A synthesis of evidence for the effects of interventions to conserve peatland vegetation: overview and critical discussion

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SUMMARY

Peatlands are valuable but threatened ecosystems. Intervention to tackle direct threats is often necessary, but should be informed by scientific evidence to ensure it is effective and efficient. Here we discuss a recent synthesis of evidence for the effects of interventions to conserve peatland vegetation - a fundamental component of healthy, functioning peatland ecosystems. The synthesis is unique in its broad scope (global evidence for a comprehensive list of 125 interventions) and practitioner-focused outputs (short narrative summaries in plain English, integrated into a searchable online database). Systematic literature searches, supplemented by recommendations from an international advisory board, identified 162 publications containing 296 distinct tests of 66 of the interventions. Most of the articles studied open bogs or fens in Europe or North America. Only 36 interventions were supported by sufficient evidence to assess their overall effectiveness. Most of these interventions (85 %) had positive effects, overall, on peatland vegetation - although this figure is likely to have been inflated by publication bias. We discuss how to use the synthesis, critically, to inform conservation decisions. Reflecting on the content of the synthesis we make suggestions for the future of peatland conservation, from monitoring over appropriate timeframes to routinely publishing results to build up the evidence base.

KEY WORDS: bog, fen, mire, peat swamp, restoration

INTRODUCTION

Areas with peat soils that are more or less permanently saturated with fresh water, herein referred to as peatlands (Figure 1), support unique ecosystems with characteristic plant communities. Peatlands probably cover less than 3 % of the world's land area (Xu *et al.* 2018) but may constitute around 50 % of all wetlands (Bragg & Lindsay 2003). They occur on all continents and in a range of eco- or biogeographical regions from boreal and temperate peatlands in Europe, Canada, Russia, Australia, New Zealand, Patagonia and Antarctica to mountain peatlands in the Andes, China and southern Africa and vast tropical peat swamps in the Amazon basin, central Africa and South East Asia (Rydin & Jeglum 2013, Grundling *et al.* 2015, Loisel *et al.* 2017, Xu *et al.* 2018).

Many peatlands are in need of conservation attention because they are both valuable and threatened. Peatlands contain distinctive and specialised species, and sometimes rich and diverse communities (Posa *et al.* 2011, Minayeva *et al.* 2017). They provide multiple benefits to humans, from storing carbon and water to providing food, medical supplies and building materials, and offering a wilderness for recreation (Bonn *et al.* 2016). Meanwhile, peatlands face a variety of interlinked threats including land use change (e.g. conversion to farmland or forestry, construction of transport or service corridors, residential and/or commercial development), water abstraction, peat extraction, vegetation harvesting, recreational use, pollution, invasive species and climate change (Taylor *et al.* 2018a). Large areas of peatland have been, and are currently being, degraded in boreal (e.g. Rochefort & Lode 2006), temperate (e.g. Bragg & Lindsay 2003) and tropical (e.g. Miettinen *et al.* 2012) regions. Other natural peatlands face imminent threats (Crump 2017, Roucoux *et al.* 2017).

Conservation is often based on common sense, personal experience or expert advice (Sutherland *et*

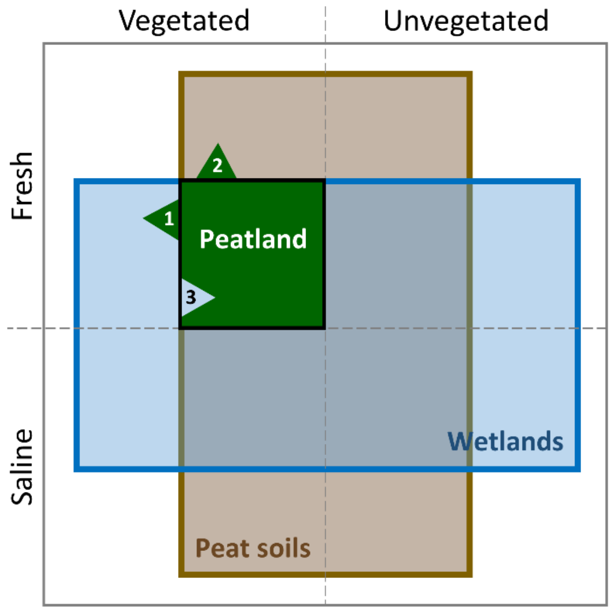

Figure 1. The scope of the Peatland Evidence Synthesis (dark green area) includes vegetation in peatlands (areas with non-saline, wet, peat soils; black box), typical peatland vegetation that is not currently on peat soil (e.g. restoration after some mining activities; arrow 1) and fen meadows (which may sit at the wetland-upland boundary; arrow 2). However, the synthesis does not include wetland vegetation types that sometimes, but often do not, occur on peat soils (e.g. reedbeds; arrow 3). Note that peatlands are often defined as any area with peat soil (brown box) and that our definition is closer to the mire and suo/swob concepts used elsewhere (Joosten *et al*. 2017). Figure adapted from Bragg & Lindsay (2003).

al. 2004, Fabian *et al.* 2019). Yet efficient and effective conservation should, where possible, be informed by careful interpretation of the scientific evidence (Sutherland *et al.* 2004, Pullin & Knight 2009, Rochefort & Andersen 2017, Salafsky *et al.* 2019). Interventions that ignore evidence can be costly, ineffective and even harmful. For example, a US$17 million programme to plant mangrove trees in the Philippines, without considering evidence for where they would best be planted, produced few surviving trees and damaged healthy ecosystems in the process (Samson & Rollon 2008). Similarly, planting trees in tropical peat swamps with little information about the ecology of the planted species and local vegetation can produce low success rates (van Eijk *et al*. 2009).

