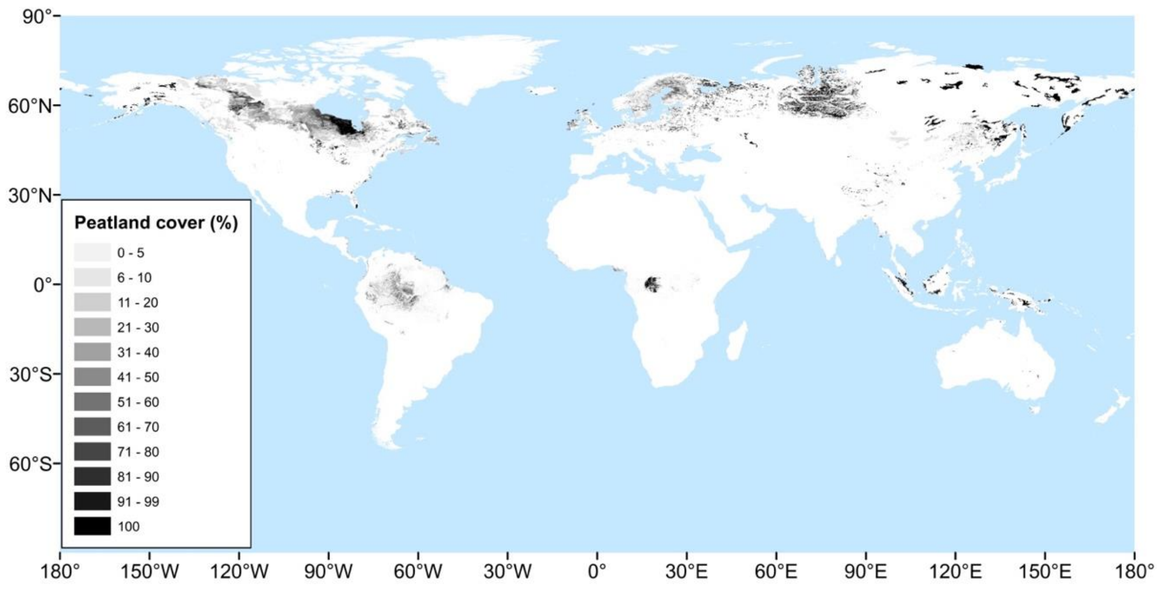

Figure 1. Global distribution of peatlands derived from PEATMAP (Xu et al. 2018)(CC BY 4.0). Note: our review excluded tropical peatlands, as they have very different peat-forming processes and threats, and peaty soils, both of which are included in this map.

Peatlands face many interacting threats from human activities, especially habitat modification. For example, nearly 25% of all mires (peatlands actively forming peat; Glossary, Appendix 1) have been destroyed globally (Parish et al. 2008) for forestry, agriculture, peat extraction, and infrastructure developments (Nieminen et al. 2017; Sloan et al. 2018). During conversion to other land uses, peatlands are often drained and the vegetation degraded (Page & Baird 2016; Webster et al. 2015). This increases erosion, degradation of peat (Li et al. 2018) and therefore greenhouse gas emissions (Hatano 2019; Tan et al. 2020), while hindering water purification processes (Kritzberg et al. 2020), altering peatland chemistry and promoting non-native species invasions (Grzybowski & Glińska-Lewczuk 2020). Warming temperatures and altered precipitation regimes under climate change have caused drier conditions that shift peatlands from carbon sinks to carbon sources through desiccation of peat-forming species, peat decomposition, permafrost thaw (He et al. 2016; Moomaw et al. 2018) and longer fire seasons (Leng et al. 2019; Page & Baird 2016). Peatland degradation from land-use change will likely reduce their resilience to climate change (Moomaw et al. 2018). Therefore, restoring degraded peatlands and conserving those that remain intact is critical for addressing climate change, conserving biodiversity and supporting human wellbeing (Leifeld & Menichetti 2018).

Peatlands are complex ecosystems characterised by strong interactions among their core features (hydrological conditions, chemical properties, biota) and processes (erosion, carbon storage). Conceptual models are a valuable tool for characterising these interactions (Suter 1999) and can help understand how threats affect ecosystems (King & Hobbs 2006) and identify how to target conservation interventions to support ecosystem recovery. The relationships among these features and processes provide important insight into the function of intact peatlands and effective management (Figure 2). For example, the distinctive hydrological conditions and chemical properties are vital to support the characteristic vegetation and peat formation (Figure 2; Page & Baird 2016). Knowledge of how threats and management interventions affect the features and processes of an ecosystem can improve conservation outcomes (Mcdonald et al. 2016). Understanding how potential interventions act to protect targeted ecosystem features and/or processes and any indirect effects on other parts of the system enables identification of effective interventions while avoiding unintended consequences. Better outcomes are possible if interventions not only target restoring the hydrological conditions, chemical properties and biota, but also consider how interactions among these features may alter conservation success.

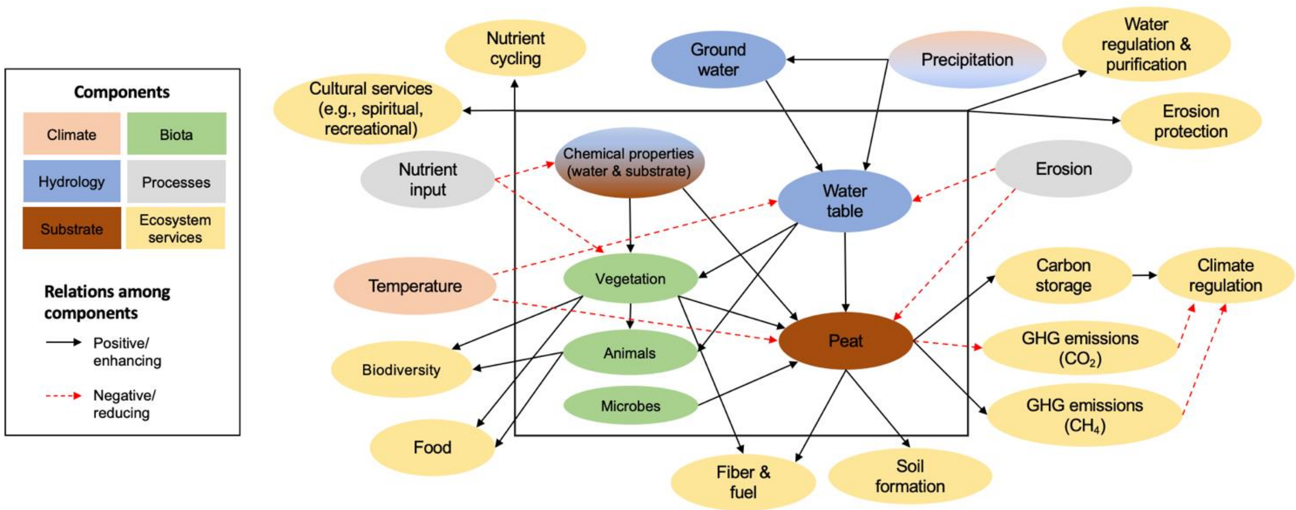

Figure 2. Conceptual model of the key components of peatlands, including the ecological features (hydrological conditions, substrate, and biota), ecological processes and ecosystem services provided by peatland ecosystems, and how they link together to form the characteristic ecosystem dynamics. The box contains the key ecological features and processes that drive peatland dynamics. Solid arrows indicate that the component has a positive effect on or enhances the component pointed to. Dashed

arrows (red) indicate that a component has a negative effect on or reduces the component pointed to. The colour of the oval indicates the corresponding ecosystem component. Arrows from the outline of the box represent where an ecosystem service is derived from the functioning ecosystem as a whole. Chemical properties include aspects of the substrate and the hydrological conditions. Nutrients inputs can have positive or negative impacts on peatlands, depending on the context and type of peatland. The model is a modified version of one developed by peatland experts during an IUCN Red List of Ecosystems assessment for Australian alpine ecosystems (Regan et al. 2020). GHG = greenhouse gas. CO_2: carbon dioxide. CH_4: methane.

Informing effective peatland conservation

Effective, evidence-based conservation is critical for threatened ecosystem recovery (Sutherland et al. 2004) but accessing, appraising and synthesising relevant evidence can be challenging (Khangura et al. 2012; Mallett et al. 2012). Syntheses of literature examining the effectiveness of these interventions support effective decision-making in conservation (Dicks et al. 2014; Walsh et al. 2015). For example, the Peatland Synopsis summarises the effectiveness of 125 interventions to conserve peatland vegetation, a core feature of the ecosystem, obtained from 161 primary studies globally (Taylor et al. 2019b). Yet filtering, synthesising and interpreting vast amounts of information using traditional synthesis methods (e.g., systematic reviews and synopses) can be very time and resource intensive (Cook et al. 2017).