The use of evidence in peatland conservation decision making may be limited by a lack of synthesis for many questions relevant to practitioners, leaving them to trawl the dense and technical scientific literature for answers (Westgate *et al*. 2018). Even when syntheses relevant to the conservation of peatland vegetation have been produced, accessibility to practitioners can be restricted by technical language, complex analyses, limited relevance of generalised conclusions and financial paywalls (Anderson 2014, Pullin & Knight 2005). Reviews and evidence syntheses relevant to peatland conservation also commonly suffer from bias in the included evidence due to non-systematic search strategies and a focus purely on actions taken rather than quantitative outcomes of those actions. To help overcome these barriers and limitations, we have produced a synthesis of evidence under the framework of the Conservation Evidence project (www.conservationevidence.com). The Peatland Evidence Synthesis is a largely systematic collation of evidence for the effects of conservation interventions on peatland vegetation, at an unprecedented scale (covering all possible interventions and including studies from around the world) and with outputs tailored to be accessible to a wide range of end users, especially peatland conservation practitioners.

Here we build on the standardised and strictly objective synthesis outputs that have already been published (Taylor *et al.* 2018a, 2018b) by:

(a) providing an overview of the content of the Peatland Evidence Synthesis as a whole;

(b) critically discussing its methods, scope and use;

(c) discussing some interventions in more detail as illustrative examples and to explore the mechanisms behind them; and

(d) offering some suggestions, based on the synthesis, to improve future work regarding the conservation of peatland vegetation.

We hope that this article will give a rapid introduction to the literature for anyone interested in conserving peatland vegetation, and help those making decisions for practical peatland conservation to use the Peatland Evidence Synthesis correctly.

METHODS

Creating the Peatland Evidence Synthesis

The methods used to create the Peatland Evidence Synthesis, summarised briefly below, follow a general protocol developed by Conservation Evidence. For further details, see Taylor *et al.* (2018a) and Sutherland *et al.* (2018). The methods adhere to the central tenets of systematic reviewing - comprehensiveness, objectivity, repeatability and transparency (Haddaway *et al.* 2016) - as closely as possible. However, we necessarily sacrifice some comprehensiveness in depth (we cannot claim to have captured every published study for every intervention, having only searched a subset of the literature) to gain comprehensiveness in breadth (a scope that includes all possible interventions in peatlands anywhere in the world, and a search strategy that benefits other syntheses within the Conservation Evidence project).

1. Define the subject and scope of the synthesis. The Peatland Evidence Synthesis collates evidence for the effects of interventions to conserve peatland vegetation. The word ‘conserve’ is used in a broad sense including protection, restoration, rehabilitation and creation of natural and semi-natural ecosystems. ‘Peatland vegetation’ refers to the overall plant community or habitat-defining species in areas with non-saline, wet peat soils - or vegetation typical of these environments but not currently on wet peat soils (Figure 1). Thus, the synthesis focuses on the vegetation of bogs, fens and tropical peat swamps (Table 1). Fen meadows are drier and more managed derivatives of fens, so may not be classified as peatlands under our definition, but were also included in the synthesis because they may be the only realistic restoration target for many degraded fens (Kotowski *et al.* 2016). Other types of freshwater wetland vegetation that sometimes occur on peat soils but often do not - such as reedbeds and flushes - were excluded from the synthesis.

For most interventions, only direct metrics of vegetation response were reported in the synthesis (e.g. community composition, species richness, physical structure). For some interventions, such as education or habitat protection, small-scale effects on vegetation are difficult to monitor and so are rarely published (Kapos *et al.* 2008). In these cases, intermediate or large-scale outcomes that may reflect effects on vegetation - such as a change in knowledge, behaviour or peatland area - were also reported. However, we caution that such links,

Table 1. Description of the six main habitat types covered in the Peatland Evidence Synthesis, adapted from Taylor *et al.* (2018a). Habitat types are based on ecological similarity, geographical similarity and existing fields of study. They are not hierarchical.

Habitat type	**Physical conditions**	**Typical/dominant vegetation**	
1. Bogs	Peat soil. Water and nutrients mainly from precipitation. Acidic. Low in nutrients.	**1a. Open**	Mosses e.g. *Sphagnum* spp.; herbs e.g. *Eriophorum* spp., *Calamagrostis* spp., *Molinia* spp., *Juncus* spp.; and dwarf shrubs e.g. *Calluna vulgaris*, *Erica tetralix*, *Empetrum nigrum*, *Vaccinium* spp.. Sometimes occasional trees.
		1b. Forested	Trees e.g. *Alnus* spp., *Fraxinus* spp., *Picea* spp., *Pinus* spp.
2. Tropical peat swamps	Peat soil, usually in raised domes. Essentially tropical forested bogs, but with distinct ecology and some unique conservation challenges compared to their temperate and boreal counterparts.	Trees e.g. *Dyera polyphylla* and *Shorea balangeran* in South East Asia. Palms e.g. *Mauritia flexuosa* in South America.	
3. Fens	Peat soil. Water and nutrients from groundwater as well as rain. More nutrients and less acidic than bogs, but variable.	**3a. Open**	Herbs e.g. *Carex* spp., *Cladium* spp., *Schoenus* spp., *Juncus* spp., sometimes limited *Phragmites australis*; and mosses e.g. *Scorpidium* spp., *Calliergon* spp., *Warnstorfia* spp.. Sometimes occasional trees or shrubs.
		3b. Forested	Tall shrubs or trees e.g. *Alnus* spp., *Betula* spp., *Fraxinus* spp., *Picea* spp., *Pinus* spp.
4. Fen meadows	Derived from fens, so based on peat or peaty soils - but not forming new peat. Slightly drained and maintained by regular management such as mowing or grazing.	Herbs e.g. *Carex* spp., *Cladium* spp., *Molinia caerulea*, *Cirsium* spp.. Fewer tall reeds and rushes than fens. Mosses similar to those in fens. No trees or shrubs.	

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especially between education and behaviour change, are not always straightforward (Christiano & Neimand 2017).

2. Create a list of all interventions that have been used, or suggested, to conserve peatland vegetation. Interventions were derived from initial scans of the literature and an international advisory board of 11 peatland conservation experts. The list focused on interventions to tackle proximate, direct threats to peatlands (Salafsky *et al.* 2008) although some interventions tackle ultimate, underlying causes, such as those designed to change awareness and behaviour.

3. Collate candidate publications. These were largely derived from systematic manual screening of over 230 academic journals and grey literature sources (approximately 600,000 individual documents). Candidate publications were those that appeared to contain quantitative results about the effects of conservation interventions on peatland vegetation, based on their title plus abstract or summary. They must have been published in 2016 or earlier but could be from any country and written in any language (although most sources searched were in English). Much of the screening had already been completed as part of the Conservation Evidence project, with candidate publications stored in a database.

Some additional candidate publications were identified by other means: (a) by querying the Conservation Evidence website with search terms (i.e. peat, peatland, bog, fen, mire and appropriate plurals), because it contains some publications not in the screening database; (b) from cited quantitative data in reviews (see Step 4); and (c) from advisory board suggestions (see Step 6).

4. Summarise relevant studies from the publications in brief, plain-English paragraphs. Each conceptually distinct test of an intervention was considered as a separate study, meaning a publication could contribute more than one study (paragraph) to the synthesis. A study was considered relevant if it contained quantitative results about the effects of conservation interventions on peatland vegetation. Each summary paragraph contains details of methods, results and essential context such as site location and history. Reported results were based on statistical tests where possible, but raw data were also included to indicate the magnitudes of effects. Reviews were summarised when they contained new or collective data. When reviews presented isolated cases of quantitative secondary data, the original cited publications were summarised instead.

5. Write key messages as an index to the evidence for each intervention. The key messages highlight study designs, where the studies were carried out (geographical location and habitat type), which metrics were reported and the direction of any reported effect. They guide users to the relevant summary paragraphs, which should also be read to get a full understanding of study quality, context and effect size. Sometimes the key messages simply highlight that no evidence was found for the effects of an intervention on peatland vegetation. This does not necessarily mean the intervention had no meaningful or significant effects, just that we found no studies testing the intervention.

6. Gather feedback from advisory board. The advisory board reviewed the draft synthesis. They identified further candidate publications from sources not covered by systematic searches, especially grey literature and publications outside the scope of the systematic searches. Relevant publications were summarised as above (Step 4) and incorporated into the synthesis. These publications contributed 26 % of those used in the final synthesis.

7. Expert assessment. Based purely on the evidence included in the synthesis, a panel of 13 experts scored each intervention for effectiveness (at conserving peatland vegetation), certainty (how certain we are that the effectiveness score applies across all peatlands where the intervention might realistically be carried out, based on the quantity, quality and distribution of evidence) and harm (caused to peatland vegetation). Harm to anything other than peatland vegetation (e.g. to animals, ecosystem service provision or the wider environment) would not have been systematically captured by the search process. Scores for these three dimensions were combined into an “overall effectiveness category” for each intervention: a generalised indication of the benefit and harm of the intervention to peatland vegetation (Sutherland *et al*. 2018).

The scoring followed a modified Delphi process (Mukherjee *et al.* 2015, Sutherland *et al.* 2018). Assessors initially scored each intervention independently but could later revise their scores, with the help of anonymised scores and comments from the other assessors, for any contentious interventions (more than two assessors disagreed with the overall effectiveness category allocated using the initial scores). The overall effectiveness category was based on the initial scores for 35 interventions and revised scores for 31 interventions. The other 59 interventions were not assessed because no evidence was captured.

8. Create synthesis products that meet the needs of different users. A searchable database at www.conservationevidence.com contains the narrative synthesis (study summaries and key messages, plus background information) and expert assessments for peatland vegetation, alongside other subjects reviewed as part of the Conservation Evidence project. A Peatland Conservation synopsis, available online as a PDF, contains the narrative synthesis (Taylor *et al.* 2018a). A Peatland Conservation chapter in the book *What Works in Conservation* (Taylor *et al.* 2018b) presents the key messages and expert assessment scores for each intervention, with links to the online database.

Creating an overview of the Peatland Evidence Synthesis

For each publication we counted all countries in which studies were carried out and all broad habitat types (Table 1) conserved. We defined the conserved habitat type as the desired outcome of the intervention, which sometimes differed from the pre-disturbance or pre-intervention state.

We analysed publication rates as: (a) the absolute numbers of publications in the synthesis per year; and (b) for the 10 journals contributing at least three papers to the synthesis (*Applied Vegetation Science*, *Biological Conservation*, *Journal for Nature Conservation*, *Journal of Applied Ecology*, *Journal of Ecology*, *Mires and Peat*, *Plant Ecology*, *Restoration Ecology*, *Wetlands* and *Wetlands Ecology and Management*), the number of papers standardised by total publishing effort. This was calculated as n_i/N_i, where n_i is the number of relevant papers (summarised in the synthesis) published in these journals in a given year i, and N_i is the total number of research papers published in these journals in year i. Where possible, an estimate of the number of papers published per year was obtained using Web of Science. Otherwise, papers were counted manually from journal websites. For three journals, searches commenced at the first available digitised issue rather than the first ever issue. Counts of papers included original articles, letters and reviews/editorials but excluded documents like conference abstracts, obituaries and book reviews which are not consistently indexed in Web of Science.

We also extracted the longest monitoring period per publication ($LMPP^{-1}$) - the longest time in each publication between carrying out or starting an intervention and monitoring its effects on vegetation. In some publications the duration of monitoring differed between metrics and/or studies. We estimated time to the nearest month, assuming intervals of three months between seasons and twelve months between years if no finer resolution was provided in the publication.

RESULTS

The Peatland Evidence Synthesis reviews 125 possible interventions to conserve peatland vegetation (see Appendix). There are 296 paragraphs (conceptually distinct summaries) derived from 162 separate publications.