Rapid evidence reviews have emerged as an efficient method of synthesising information in a limited timeframe whilst maintaining much of the methodological rigor of systematic reviews (Khangura et al. 2012). Rapid reviews can achieve this by systematically searching the literature for reviews rather than primary studies (Khangura et al. 2012; STARR 2019).

Importantly, the essential conclusions of rapid reviews and systematic reviews do not differ substantially (Watt et al. 2008). Rapid reviews originated to support healthcare policy and practice, and have subsequently been applied in hydro-ecology (Miller et al. 2018), environmental change (Hillebrand et al. 2020) and social sciences (Wray et al. 2020). Rapid reviews offer a promising approach for addressing conservation challenges, particularly where time and financial resources are limited (McCarthy et al. 2012).

Advancing peatland conservation requires integrating knowledge about how interventions may influence the core features and processes of the whole ecosystem. The significant challenge of peatland conservation and need for timely action provides an excellent opportunity to explore the use of a rapid review approach for synthesising the vast evidence on management interventions. Our aim is to evaluate the benefits of using rapid evidence review, in combination with a conceptual understanding of ecosystem function, to inform effective peatland conservation. We evaluated the effectiveness of interventions that contribute to the conservation of degraded boreal, montane, alpine and temperate peatlands (i.e., peatlands in cool-climate regions; hereafter, cool-climate peatlands), which include bogs and fens (Glossary, Appendix 1), using a rapid evidence review approach. Our approach assembles critical information to support effective, evidence-based conservation of globally important peatland ecosystems and provides valuable insight into the applicability of the rapid review method to conservation.

Methods

We adapted a conceptual model of the core features and processes that characterise intact peatlands (Figure 2). We then conducted a rapid evidence review to identify the effectiveness of management interventions to improve peatland condition as reported in published literature reviews, which we compared with a comprehensive summary of evidence for one core element of ecosystems (i.e., peatland vegetation; Peatland Synopsis). We mapped this evidence onto our conceptual model of peatlands to understand the role of different interventions in a system-wide context.

Linking evidence to peatland dynamics

The conceptual model details the defining features (hydrological conditions, chemical properties, biota), processes and ecosystem services (carbon storage) of peatlands and how these aspects link to form the characteristic ecosystem dynamics. The model was adapted from a conceptual diagram developed by peatland experts during an IUCN Red List of Ecosystems assessment for Australian alpine ecosystems (Regan et al. 2020). Our conceptual model was used to frame the inclusion criteria (i.e., which ecological responses to include) and organise the results. Finally, we mapped the review findings onto the conceptual model to demonstrate the potential system-wide influences of each intervention on peatlands.

Rapid evidence review

We followed the approach to rapid evidence reviews outlined by Khangura et al. (2012), to efficiently synthesise evidence reported in published literature reviews. The process entailed a systematic search of scientific databases using a comprehensive search string, screening the search results to identify relevant reviews, extracting and synthesising the relevant information and critically appraising the quality of each reviews to understand the reliability of the review findings. While rapid reviews can include grey literature where applicable, we restricted this first application in conservation to the peer-reviewed literature.

Search strategy

We developed a search string to identify relevant papers and refined this with input from content-area experts in the research team and review methodologists (CC, JM, PB, KT). The search string was refined using a pilot set of 10 core papers to ensure it returned relevant reviews. Our final search string (Table S2) included keywords for the peatland type (e.g., peatland, bog, fen, mire) and review type (e.g., "narrative review", "systematic review"). Searches were conducted in *Web of Science* and *Scopus*, limited to references from 2015 to March 2020 (Appendix 2). Date restrictions are often employed in rapid reviews. This range was chosen as systematic reviews in this period (which usually have no date range for the studies they include) summarise the most recent published evidence.

Two reviewers (JR, CB) independently screened the title and abstract of citations returned from the database search to identify potentially relevant papers, and then screened each paper using the full text. The title-abstract screening stage was conducted using the R package *revtools*, which provides an interface to easily categorise each paper as 'included' or 'excluded'. Conflicts at each screening stage were resolved via consensus or by a third person (JW). To ensure consistency in the full-text review, both reviewers initially screened 10% of the papers and discussed conflicts before completing the full-text review stage (Appendix 6).

Inclusion criteria

We used the PICOS framework (Population, Intervention, Comparator, Outcome, Study Design; Moher et al. 2009) to develop inclusion criteria, with modifications to reflect a focus on non-human studies. The papers had to target cool-climate peatlands (Population, excluding tropical peatlands or peaty soils), evaluate the effectiveness of interventions applied to peatlands (Intervention) and report a response variable measuring the core features, processes and/or ecosystem services (Outcome; Figure 2). Our review excluded tropical peatlands (peat swamp forests) as they have very different peat-forming processes – peat forms from deeper tree roots in peat swamp forests, whereas in bogs and fens peat forms at or near the surface from mainly mosses and reeds in bogs and fens (Parish et al. 2008). We excluded papers or results where the specific intervention was not clear. Papers had to be systematic or narrative reviews or meta-analyses (Glossary, Appendix 1) (Cook et al., 2017) published in a scientific journal or book chapter (Study Design) written in English. The "Comparator" category was excluded as our study design was limited to literature reviews.

Data extraction

Two reviewers independently identified the type of conservation intervention used and the ecosystem response reported in a set of 7 reviews and resolved conflicts through discussion. One reviewer (JR) extracted the data from the remaining reviews, including the aim, review type, geographic location and number of relevant studies included (Appendix 6). We were unable to conduct a meta-analysis on the effect size due to inadequate reporting in each review. Therefore, we used a vote-counting approach where we recorded whether the intervention had a positive, negative, neutral or mixed/conditional response in the ecosystem, determined based on absolute numerical values in each review (see Appendix 6 for definitions). We tallied the number of reviews in each response category to determine if there was general support for or against an intervention. The number of relevant papers in each review was defined as the number of papers referenced in the relevant text (Appendix 6).

Critical appraisal

Vote-counting does not typically weigh studies according to their quality (Cook et al. 2017). Therefore, we critically appraised the quality of the reviews to ensure that the results in the higher quality reviews are given more weight.

To evaluate the methods of each systematic review, we used the AMSTAR (*'A MeaSurement Tool to Assess systematic Reviews'*) quality appraisal assessment tool. AMSTAR is a validated tool that considers the use of an appropriate search strategy, quality appraisal and approach to synthesising results (Shea et al. 2007). We critically appraised the narrative reviews using SANRA ('*Scale for the Assessment of Narrative Review Articles'*), an approach that considers the clarity of the review's justification and objectives, search strategy and reporting of the evidence (Baethge et al. 2019). Initially, two reviewers (JR, CB) independently appraised a set of 4 systematic reviews and 4 narrative reviews to ensure accuracy**,** discussing any conflicts; one reviewer (JR) appraised the remaining reviews. To improve the readability of our results, we coded the type of review (systematic = *S*; narrative = *N*) and numbered each based in alphabetical order of the references (e.g., *S1, N1*; Table 1). Codes with an * indicate a critical appraisal score of ≥ 5 for systematic reviews and ≥ 8 for narrative reviews.

Comparison with Peatland Synopsis

To complement our rapid review, we extracted relevant findings from an evidence synthesis of interventions aimed at improving peatland vegetation: the Peatland Synopsis (results code = *PS*; Taylor et al. 2019b). The effectiveness of interventions to conserve other core features of peatlands (e.g., hydrological conditions, chemical properties and animals) were not examined. The book and database (https://www.conservationevidence.com) present a synopsis of evidence compiled by systematically searching for studies from relevant journals that evaluate the success of plausible interventions for peatland vegetation conservation.

Two reviewers (JR, CB) collated all relevant interventions in the synopsis that sought to improve peatland vegetation. For each study listed in the synopsis, we recorded whether the intervention had a positive, negative, neutral or mixed/conditional response in the ecosystem (Appendix 6). Any uncertainties were resolved through discussion and consensus.