Most of the publications in the evidence synthesis report on peatlands in Europe (64 %) or North America (20 %) (Figure 2a,b). The countries featuring in the most publications are the UK (19 %) and Canada (14 %). Only 16 % of publications report on peatlands in Asia, South America or Oceania combined, and only 6 % of publications report on peatlands other than tropical peat swamps in these continents. Some individual sites, especially in the UK and Canada, feature in multiple publications.

The distribution of habitat types studied (Figure 2c) matches the geographical distribution of publications. In most publications, interventions aimed to conserve bog vegetation (41 %) or fen vegetation (28 %) or a mixture of both (4 %), with only 18 publications (11 %) containing studies of fen meadow vegetation, and 16 (10 %) containing studies of tropical peat swamp forest vegetation. Of the publications involving bogs and/or fens, 92 % are relevant to the conservation of open habitats and only 8 % are relevant to the conservation of forested habitats. Nine publications (6 %) focus on peatlands but do not provide sufficient information to classify the habitat type further. Four publications describe a conservation intervention that aimed to create or restore a different habitat type from that present immediately before degradation or intervention. In three of these, the intervention aimed to restore fen vegetation in bogs where peat had been extracted. Removal of surface bog peat exposes deeper fen peat, the chemistry of which supports restoration of fen vegetation better than bog vegetation (Wind-Mulder *et al.* 1996, Lindsay & Clough 2016).

Unsurprisingly, given increasing scientific publication rates over time (Godet & Devictor 2018), 67 % of all publications in the synthesis are from the 10 most recent years (2007–2016; Figure 3a). This reflects an increasing number of publications per year in most journals, as well as the inception of new journals such as *Mires and Peat* in 2006. However, there also appears to be increased interest in testing the effects of conservation interventions on peatland vegetation when increased overall publication rates are controlled for. In the 10 key journals contributing

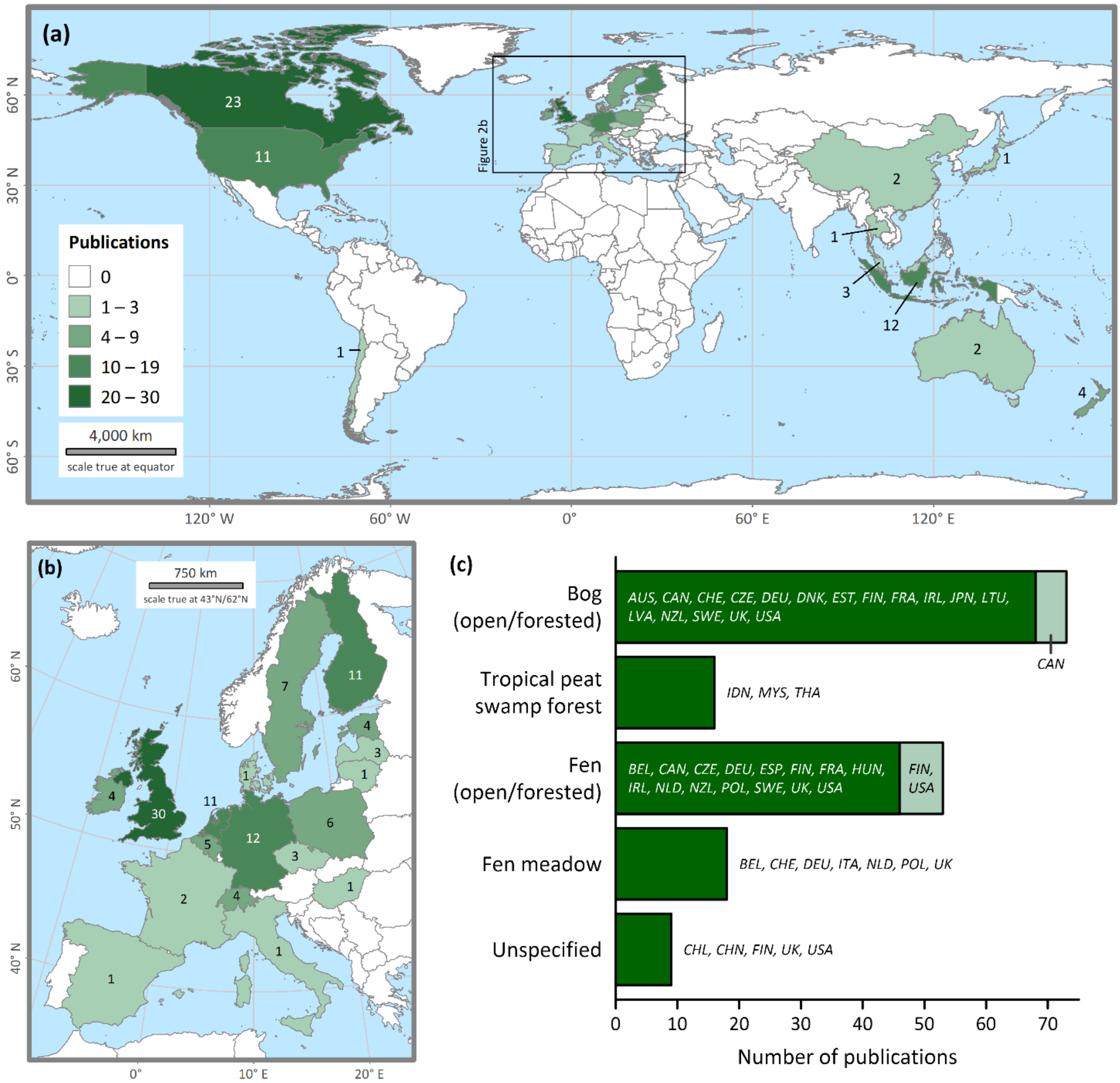

Figure 2. Distribution of publications in the Peatland Evidence Synthesis (a) globally, (b) in Europe, and (c) by habitat type. Publications could contribute more than one country or peatland type to the dataset. Hence, 162 publications generated 167 country data points and 169 habitat type data points. In (c), countries are those in which conservation interventions were tested in each habitat type (ISO (2019) Alpha-3 country codes, except UK for United Kingdom). 'Unspecified' refers to a habitat that could not easily be classified into one of the six habitat types. Projections: (a) WGS1984 Plate Carée; (b) Lambert Conformal Conic.

at least three papers to the evidence synthesis (see Methods), the *proportion* of all papers reporting the effects of interventions on peatland vegetation has also, amongst much interannual variation, increased over time (Figure 3b). For these journals, 0.18 % of all papers published between 1979 and 1996 are included in the Peatland Evidence Synthesis (11 of 6,240 papers). This rose to 0.35 % between 1997 and 2006 (27 of 7,623 papers) then to 0.46 % between 2007 and 2016 (56 of 12,047 papers). This increase is statistically significant (chi-square test of equal proportions in each period, $\chi^2 = 9.49$, $df = 2$, $P = 0.009$).

The $LMPP^{-1}$ varies between ten weeks and 161 years (Figure 4). The median $LMPP^{-1}$ is 4 years. The study lasting 161 years is exceptional, using historical records and contemporary monitoring to examine changes in the vegetation of a protected bog (Kollmann & Rasmussen 2012). All other publications report monitoring for 50 years or less. The shortest monitoring periods are in publications

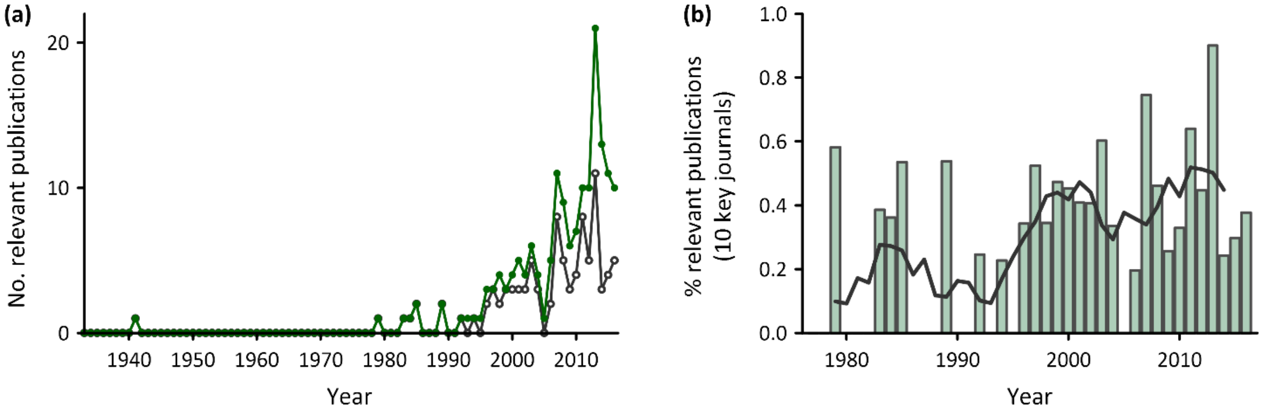

Figure 3. Temporal trends in publications relevant to the Peatland Evidence Synthesis (i.e. quantitatively reporting the effects of conservation interventions on peatland vegetation). Panel (a) shows the total number of relevant publications (green filled circles) and the total number of relevant publications from 10 key journals (black open circles) since the earliest journal issue searched (1933). Panel (b) shows the percentage of all publications in the 10 key journals that were relevant to the synthesis (green bars), with a five-year moving average (black line), since 1979. The ten key journals were those that contributed the most publications to the synthesis (see Methods).

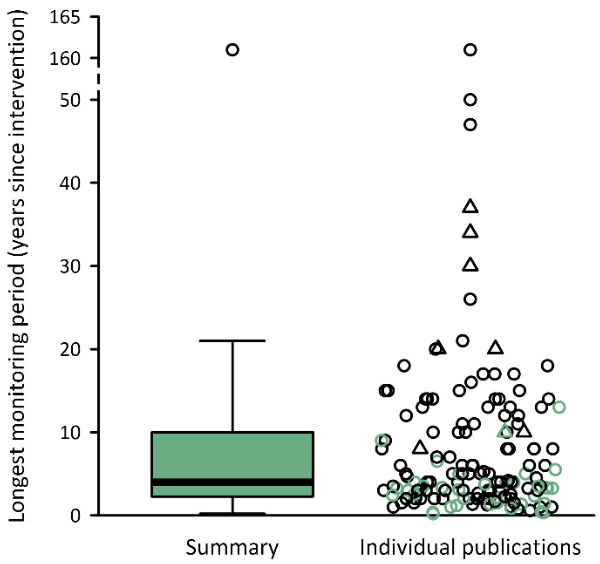

Figure 4. Longest time for which the effects of conservation interventions were monitored in Peatland Evidence Synthesis publications (n = 153). Five publications containing studies of unclear duration and four publications testing education / awareness-raising interventions are not included. Boxplot (left) summarises data (right). In the boxplot: bar = median; box = interquartile range; whiskers = maximum and minimum values within 1.5 × interquartile range; circle = outlier. For the data: triangles indicate times reported in publications as "approximately" or "at least" x years; black symbols are based on an intervention that modifies the physical environment; light green symbols are based on an intervention involving planted peatland vegetation. Note break in y axis.

that study the effects of planting peatland vegetation or actions to complement planting. When these are excluded, the median LMPP^{-1} is still only 5 years 3 months.

We captured no evidence for the effects on peatland vegetation of 59 of the 125 interventions listed in the synthesis (Figure 5). Of the 66 interventions with some evidence, 40 were assessed as having unknown effectiveness because the evidence base was limited in size, scope and/or quality. Of the 26 remaining interventions, 22 (85 %) were allocated to the categories *beneficial* or *likely to be beneficial*. The three interventions assessed as *beneficial* were: (1) rewet peatlands (by raising the water table); (2) add mosses to the peatland surface; and (3) add mixed vegetation to the peatland surface. There is clear evidence that these actions generally produce more natural or desirable vegetation when used in appropriate conservation situations. The 19 interventions assessed as *likely to be beneficial* ranged from directly planting peatland trees/shrubs to legally protecting peatlands. Based on the collated published evidence, just one intervention was assessed as *likely to be ineffective or harmful*: add lime to complement planting. Note that adding lime without planting peatland plants, and adding lime as one of multiple interventions, are dealt with separately in the evidence synthesis (see Discussion).