Results

Our search identified 822 unique papers, of which 23 reviews met our inclusion criteria (Figure S1; Appendix 5). This comprised six systematic reviews (two with meta-analyses) and 17 narrative reviews, which collectively summarised the results of 453 individual studies. The methodological quality of the reviews was poor (Appendices 3, 6), so the findings must be interpreted with caution. Out of a maximum score of 11, the systematic reviews scored between 3 and 7 (median = 4), and the narrative reviews scored between 2 and 9 (median = 6) out of a maximum score of 12. Common shortcomings of systematic reviews included that no reviews used a comprehensive literature search, validated the study selection and data extraction by more than one reviewer nor assessed the likelihood of data bias (see Appendices 3, 5 for details). Common shortcomings of narrative reviews were the lack of a literature search description (n = 1 of 17 narrative reviews), inconsistency in providing evidence to support key arguments (n = 2) and inappropriately presenting the data (n = 2) (see Appendices 3, 5 for details).

Seven reviews focused on peatlands globally and the other reviews focused on peatlands in Europe (9 reviews), North America (5), Asia (1) and/or northern latitudes (2), including one review that focused on both North America and Europe (Table 1). The reviews targeted conservation of peatlands affected by a range of threats, including agriculture (13), resource extraction (e.g., peat harvesting, oil mining; 12), forestry (7), developments (e.g., golf-courses, roads; 5), invasive or problematic species (3), pollution (e.g., agricultural runoff, browning water; 3), climate change (2) and tourism (1). Ten reviews focused on conservation with respect to a specific threat, 11 reviews included peatlands affected by multiple threats and two reviews did not explicitly discuss threats.

We identified 11 interventions evaluated for their impacts on seven ecosystem responses across the rapid evidence review and Peatland Synopsis (Figure 3). We organised our findings by these responses and mapped the overall effect of the interventions onto the conceptual model. Our whole-system assessment identified several interventions, such as rewetting and reprofiling, that affected multiple features and processes, either directly or indirectly; thus they are repeated under several sub-headings to capture the different responses measured.

Table 1. Details of the reviews in the rapid evidence review, including the code for the paper used in the results (Code), reference for the review, type of literature review (Review Type), geographic focus of the review (Location), type of peatland (Peatland type), interventions reported, features or processes of the ecosystem affected by the interventions (Response), and the quality of the review (Quality appraisal). "Peatlands" is recorded where the type of peatland is not specifically stated. The maximum score for the quality appraisal for the systematic reviews is 10, systematic reviews with meta-analyses is 11, and narrative reviews in 12. See Appendix 4 and 6 for full details and references.

Code	Reference	Review type	Location	Peatland type	Intervention	Response category	Review quality
S1	Abdalla et al. (2016)	Systematic, Meta-analysis	Northern hemisphere	Bogs, fens	Rewetting	Carbon storage	5
S2	Harper et al. (2018)	Systematic	United Kingdom	Bogs, peatlands	Prescribed burns	Chemical properties, biota, carbon storage	4
S3	Jones et al. (2017)	Systematic	Global	Bogs, fens/marshes/ swamps	Rewetting, cutting/mowing, grazing, prescribed burns	Erosion, chemical properties, biota, carbon storage	4
S4	Li et al. (2018)	Systematic	Global	Bogs, peatlands	Rewetting, reprofiling, revegetation, grazing control, prescribed burns	Erosion	3
S5	Taylor et al. (2019a)	Systematic	Global	Bogs, fens, peatlands	Rewetting, fertiliser, prescribed burns	Biota	4
S6	Xu et al. (2019)	Systematic, Meta-analysis	Northern hemisphere	Peatlands	Rewetting, revegetation	Carbon storage	7
N1	Anderson et al. (2017)	Narrative	Western Europe	Bogs, peatlands (afforested)	Rewetting, reprofiling, revegetation, fertiliser	Hydrology, biota, carbon storage	6
N2	Chimner et al. (2017)	Narrative	North America	Fens, peatland	Rewetting, shade/mulch, grazing control	Hydrology, biota, carbon storage	4
N3	Decker & Reski (2020)	Narrative	Global	Peatlands	Revegetation	Carbon storage	2

N4	Ferré et al. (2019)	Narrative	Switzerland	Peatlands (cultivated)	Rewetting	Hydrology, carbon storage	9
N5	Gaudig et al. (2018)	Narrative	Global	Bogs, peatlands (cultivated), greenhouses	Rewetting, reprofiling, shade/mulch, revegetation, cutting/mowing, weed/fungi control	Chemical properties, biota, carbon storage	8
N6	Grand-Clement et al. (2015)	Narrative	Global	Shallow peatlands	Rewetting, revegetation	Hydrology, chemical properties, erosion, biota, carbon storage	8
N7	Karofeld et al. (2017)	Narrative	Baltic countries	Bogs, peatlands (extracted)	Rewetting, reprofiling, shade/mulch, revegetation, cutting/mowing	Hydrology, biota, carbon storage	5
N8	Ketcheson et al. (2016)	Narrative	Canada	Fens (extracted)	Rewetting, revegetation	Hydrology, biota, carbon storage	8
N9	Kløve et al. (2017)	Narrative	Nordic	Peatlands (cultivated)	Rewetting, reprofiling, revegetation, fertiliser	Hydrology, chemical properties, biota, carbon storage	6
N10	Kritzberg et al. (2020)	Narrative	Scandinavia	Peatlands (cultivated)	Rewetting	Hydrology, carbon storage	6
N11	Lamers et al. (2015)	Narrative	Europe, North America	Fens	Rewetting, reprofiling, shade/mulch, revegetation, cutting/mowing, grazing control	Hydrology, chemical properties, erosion, biota, carbon storage	6
N12	Miller & Gardiner (2018)	Narrative	Western Europe	Bogs, mires	Cutting/mowing, grazing	Biota	6
N13	Page & Baird (2016)	Narrative	Global	Bogs, peatlands	Rewetting, revegetation, policy	Hydrology, biota, protection, carbon storage	4
N14	Richardson (2018)	Narrative	USA	Fens	Policy	Chemical properties	4
N15	Stratford &Acreman (2016)	Narrative	United Kingdom	Bogs, mires, marshes,	Rewetting, cutting/mowing, grazing	Hydrology, biota, carbon storage	6

				peatlands (managed)			
N16	Webster et al. (2015)	Narrative	Canada	Bogs, fens, marshes, swamps (extracted)	Rewetting, shade/mulch, revegetation, policy	Hydrology, biota	8
N17	Yang et al. (2017)	Narrative	China	Alpine peatland (marsh)	Rewetting	Carbon storage	5
PS	Taylor et al. (2019b)	Synopsis	Global	Bogs, fens	Rewetting, shade/mulch, reprofiling, revegetation, cutting/mowing, grazing, grazing control, weed/fungi control, fertiliser, prescribed burns	Biota	NA

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Improving hydrological conditions

Specific hydrological conditions are fundamental to the development and persistence of peatlands and to provide fresh water to millions of people (Page & Baird 2016) (Figure 2). Peatlands have waterlogged soils with precipitation exceeding water loss, although the water table may fluctuate seasonally (Taminskas et al. 2018). These conditions are vital to support peatland vegetation (importantly *Sphagnum* moss) and peat formation through the accumulation of partially decomposed organic matter (Page & Baird 2016). Across 12 narrative reviews, we identified four interventions aimed to directly restore and maintain hydrological conditions (i.e., water table; rewetting, shading or mulching, and implementing policy) and one that indirectly affected hydrological conditions (cutting vegetation) (Figure 3). No systematic review examined hydrological responses.