Although there was considerable variation amongst assessors in their scores for effectiveness, certainty and harm, the overall effectiveness categories almost always represent a consensus. For 64 of 66 assessed interventions, more than half of the 13 assessors agreed on the overall effectiveness

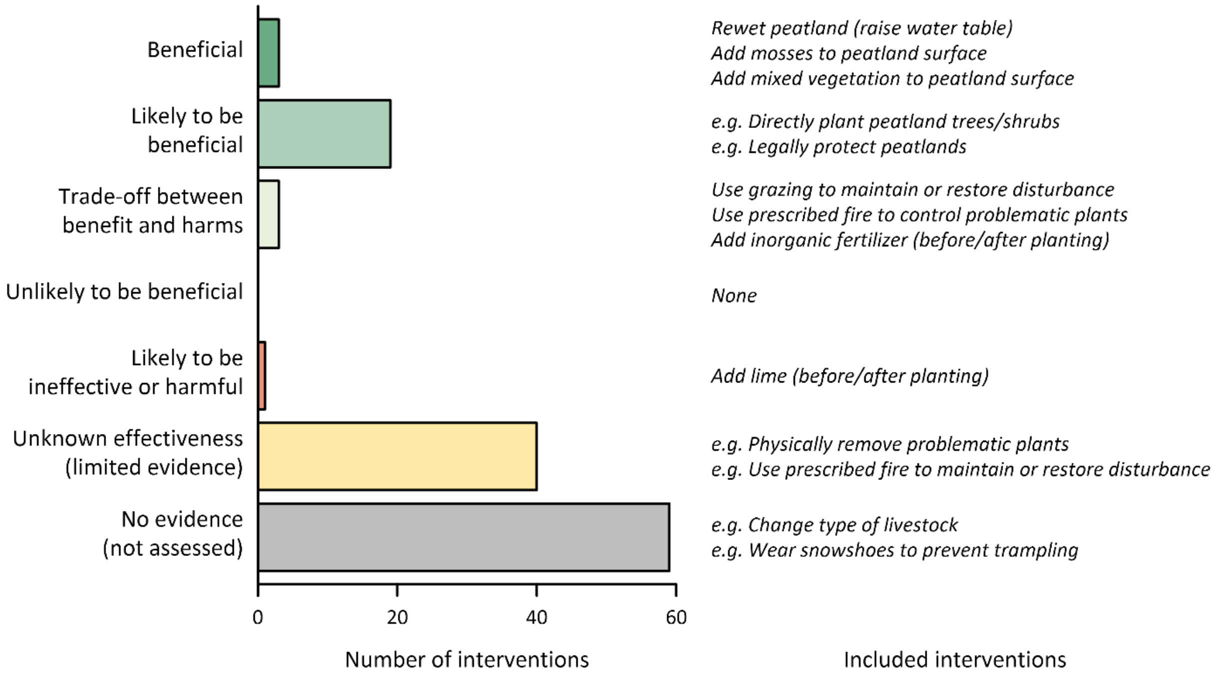

Figure 5. Number of interventions (total = 125) in each overall effectiveness category, based on expert assessment of effectiveness, certainty and harm (n = 13 experts). Scores were based solely on the collated evidence from the published literature. Effectiveness categories reflect the likely effects of interventions in all relevant habitat types. Thus, for a beneficial intervention there is clear evidence to suggest benefits to peatland vegetation in all peatland habitats where one might realistically carry out the intervention. See Sutherland *et al*. (2018) for further information about effectiveness categories.

category. The two contentious interventions were: (1) add lime to complement planting (four assessors agreed with the category assigned on the basis of the median of final scores, *likely to be ineffective or harmful*, with the others were split between three categories but mostly *unknown effectiveness*); and (2) add inorganic fertiliser to complement planting (six assessors agreed with the assigned category *trade-off between benefit and harm*, with the others split between all other categories except *beneficial*). Ten or more assessors agreed on the overall effectiveness category for 46 of the 66 interventions.

DISCUSSION

How the Peatland Evidence Synthesis fits into conservation planning

The Peatland Evidence Synthesis is the most comprehensive guide, to date, to interventions that could be used to conserve peatland vegetation and to the available evidence for their effects. The evidence synthesis should be used critically as part of a decision-making process (outlined in Figure 6 and discussed below) rather than as a list of recommended solutions.

1: Decide if intervention is necessary

Interventions are generally used to prevent a threat, remove a threat, reduce the intensity of a threat, or repair damage caused by a threat. Intervention is especially important if a threshold has been crossed such that natural regeneration is unlikely (Page *et al*. 2009, Graham *et al*. 2017). In peatlands, a water table below a certain threshold level could render the surface peat too dry for characteristic peatland vegetation (Page *et al*. 1999, Rydin & Jeglum 2013), whilst fire frequency above a certain threshold could exclude characteristic peatland vegetation (Page & Hooijer 2016). Multiple interventions may be needed to tackle multiple threats. For example, in peatlands used for grazing, livestock access and drainage might both require management.