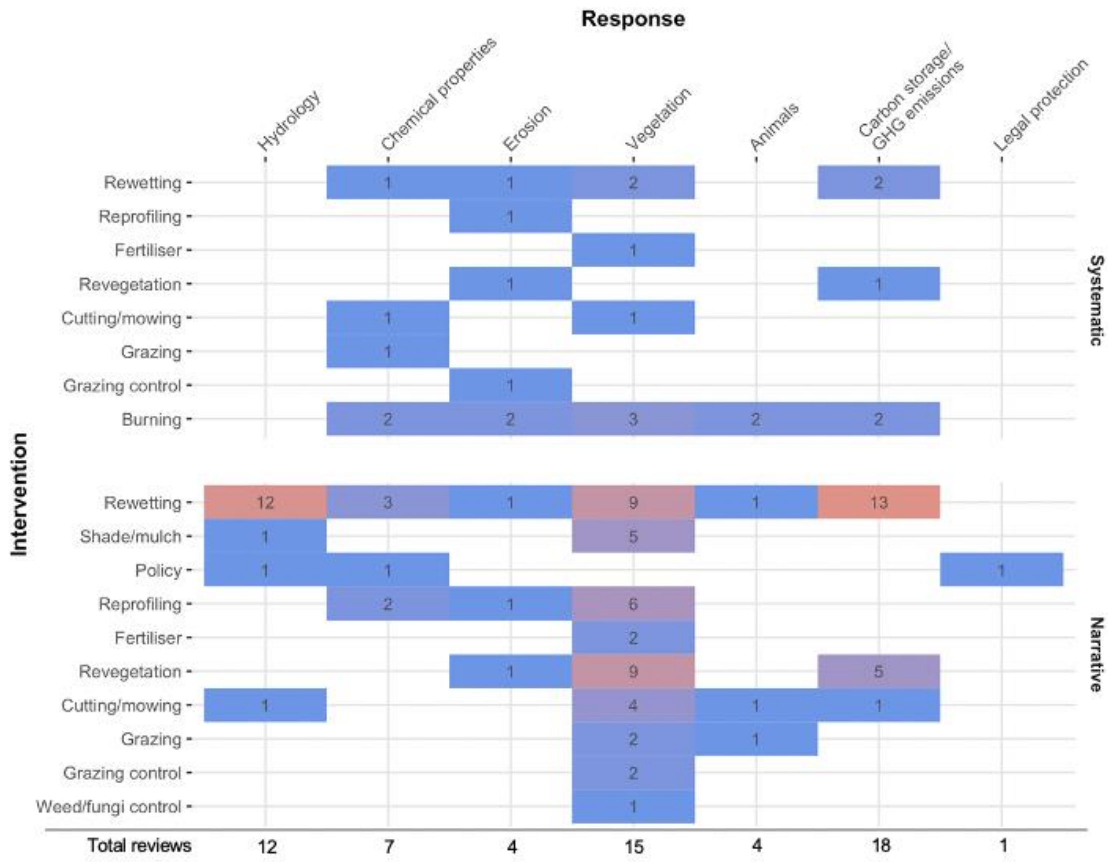

Figure 3. Heatmap of the number of systematic (n = 6) and narrative reviews (n = 17) that reported each response category (i.e., the feature or processes in peatlands) affected by each management intervention. GHG = greenhouse gas.

Rewetting was the most employed intervention to improve peatland hydrological conditions, reported in all 12 narrative reviews that considered hydrological conditions. Rewetting aims to restore waterlogged soils that have been drained (often via construction of drainage channels) by blocking drainage points to allow water to accumulate and/or watering to re-saturate (Taylor et al. 2019a). Overall, rewetting was effective at restoring peatland hydrological conditions (Figure 4); eleven of twelve narrative reviews reported that rewetting can effectively raise the water table and retain groundwater (*N1, N2, N4*, N6*, N7, N8*, N9-11, N15, N16**). Rewetting was reported to reduce water level fluctuations and regulate hydrological conditions (*N1, N4*, N7*), reduce peak flow during storms (*N15*) and/or increase water lag and flooding (e.g., during snowmelt) (in shallow peatlands: *N6**). However, some evidence suggests these interventions may not rapidly restore natural hydrological conditions (*N13*), which may take years to stabilise (e.g., 2 years in extracted fens: *N8**; 15 years: *N2*) or may not fully return to natural levels (e.g., in afforested peatland: *N1*). Several interventions to stop water leaving the system via drainage channels were reported. Blocking ditches/drains and/or damming with wood or peat were most often reported as successful, whereas other interventions had mixed results (Table 2). Interventions to increase water flowing into the peatland improved hydrological conditions, including removing blockages to water entering the system (e.g., raising roads; *N2*, *N7*) or adding water (e.g., installing aquifers, pumps, sluices; *N8**, *N15*) (Table 2). The evidence shows that the most effective intervention is dependent on the nature of the hydrological disturbance and features of the peatland, such as peat depth, ditch size, slope, vegetation, erosion status and water level (*N2*, *N6**, *N11*, *N15*).

The effectiveness of three other interventions affecting hydrological conditions is uncertain as they were less comprehensively studied (Figure 4). **Shading and/or mulching** aims to prevent desiccation of peatland surfaces and vegetation (Clarkson et al. 2017). One review stated that it can reduce hydrologic impacts when used alongside other interventions such as reprofiling surfaces, rewetting and active planting in extracted peatlands (*N16**). **Cutting** and removing planted trees was reported to increase the water table in managed peatlands (*N15*). Lastly, one review described positive outcomes from changing water **policy** to charge users the actual economic value of water, which promoted responsible use in extracted peatlands, including stimulating innovation in recirculation or recycling water (*N16**).

Figure 4. The effect of conservation interventions (columns) on (a) the ecosystem responses identified in the rapid evidence review, and (b) a subset of vegetation responses (rows) summarised in the Peatland Synopsis (Taylor et al. 2019b). Each bar shows (a) the proportion of reviews papers or (b) the proportion of results across the studies that were reported in the Synthesis for each effect of the intervention. The *Mixed/conditional* effect represents where the response was a mix of positive, negative and/or no change, or was conditional on other factors. GHG = greenhouse gas. See Figure S2 for full list of responses (Appendix 5) and Appendix 6 for full list of specific interventions summarized in the Peatland Synopsis.

Table 2. Rewetting interventions to restore peatland hydrological conditions based on 12 narrative reviews. See Table 1 for references associated with each code. * indicates a narrative review with a critical appraisal score ≥8.

Successful interventions	**Code**
Blocking ditches/drains (broadly)	*N2, N7, N9-11, N15, N16**
Limitations/conditions:	
• May not be sufficient to allow local hydrological control across a peatland to avoid a fluctuating water table	*N9*
• Large-scale hydrological actions may be required to restore the water table and ground water discharge patterns	*N11*
Damming with:	
• Wood or peat	*N1, N6*, N7, N10, N15*
Limitations/conditions:	
○ Wooden dams were useful for deeper, wider drains, whereas impermeable dams with stakes were effective if peat was deep with steep gradients and non-continuous water flow	*N6**
○ Blocking ditches with peat was only effective in low-flow peatlands, not in peatlands with steep slopes, erosion, exposed mineral substrate and in very wet or dry conditions	*N2*
• Plastic sheeting	*N15*
• Local vegetation	*N6**
• Straw bales	*N15*
Limitation/conditions:	*N6**
○ Tended to fail quickly	
Filling ditches with:	
• Peat	*N2, N7*
• Mineral soils, alongside stabilising soils with geotextiles and vegetation to reduce erosion	*N2*
Creating peat terraces/banks and shallow depressions	*N16**
Installing an upland aquifer to supplement ground water and maintain a uniform water table	*N8**
Levelling soils and adding mineral substrate	*N4**
Installing seepage reservoirs	*N16**
Removing blocks to groundwater flow (e.g., raising road surfaces, berms)	*N2, N7*
Pumps and sluices	*N15*
Limitation/conditions:	
• Success to raise the water table depended on the water volume and ability of water to move into the soil, which can be highly variable	*N15*

Improving other peatland properties and processes

Chemical properties

Peatlands have characteristic water and substrate chemistry whose properties support the distinctive vegetation and peat formation (Figure 2) (Keith et al. 2020). Fens are rich in mineral nutrients that can create slightly alkaline or acidic environments, whereas bogs are nutrient poor and acidic, partly due to the presence of *Sphagnum* (Keith et al. 2020). The low oxygen, waterlogged soils slow decomposition and allow for peat to form over decadal timeframes. Excessive nutrients enter peatlands from a range of sources, such as fertilisers in agricultural runoff (Richardson 2018) or the atmosphere (Bragazza et al. 2006). This can have detrimental impacts on the ecosystem and the provisioning of freshwater for people (Page & Baird 2016), although may increase primary productivity (Loisel et al. 2021). High nitrogen levels, in particular, can reduce plant biodiversity (Weisner & Thiere 2010) and enhance microbial decomposition of organic matter, resulting in higher carbon dioxide emissions and loss of soil carbon stores (Bragazza et al. 2006). We identified six interventions that directly alter water and substrate chemistry (reprofiling, cutting, mowing, grazing, prescribed burns and implementing policy) and one that indirectly affects water and substrate chemistry (rewetting) across two systematic reviews and six narrative reviews (Figure 3).

We found that in eutrophic peatlands, rewetting, reprofiling, mowing and implementing new policy may improve the water and substrate chemistry, whereas prescribed burns had mixed results and grazing was largely detrimental (Figure 4). **Rewetting** primarily aims to restore the hydrological conditions (see above); however, it may reduce excess nitrogen levels by restoring peat formation processes (*S3*) and the characteristic anoxic (cultivated peatlands: *N4**) and acidic conditions (fens: *N11*) of some peatlands. However, the material for damming drains (e.g., straw bales) can introduce nutrients (shallow peatlands: *N6**) and rewetting using agricultural water can cause eutrophication (excessive enrichment of nutrients) that may be toxic to *Sphagnum* (*N5*, N11*). In one instance, implementing **policy** to treat wastewater before release into a eutrophic fen significantly reduced phosphorus levels, but not consistently to within safe ecological limits (*N14*). Removing the eutrophic topsoil (i.e., **reprofiling**) may alleviate eutrophication and restore desirable conditions (*N9, N11*).

One review reported that **mowing** or **cutting vegetation** can improve or maintain fen conditions when affected by nitrogen pollution by removing plant matter, and may reduce nitrogen impacts indirectly by reducing growth of highly competitive non-characteristic species (*S3*). **Grazing**, however, had low potential to improve the chemical properties of fens and negatively altered other soil processes (*S3*). **Prescribed burns** have been trialled to immobilize or remove excess nitrogen (deposited from the atmosphere) or agricultural runoff and improve the suitability for peatland plants. Burning had “high potential” to immobilise and/or remove excess nitrogen in both bogs and fens (*S3*). Yet the “potential effectiveness” of burning to mitigate the negative impacts of nitrogen on habitat suitability for peatland plants was low in bogs and medium in fens (*S3*). Burning was also reported to cause the nitrogen stored in vegetation and peat to be released into the water and substrate as nitrogen oxides (*S3*). In contrast, another systematic review reported inconsistent impacts on water pH, nutrient levels and metal concentrations from prescribed burns, and cited the need for further research (*S2*).

Erosion

Erosion from water and wind is a natural process in peatlands, but overall peatlands can provide the regulating ecosystem service of protecting against high erosion rates (Figure 2)

(Page & Baird 2016). Human activities (such as installing drainage channels, introducing ungulate grazers) can enhance erosion resulting in degradation (Parry et al. 2014; Li et al. 2018). For example, rain-splash and runoff from surrounding areas can cause erosion when peat surfaces are bare and desiccated, high water flow along drainage channels can cause channel walls to erode and collapse, trampling by ungulates can erode peatland surfaces, and erosion underneath the peat surface can occur when very small channels form within the peat (Parry et al. 2014; Li et al. 2018). Across two systematic reviews and one narrative review, we identified that five of the 11 interventions were reported to alter erosion rates (rewetting, reprofiling, revegetating, reducing grazing pressure and prescribed burns) (Figure 3).

Rewetting, reprofiling and revegetating degraded peatlands can work collectively to reduce erosion and sediment flow (*S4*, *N6**; Figure 4). **Rewetting** techniques that slow water flow and limit drainage from the system to ensure topsoil remains waterlogged (e.g., blocking drains at intervals, installing permeable peak runoff control dams) can reduce erosion, stabilise drainage channels, trap sediment and enhance revegetation (*S4*, *N6**). The evidence suggests that the best intervention may vary with peat depth and ditch size (shallow peatlands: *N6**). Similarly, **reprofiling** to remove the topsoil layer degraded by eutrophication (fens: *N11*), or to reduce the gully steepness (*S4*), can reduce erosion and sediment flows, especially combined with rewetting and revegetation (*S4*). **Revegetating** gully walls substantially reduces erosion and sediment flow (*S4*, *N6**) by covering bare substrate and filtering sediment in the water, including after rewetting in a shallow peatland (*N6**) or reprofiling (*S4*), but the maximum capacity of vegetation to filter sediment is uncertain (*S4*). **Reducing grazing** intensity may lower erosion (*S4*), likely due to less trampling (Figure 4). However, **prescribed burns** can promote erosion (*S3, S4*) by damaging the vegetation and underlying substrate (Figure 4).

Improving peatland biota

Peatlands are characterised by their distinctive vegetation (Figure 2). Fens are dominated by water-tolerant grasses, sedges and/or forbs, and bogs are dominated by water-loving mosses, graminoids, shrubs and occasionally scattered trees (Keith et al. 2020). These characteristic plant species are adapted to waterlogged soils and characteristic chemical properties, and form the organic matter in peat (Parish et al., 2008). Peatlands provide habitat for a wide variety of taxa, from birds to invertebrates (Minayeva & Sirin 2012). We identified eleven interventions that affected the characteristic plant and/or animal species across three systematic reviews, 12 narrative reviews and the Peatland Synopsis (Figure 3). These included interventions that improve the hydrological conditions or chemical properties to provide suitable conditions for peatland vegetation (i.e., rewetting, shade/mulching, reprofiling, fertilisers), directly restore the vegetation (active or passive revegetation) or manage the existing vegetation (i.e., mowing, cutting or grazing vegetation, weed/fungi control, controlling grazers, prescribed burns) (Figure 4). All 15 relevant reviews reported effects on vegetation, whereas only four reviews reported fauna responses (Figure 3).

Interventions to restore the hydrological conditions and chemical properties

Four interventions aimed to restore characteristic properties favourable to recovery of peatland vegetation – rewetting, reprofiling, shading or mulching, and fertilising (Figure 3). **Rewetting** was reported to affect peatland vegetation in two systematic reviews, nine narrative reviews and the Peatland Synopsis (*PS*). By restoring the natural hydrological conditions, rewetting primarily increased vegetation cover of characteristic species (*PS, S3, S5, N1, N2, N5*, N6*, N7*) (Figure 4). The success of rewetting at increasing vegetation cover was typically conditional on several factors, including the initial peatland condition and use of other interventions. Revegetation after rewetting was more successful when the peatland degradation was less severe (*S5*), when there were nearby seed sources and dispersal vectors (*S5*, *N15*), and peatlands were not flooded, washing away plant propagules (*N5**). Revegetation after rewetting was often impaired if the peatland was eutrophic (e.g., if agricultural water was used) (*S3*, *S5*, *N5**), which created conditions that can support invasion by non-peatland species (*N2*, *N11*); although rewetting eutrophic peatlands can improve conditions to support revegetation to a degree (*S3*). The success of rewetting was also conditional on other interventions, such as reprofiling to improve the chemical properties and growing surface (see above) (*N1, N2, N7*), active planting (*N2*, *N5*, N6**, *N7*, *N13*, *N15*), mulching (extracted peatlands: *N7*) and/or cutting trees (extracted peatlands: *N7*) (see below for all). Other important factors influencing the long-term success of plant regeneration were (i) allowing time (decades) after rewetting for vegetation to recover (*N1, N2, N9, N11, N15*; although non-peatland species may initially invade: *N1*, *N2*), (ii) active revegetation (*N1, N2, N5**, *N6**, *N7*, *N9*, *N13*) and (iii) ensuring naturally fluctuating water levels associated with intact peatland ecosystems (*N5*, N6*, N7, N11*).

Shading and mulching primarily aims to prevent desiccation of substrates to enhance revegetation (Clarkson et al. 2017). Successful revegetation depended on the materials used (*PS*); organic mulch was typically better than other shading materials (e.g., fleece or fibre mats, plastic mesh, straw, hay) for revegetation of characteristic species (see Appendix 6 for details; Figure 4). Straw regulates surface temperature to encourage *Sphagnum* growth when the water table is low (*N5**), and hay allows for the fluctuations in light and temperature needed to break seed dormancy for many fen species (*N11*). Across all reviews, shading and mulching always occurred alongside other interventions to provide suitable growing conditions, including rewetting (extracted peatlands: *N7, N16**), reprofiling (*N7*, *N11*, *N16**) and/or active planting (extracted peatlands: *N7*, *N16**).

Two interventions influenced the revegetation of peatlands by altering the chemical properties of the substrate and water: reprofiling or fertilising. **Reprofiling** to remove degraded topsoil (e.g., nutrient rich or oxidised layer) had a largely positive effect on plant regrowth by improving the substrate's suitability for plant growth (*PS, N6*, N7, N9, N11*), including alongside cutting trees (*N7*), rewetting (*N7*) and mulching (*N11*) in extracted peatlands, and active revegetation (*N6*, N11*). However, one review reported that despite reprofiling alongside rewetting, the peatlands remained dominated by non-characteristic species (afforested peatlands: *N1*) and another noted that the value of reprofiling alone was unclear (*N5*).