By contrast, in peatlands that are not directly threatened or that have not been degraded by historical threats, intervention may not be necessary and may in fact cause more harm than good. Intervention may be undesirable even in some degraded peatlands if it is likely they will recover spontaneously within a reasonable timeframe (Lavoie *et al*. 2003, Graf *et al*. 2008, Konvalinková & Prach 2010, Triisberg *et al*. 2014). Before considering which interventions could be carried out,

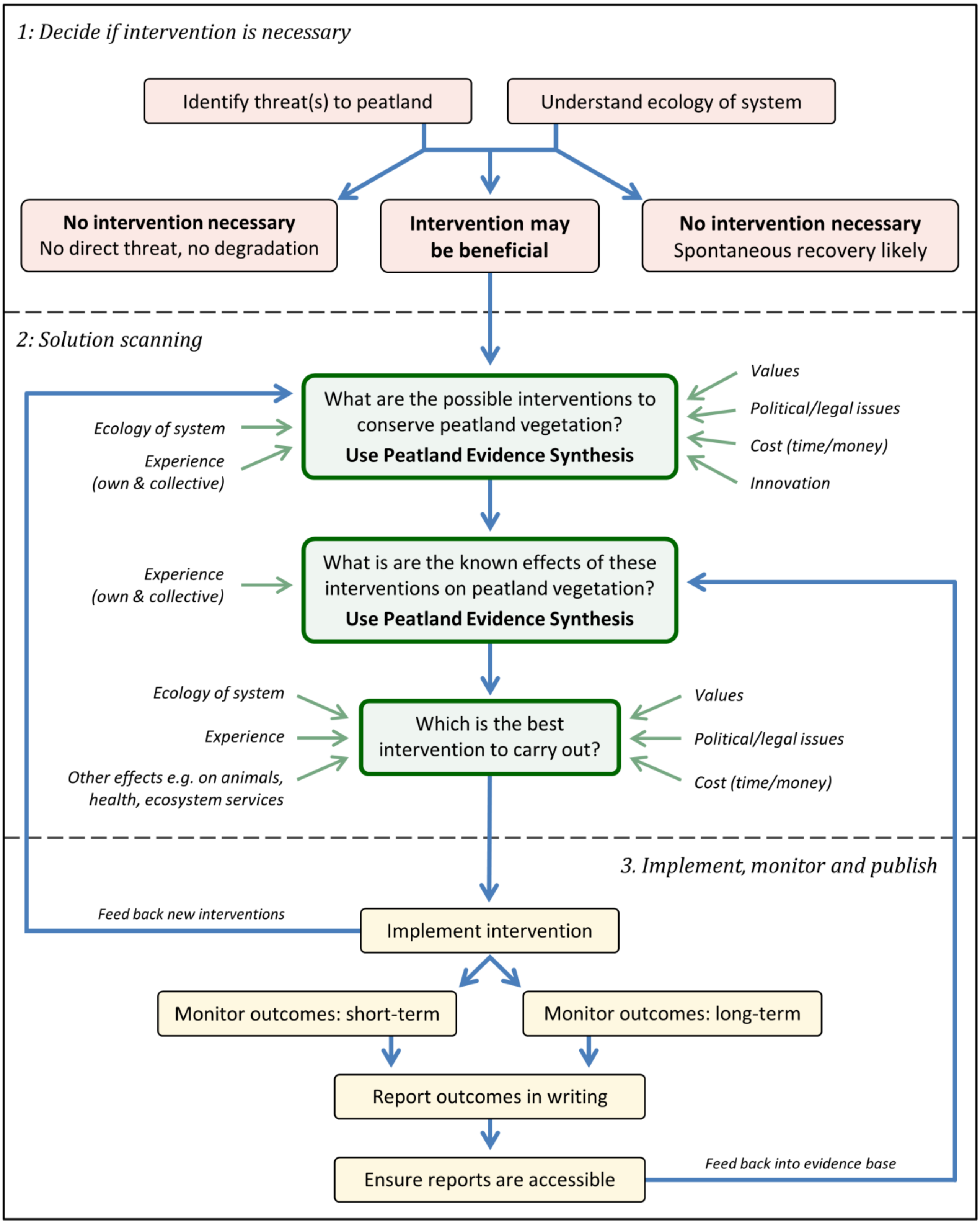

Figure 6. Possible decision making process for the conservation of peatland vegetation, indicating where the Peatland Evidence Synthesis can contribute (green boxes).

peatland conservationists should consider whether intervention is necessary at all.

Some knowledge of local peatland ecology will be necessary in making this decision (Figure 6). For example, indicators of degradation might be context specific. Purple moor grass *Molinia caerulea* is controlled as a problematic plant species in some peatland plant communities, but is a dominant and valued feature of others (Meade 2016). The potential for spontaneous recovery might be informed by a particular site's history of use, current physical conditions, and proximity to extant peatlands (Lavoie *et al.* 2003).

2: Solution scanning

If intervention is desirable, the Peatland Evidence Synthesis can help conservationists to identify and choose between possible interventions (e.g. mowing versus burning) and implementation options (e.g. mowing in summer versus winter). The information it contains about the effects of interventions on vegetation should not be ignored when designing a peatland conservation strategy (Sutherland & Wordley 2017). We feel strongly that conservation, informed at least in part by careful consideration of the available evidence, is likely to be more effective and efficient than conservation that does not consider the evidence at all. Still, we recognise that many other issues must be factored into the decision making of peatland conservationists (Anderson 2014, Evans *et al.* 2017). These include evidence for effects of interventions on other aspects of the environment (including animal groups as published in other Conservation Evidence syntheses), knowledge of the basic ecology of the focal peatland (e.g. soil and water chemistry, state of degradation, sources of colonising vegetation), local experience, values, political or legal issues, and available resources (Figure 6).

Interpreting the evidence presented in the synthesis demands some critical thinking. Evidence should be weighted in terms of quantity and quality (e.g. metrics reported, study design, timescale; De Palma *et al.* 2018). The user must also consider the similarity of the evidence to the situation at hand (e.g. habitat type, history of management or disturbance, implementation methods; Anderson 2014). The evidence synthesis includes as much information as possible about each study, but necessarily only the original papers can provide the full context and nuances. Similarly, whilst a background section for each intervention provides some ecological explanation for its design and effects, there is more space and scope for this in the published literature (e.g. Quinty & Rochefort 2003, Aggenbach *et al*. 2013, Clarkson *et al.* 2017, Graham *et al.* 2017).