Fertilisers are used to restore key nutrients or alter the pH in order to support plant growth (e.g., reduce acidity in extremely acidic bogs, or increase the pH of fens; Taylor et al. 2019b). Adding lime to increase the pH to improve vegetation growth and survival was either ineffective or harmful in the wrong dose or timing, particularly for fen vegetation and *Sphagnum* or in naturally acidic bogs (*PS, S5;* Figure 5). Adding fertilisers alongside planting to alter nutrient availability had mixed effects on peatland vegetation (*PS, S5*; Figure 5). Two narrative reviews reported that applying ash fertiliser to cultivated peatlands when they are not fully re-wet may increase *Sphagnum* and tree growth (*N9*) and applying lime to increase pH and fertiliser alongside seeds in geotextile and brash (i.e., woody debris) as shade/mulch enhanced vegetation regrowth in an afforested peatland (*N1*).

Revegetation

Re-establishing vegetation is key to restoring degraded peatlands (Figure 2, Table 3). Revegetation can occur actively, by introducing seeds or plants, or naturally without intervention. Across 12 revegetation interventions reported in the Peatland Synopsis (Figure 3), active revegetation was largely effective at restoring or increasing vegetation (Figure 4;

Table 3) (*PS*). For example, spreading herb seeds, or directly planting herb, tree or shrub seedlings and spreading mosses or moss fragments largely increased the cover, growth and/or survival of those species (*PS*). Similarly, all eight relevant narrative reviews reported that actively revegetating through direct seeding or planting can successfully facilitate establishment of desirable peatland plant species or communities (*N1*, *N2*, *N5**, *N6**, *N7*, *N11*, *N13*, *N16**; Table 3). Spreading *Sphagnum* and other bryophytes was the most commonly reported successful intervention. Most reviews focused solely on restoring moss carpets (typically *Sphagnum*), the primary peat-forming species (*N2*, *N5**, *N6**, *N7*, *N8**, *N11*, *N13*). However, successful revegetation often only occurred after interventions to ensure suitable hydrological and growing conditions, including rewetting (*N5**, *N7*, *N8**, *N13*, *N16**), shade/mulching (*N1*, *N7*, *N16**), reprofiling (*N2*, *N6**, *N7*, *N16**) and/or fertilising (afforested peatlands: *N1*), as revegetation can be less successful if hydrological and growing conditions are unsuitable (extracted peatlands: *N7*). Three narrative reviews explored whether vegetation would regenerate naturally (*N7*, *N8**, *N11*); vegetation did return after abandonment of an extracted peatland (no intervention: *N7*), and in fens, spontaneous recolonization of vegetation may be limited (*N11*), and occurred after reprofiling and restoring hydrological conditions (*N8**) (see above).

Table 3. Revegetation interventions to restore peatland vegetation based on the peatland global evidence synopsis and 10 narrative reviews. See Table 1 for references associated with each code. * indicates a narrative review with a critical appraisal score ≥8.

Successful interventions	**Code**
Introducing seeds of peatland herbs	*PS*, *N11*, *N13*
Adding mixed vegetation	*PS*
Replacing blocks of vegetation after mining or peat extraction	*PS*
Adding mosses to the surface Limitations/conditions: • Most effective after sown fresh (rather than refrigerated), larger *Sphagnum* plantlets at higher cover (1-5 cm thick) at the start of the growing season • Large-scale mechanised moss revegetation methods are inefficient • Use of propagules (e.g., seeds, rhizomes, moss fragments, moss spores) may give variable results based on the seed viability and germination conditions	*PS*, *N2*, *N5**, *N6**, *N11*, *N13* *N5** *N2* *N5**, *N11*
Moss layer transfer technique	*PS*
Directly planting mosses, herbs or trees/shrubs	*PS*, *N2*
Passive restoration Limitations/conditions: • Effective after reprofiling and restoring hydrological conditions • Effective after some active restoration • Due to short longevity of many characteristic species (< 5 years), short dispersal distances (<100 m) and often highly fragmented landscapes, spontaneous recolonization of vegetation may only be possible by clonal growth of plants if still present or dispersal from nearby peatlands occurs	*N7* *N8** *N11* *N11*

Vegetation management

We found several interventions that aimed to enhance existing vegetation on peatlands, including mowing, cutting or grazing vegetation, weed/fungi control, controlling grazers, and prescribed burns (Figure 3). One review reported that changes in **policy** (and environmental and social settings) over the past decade have stimulated countries and organisations to increase protection of intact peatlands and restore degraded sites (*N13*; Figure 4).

Cutting or mowing vegetation or **weed/fungi control** are often undertaken to manage competitive plants. Cutting, removing or thinning forest plantations and cutting or mowing herbaceous vegetation generally had a positive impact on peatland vegetation (*PS;* for full list see Appendix 6; Figure 4). Similarly, removing plant biomass supported rare species by reducing competition with common species, whose growth was limited by low levels of phosphorus or potassium (*S3*). Cutting grasses increased *Sphagnum* cover but could also reduce non-target and fragile species (*S3*). Several narrative reviews also reported that regular mowing (*N5*, N11, N15*) or cutting trees and shrubs (extracted peatlands: *N7*) could suppress competitive non-peatland species to maintain desirable peatland vegetation and high plant species diversity (*N5**, *N7*, *N11*, *N12*, *N15*). The effectiveness depended on the mower type (*N5**), and mowing can kill or displace invertebrates or ground-nesting birds (*N12*). Employing **weed/fungi control** such as biocontrol and herbicides generally improved the peatland vegetation by controlling problematic plant species (*PS*; Figure 4). Applying fungicide (Myclobutanil) with the fungus (*Trichoderma virens*) in a greenhouse trial effectively controlled a fungal parasite of *Sphagnum* (*Sphagnurus paluster*) (*N5**; Figure 4).

Grazing (e.g., by cattle or ponies) had inconsistent impacts (both positive and negative) across aspects of peatland biota, such as plant community composition, plant richness or diversity and cover of characteristic species (*PS*, *N12*, *N15*; Figure 4). The impacts of grazing may depend on the type of grazer or peatland wetness: trampling by grazers damages vegetation in wetter peatlands, and the impacts on biodiversity can vary by species, with ponies negatively impacting vegetation structure, whereas cattle can cause more trampling, killing or displacing invertebrates or ground-nesting birds (*N15*). **Controlling grazers** can be employed to enhance vegetation when intensive herbivory or trampling damage occurs. Excluding or removing grazing livestock can increase vegetation biomass but can also have no or mixed effects on cover of key vegetation types or community composition (*PS*; Figure 4). Excluding wild herbivores (boars and deer) also had mixed effects on vegetation (*PS*).

Removing grazers may stop intensive herbivory (e.g., netting to exclude birds and fish; *N11*) and support passive revegetation in overgrazed fens (*N2*).

Prescribed burns are used to control problematic plant species and to maintain or restore disturbance regimes. Prescribed burns were reported to have mixed or negative impacts on peatland vegetation (*PS, S2, S3, S5*) and animals (*S2, S3*; Figure 4). Burning may lead to replacement of sensitive species (such as *Sphagnum*) by fire-tolerant species and destroy the seedbank (*S2, S3, S5*). However, the Peatland Synopsis reported that using prescribed fire generally increased moss cover (including *Sphagnum*), decreased tree/shrub cover, and had mixed outcomes for overall plant richness/diversity and cover of grasses, non-characteristic species, forbs, sedges, rushes and/or reeds (*PS*). Yet burning ultimately was not recommended for routine peatlands management (*S5*). One review suggested the impacts of burning may be affected by external factors, such as weather, burn dynamics, overgrazing, pollution and drainage (i.e., *Sphagnum* may be able to recover from fire in wetter conditions; *S2*). Burning was consistently linked with negative impacts on animal species; fires led to declines in species richness and community structure of aquatic macroinvertebrates (*S2*) and replacement of fire-sensitive animal species with those tolerant of burns (*S3).*

Regulating greenhouse gas emissions and carbon storage

As carbon sinks, peatlands play an important role in climate regulation (Minayeva & Sirin 2012). Peatlands naturally sequester carbon dioxide and nitrous oxide, two potent greenhouse gases (Moomaw et al. 2018). The anoxic, waterlogged conditions and characteristic vegetation of peatlands (e.g., *Sphagnum* moss) support carbon sequestration through photosynthesis, accumulation of organic carbon in sediments and development of peat (Figure 2; Foster et al. 2012). Methane, however, is naturally emitted by peatland soil microbes and plants under the characteristically low oxygen conditions (Moomaw et al.

2018). We identified four interventions that alter the capacity of cool-climate peatlands to provide carbon storage and sequester greenhouse gases (rewetting, revegetation, grazing/mowing, and prescribed burns) in four systematic reviews and 14 narrative reviews (Figure 3).

Rewetting was the most commonly reported intervention to affect carbon storage and greenhouse gas emissions (Figure 3). Drained and degraded peatlands can become net carbon sources as dry soil creates conditions whereby peat oxidises and releases carbon dioxide (Foster et al. 2012). We found that rewetting had a complex impact on greenhouse gas emissions and/or soil carbon stocks, which varied over time (Figure 4). Twelve of 13 narrative reviews suggested that the time since rewetting affects emissions as it takes time for ecosystem function to be restored. Net emissions (particularly carbon dioxide) tend to decrease over longer timeframes after rewetting (between 4 and 30 years) (*N1, N5*, N6*, N7, N8*, N9*, *N10*, *N15*, *N17*), although methane emissions may increase over time (*N1*, *N6**), as is typical for intact peatlands (Moomaw et al. 2018). However, short-term changes in emissions and carbon exports can initially be imperceptible (*S1*, N13*), variable (*S6**, *N11*) or can increase (*N2*, *N6**, *N9-11*) in response to re-wetting, particularly if the water table fluctuates significantly (cultivated peatlands: *N9*) or peatlands are rapidly inundated (cultivated peatlands: *N10*), and the nutrient content is high (cultivated peatlands: *N10*).

Vegetation management can strongly affect carbon storage because vegetation sequesters carbon through photosynthesis and ultimately forms peat (Foster et al. 2012). **Revegetation** was reported to affect greenhouse gas emissions and soil carbon stocks in one systematic review/meta-analysis and five narrative reviews (Figures 3). Actively and passively restored peatlands had higher soil organic carbon compared to cultivated peatlands (*S6**). However, dissolved organic carbon concentrations increased in the two years after planting as fen vegetation matured (*N8**). Emissions halted or decreased as vegetation increased (*N3*, *N7*, *N11*), often after interventions to restore the hydrological conditions or water and substrate chemistry (i.e., rewetting: *N3, N7*; mulching and/or reprofiling in extracted peatlands: *N7*). Peat quality (indicated by higher organic matter content) improved after restoring moss and vascular plant seedlings (extracted fens: *N8**). Yet there may be mixed results for different gases; nitrous oxide emissions may not stop after revegetation, while afforested peatlands may remain carbon sinks while the forest persists (*N9*). Interventions for management of existing vegetation, however, tended to negatively affect peat production and greenhouse gas emissions. **Prescribed burns** substantially decreased carbon stores (*S2, S3*; Figure 4), primarily through combustion of vegetation, but also by degrading surface peat and potentially reducing the rate of peat accumulation (*S2*). However, some research noted that burning may reduce carbon loss by promoting primary productivity and reducing respiration, so long-term monitoring of trends is needed (*S2*). In comparison, regular **mowing** in eutrophic fens may reduce peat production (*N11*) by reducing the organic matter available to form peat (Figure 4).

Linking evidence across ecosystem components

Synthesising the evidence of interventions on each key feature and ecological process allowed us to provide guidance for an integrated, systems-wide approach to peatland management (Figure 5). This accentuated the importance of explicitly considering the interconnected nature of peatland ecosystems. Most interventions ultimately affected other features and processes despite being targeted to improve a specific component. Overall, 82% of interventions altered more than one response category and 64% affected at least three categories (Figure 5). Interventions with the most indirect (or secondary) effects were rewetting, prescribed burning and cutting or mowing, whereas two vegetation management interventions (fertilisers, weed/fungi control) were only reported to affect vegetation (Figure 5). Vegetation, for example, was affected by 10 of 11 interventions, four of which were through secondary effects. Several interventions had indirect effects that primarily enhanced peatland conservation, including rewetting or reducing herbivory (Figures 4, 5; Appendix 6); for instance, through restoring hydrological conditions, rewetting can re-establish the natural chemical properties, reduce erosion by slowing water flow and saturating the topsoil, enhance vegetation regeneration, increase native animal abundance, and alter greenhouse gas emissions by supporting revegetation and peat formation. Similarly, beyond reducing herbivory, controlling grazing reduced erosion and supported revegetation of characteristic species.

Other interventions had primarily negative effects. For example, prescribed burning is primarily used to control problematic plants or maintain or restore disturbance regimes, but can promote erosion and loss of carbon stores, alter the chemical properties, and change the types of animal species inhabiting peatlands. Some interventions had impacts that varied across response categories, such as mowing or grazing (Figures 4, 5; Appendix 6); mowing can improve the chemical properties by removing excess vegetation but can reduce peat production. Likewise, vegetation management through grazing can negatively affect the chemical properties, while the impact on animals can be varied; grazing can improve the habitat suitability for invertebrates but cause mortality from trampling. The prevalence of secondary effects emphasises the importance of considering the broader impacts on the system when implementing an intervention. Mapping evidence on to the conceptual diagram also highlighted under-studied processes and ecosystem services; the effect of interventions on many ecosystem processes associated with peatlands (Figure 2) were not included in our evidence base and so were not included in our review.

Interventions often occurred in combination with other interventions (Figure 5). Six of eleven interventions were frequently reported to co-occur – rewetting, shading or mulching, reprofiling, fertiliser, revegetation and cutting or mowing. Rewetting and revegetation were most often reported together (conditional effects; *S4*, *S5*, *N2*, *N5**, *N6**, *N7*, *N8**, *N15*, *N16**), followed by reprofiling and revegetation (*S4*, *N2*, *N6**, *N7*, *N11*, *N16**) and rewetting and reprofiling (*S4*, *N1*, *N2*, *N7*, *N16**). Further, the effectiveness of some interventions was contingent on other interventions being implemented. For example, the success of revegetation was highly dependent on other features of the ecosystem being restored, including hydrological conditions (rewetting, shade/mulch; *N1*, *N5**, *N7*, *N8**, *N13*, *N16**), chemical properties (reprofiling, fertiliser; *N1*, *N2*, *N6**, *N7*, *N16**). Of the five interventions not reported to occur alongside others, one was implementing targeted policy and four were targeted at managing the existing vegetation (prescribed burning, grazing, grazing control, weed/fungi control).

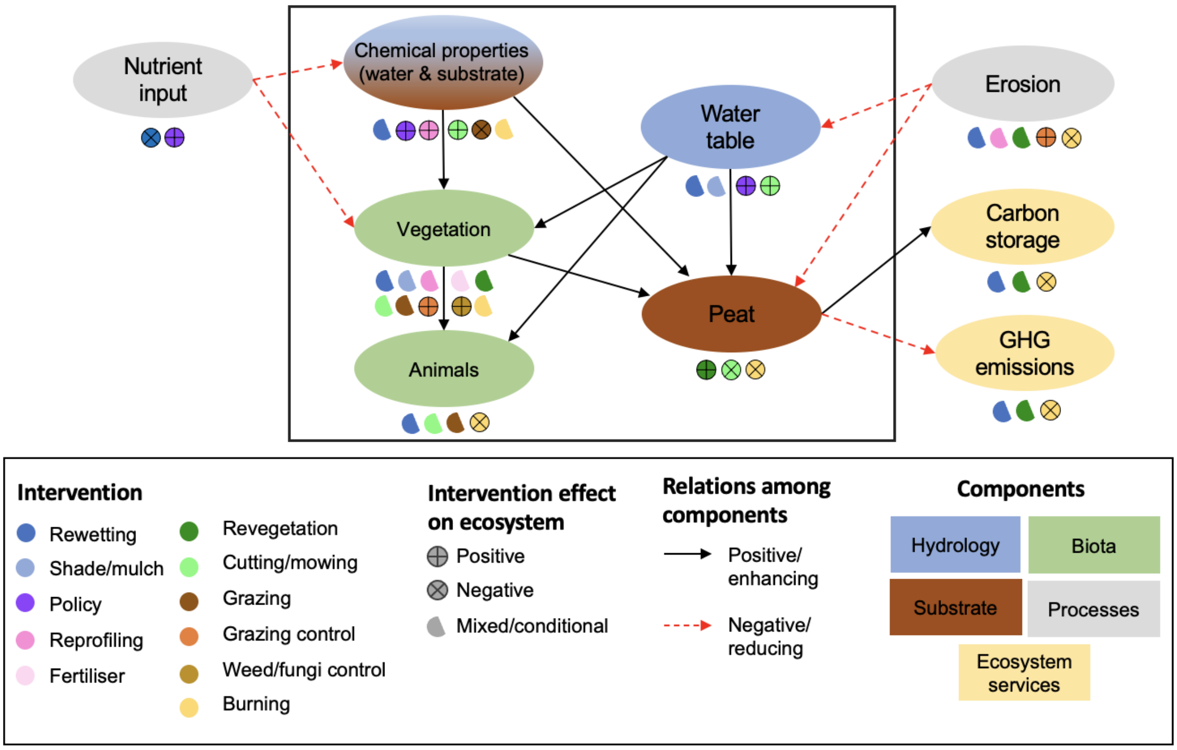

Figure 5. Conceptual model with the effect of each intervention on the core components of peatland ecosystems and their relationships to one another. Intervention effect was evaluated as the overall effect on the intervention reported among the relevant reviews. The box contains the key ecological features and processes that drive peatland dynamics. Solid arrows indicate that the component has a positive effect on or enhances the component pointed to. Dashed arrows (red) indicate that a component has a negative effect on or reduces the component pointed to. The colour of the oval indicates the corresponding ecosystem component. Chemical properties include aspects of the substrate and the hydrological conditions. The model is a modified version of one developed by peatland experts during an IUCN Red List of Ecosystems assessment for Australian alpine ecosystems (Regan et al. 2020). GHG = greenhouse gas. Components or links from Figure 2 that are missing from Figure 5 indicate lack of evidence reported in the reviews. Note: This figure is illustrative only as it does not consider the quality of the study nor the effect sizes.

Discussion

Our rapid evidence review provides both a valuable summary of the effectiveness of interventions to conserve peatlands and their ecosystem services, and a clear demonstration of the usefulness of rapid evidence reviews as an alternative evidence synthesis approach than systematic reviews for conservation. We demonstrate the value of using conceptual models in conjunction with rapid evidence synthesis to summarise the effectiveness of management interventions at influencing key ecosystem features, processes and threats, and map their interactions across the system.

Understanding the effectiveness of interventions is critical for successful peatland conservation to support biodiversity and ecosystem services. Our findings underscore the importance of taking a whole-systems approach to guide peatland conservation, as hydrological conditions, chemical properties and biota are intrinsically linked (Figure 5). By influencing multiple ecosystem components, interventions may be used to efficiently enhance conservation or drive trade-offs that benefit some components over others. Restoration of one component, such as vegetation, may be ineffective or limited if other aspects, such as hydrological conditions, remain degraded. Understanding the condition of the defining features of an ecosystem is therefore vital to inform selection of interventions to target key degraded components, eliminate threats and prioritise the order of implementation to improve conservation success (Roni et al. 2002).

Our review revealed that conservation interventions varied substantially in their capacity to improve degraded peatlands. Overall, rewetting, shading or mulching, reprofiling, mowing, controlling grazers and active revegetation principally improved peatland condition across all response categories, whereas prescribed burns and applying fertilisers had varied impacts and grazing was largely detrimental. Furthermore, taking a systematic approach enabled our review to reveal gaps in the literature on peatland management. Peat formation is a defining process in peatlands (Page & Baird 2016), yet only three reviews briefly reported the consequences of interventions (mowing, prescribed burns and revegetation) on peat formation or peat quality. Similarly, review-level information on management impacts on peatland animals was minimal compared to the comprehensive assessment of vegetation, despite peatlands providing important habitat for endangered species, and food resources through fishing and hunting (Parish et al. 2008). Few reviews described the impacts across peatland features of reducing or eliminating threats, such as controlling grazers, implementing policy (including legal protection), and weed or fungi control, although those that did reported largely positive outcomes. While the Peatland Synopsis provided copious information on the impacts of management interventions on vegetation (Taylor et al. 2019b) to supplement the findings from our rapid evidence review, future syntheses could delve into the detailed impacts of interventions on hydrological conditions and peat dynamics.

Restoring peatlands is important for reinstating the ecosystem services they provide, such as carbon storage, reducing erosion and providing freshwater (Bonn et al., 2016). The United Nations Environment Programme has recognised that retaining intact and restoring degraded peatlands provides a significant opportunity to mitigate climate change (Parish et al. 2008). Our review revealed consistent evidence that rewetting and actively revegetating degraded peatlands will likely transition the ecosystem back to a carbon sink in the long-term (decades, rather than years), despite initial increases or fluctuations in greenhouse gas emissions. Similarly, we showed that there is consistent evidence that rewetting, reprofiling and/or actively revegetating peatlands reduces erosion and thus improves water quality (Grand-Clement et al. 2015; Li et al. 2018). We found conflicting evidence of impacts on restoring hydrological conditions and storm protection services; restoring hydrological conditions can reduce peak flow downstream during storms (Stratford & Acreman 2016), but may reduce stormwater storage capacity and increased flooding risk (Grand-Clement et al. 2015; Lamers et al. 2015) if peatlands are oversaturated. However, the benefits of erosion protection and provision of freshwater from restoring the hydrological conditions and reducing erosion of degraded peatlands were not directly measured. This indicates an important gap in evidence of the effectiveness of interventions in restoring peatlands to directly reinstating critical ecosystem services. While restoring peatlands has high potential to re-establish ecosystem service provision, long-term studies are needed to better understand these processes.

The rapid review approach enabled the scientific evidence from reviews to be efficiently harnessed across a challenging breadth of topics. Our review captured evidence from 453 unique papers in the 23 reviews. Taking a whole-systems approach would be almost impossible if synthesising the underlying primary studies; each ecosystem response or intervention alone could easily be the focus of an individual systematic review, which could be too time and resource intensive for conservation managers and fail to capture the overarching ecosystem-level interactions. Of course, the rapid evidence review approach trades-off comprehensiveness and speed when gathering and synthesising information (Khangura et al. 2012), with a key assumption that the output reliably represents the primary literature. In the health field, rapid evidence reviews have provided similar information to systematic reviews (Watt et al. 2008), but comparisons are currently lacking in conservation.

Importantly, the degree of effectiveness of each intervention may be moderated by the level of degradation and/or timeframes over which the effectiveness is judged. Yet this information was not always reported in the reviews. Clearly reporting the state of the peatland pre-intervention and the timeframes over which recovery was monitored should be better captured by future reviews.

By limiting our search to reviews from 2015 onwards, we may have overlooked older informative reviews; however, our aim was to capture a representative sample of recent literature rather than comprehensively review it. We restricted our search to published reviews and book chapters, but acknowledge that grey literature reviews could provide additional information (Haddaway & Bayliss 2015). However, insights from the grey literature were captured in some of the reviews included in our study. Lastly, we used vote-counting in lieu of sufficient data to conduct a meta-analysis; we critically appraised the reviews to ensure the results are considered alongside each review’s quality.

Our rapid evidence review demonstrates the critical importance of a whole-systems approach to peatland management for effective conservation, especially where the restoration of one component may be ineffective or limited if other components remain degraded or interventions are not conducted in concert. Our review also showed that there is consistent evidence that restoring peatlands over decadal timeframes can re-establish ecosystem services provided by peatlands, particularly carbon storage. This is the first known review linking a system-level understanding of peatlands to operational-level conservation management decisions. Our demonstration of the value of a rapid review approach to facilitate the linking of vast systems-level evidence of conservation effectiveness to our understanding of ecosystem dynamics (represented as a conceptual model) should encourage broader use of this approach to inform the management of important ecosystems, combined with practical knowledge and experience of individual systems. Given the calls for improved efficiency in evidence synthesis methods for sharing and collating scientific knowledge for evidence-based decision-making (Dicks et al. 2014; Pullin et al. 2020) and the emphasis on ecosystem conservation as part of international conservation targets (SBSTTA 2020), our study offers a potential blueprint to advance evidence-based ecosystem management.

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Supplementary material

Appendix 1 – Glossary of terms

Appendix 2 – Details of literature search, including the pilot search and search string

Appendix 3 – Supplementary results: critical appraisal details

Appendix 4 – Supplementary figures

Appendix 5 – Supplementary references

Appendix 6 – Spreadsheet including metadata for each tab (tab 1), details of included/excluded papers (tab 2), details of included papers (tab 3), critical appraisal of systematic reviews (tab 4) and narrative reviews (tab 5), data extracted from included reviews (tab 6) and Peatland Synopsis (tab 7).

Conflict of interest statement

We declare no conflict of interests.

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