Evidence synthesis inevitably involves grouping distinct entities together. Each study is conducted in different circumstances. There is variation within and between peatland types - bogs are clearly different from fens, but blanket bogs also differ from raised bogs, and grass-dominated blanket bogs differ structurally and functionally from shrub-dominated blanket bogs (Elkington *et al.* 2002). Each intervention in the Peatland Evidence Synthesis includes studies from all relevant habitat types (Table 1) and the overall effectiveness category generalises across all relevant habitat types. Evidence was synthesised at this broad level because: (a) peatlands in general do form a distinct conceptual entity, characterised by wet soils rich in organic matter (Figure 1); (b) for most interventions, there would not have been sufficient information to allow synthesis for more precise habitat types; (c) splitting studies into specific habitat types was not always possible, e.g. for studies of multiple peatlands, unspecified or poorly described peatlands, or transitional peatlands; and (d) we wanted to encourage readers to consider evidence from all peatlands, but weight it on the basis of relevance to their circumstances. The reader is free, with the help of the key messages, to focus on particular individual studies to draw conclusions, and to make comparisons between habitat types and locations within each intervention.

3. Implement, monitor and publish

After considering the need for intervention and the evidence base for its effects, a conservationist might choose to intervene and manage peatland vegetation. They might employ interventions identified in the Peatland Evidence Synthesis, adapt those interventions, or attempt completely new interventions if appropriate. An evidence-based approach to conservation does not discourage innovation.

We strongly recommend that the outcomes are monitored and reported, especially when the current evidence is scant or when trying innovative methods. Results should be published in an accessible, permanent format (e.g. as journal articles or reports uploaded to organisational or third-party websites) rather than only in conference presentations or internal reports. Ideally, reporting of the effects of evidence-informed interventions feeds back into the evidence base in an iterative loop (Figure 6). Reporting "failures" - interventions that had no meaningful effect, a statistically insignificant effect, or an undesirable effect - is particularly important to minimise publication bias and the use of ineffective interventions. The quality, utility and relevance of published evidence could be improved by ensuring that studies are designed as experiments (or incorporate as many principles of good experimental design as possible; e.g. Whitlock & Schluter 2015), are clearly reported (e.g. Haddaway & Verhoeven 2015, Gerstner *et al.* 2017), and are borne from close collaboration between conservation researchers and practitioners (Arlettaz *et al.* 2010). Publication should be built into project schedules and budgets (Anderson 2014).

Whilst interventions in the Peatland Evidence Synthesis are intended to benefit peatland vegetation, it will often be desirable to monitor their effects on other aspects of the environment too (e.g. carbon storage, water quality, bird populations). Similarly, although the Peatland Evidence Synthesis (like Conservation Evidence in general) focuses on quantitative monitoring, additional qualitative data in publications is often useful. Detailed site descriptions, including visual records such as photographs and videos, will help readers to understand the context of a study (Anderson 2014).

Some example interventions: what does the evidence say?

In this section we explore three interventions in further detail, to illustrate some general points about the Peatlands Evidence Synthesis - including the context-dependency of the effects of interventions, the thinking behind the scoring process, what we mean by an intervention "working", and how similar actions might be split across subtly different interventions. We also offer some interpretation of when and why these interventions work (or don't work).

Rewetting

The most extensively tested intervention in the Peatland Evidence Synthesis was rewetting peatlands by raising the water table (including actions to block drains, retain water and restore inflows). Thirty-six studies directly tested this intervention. Other studies tested the effect of rewetting in combination with other interventions, or raised the water table as part of their effect but are synthesised as distinct interventions with different primary aims (e.g. removing topsoil, relandscaping, thinning/removing forest plantations). In fact, water is a common theme throughout the synthesis; water being a fundamental component of peatlands and thus closely related to most direct threats. For example, peatlands are drained to allow development, agriculture, forestry and peat extraction, whilst drainage can encourage the growth of undesirable upland plant species and promote further encroachment and degradation.

Most (81 %) of the studies that directly tested the effect of rewetting were conducted on bogs and fens in Europe, with some in North America (11 %), China (6 %) and New Zealand (3 %). The studies generally indicate beneficial effects on vegetation such as increased cover, often of wetland- or peatland-characteristic plants. It is unsurprising that rewetting drained peatlands generally benefits peatland vegetation, much of which will grow only in sufficiently wet soils with suitable chemistry (Page *et al.* 1999, Rydin & Jeglum 2013). However, we caution that publication bias could make interventions appear more effective and more beneficial than they actually are. Desirable effects of conservation interventions are more commonly published, and thus included in evidence syntheses, than small, insignificant or undesirable effects (Godet & Devictor 2018).

When studies reported that rewetting had small, insignificant or undesirable effects on peatland vegetation, authors typically offered contextual explanations. For example, Hedberg *et al.* (2012) suggested that rich fen plants failed to colonise a rewetted fen due to severe degradation, a lack of nearby source populations, and the absence of cattle (which could otherwise act as vectors of fen species). Aggenbach *et al.* (2013) suggested that the observed peat chemistry in rewetted fens, specifically high iron concentrations, could have explained the fact that they contained fewer characteristic plant species than natural fens that had never been drained. Observed contextual details are reported in the evidence synthesis where possible, but the reader is encouraged to explore original references for speculation about why interventions did or did not work in each study. Small sample sizes, and thus low statistical power, should also be considered as a potential explanation for statistically insignificant effects.

Study designs varied, but most studies of rewetting were simple before-and-after studies (12 studies; 33 %) or site comparisons (9 studies; 25 %). In other words, most studies did not include a designated control site, randomisation or pairing/ blocking of sites. However, the quantity of data, nature of metrics, distribution of studies and consistency of results led to a high certainty score for the beneficial effect of rewetting (80 %). More studies from outside Europe, and from tropical peat swamps, would probably have increased this score. We expect future updates of the Peatland Evidence Synthesis will be able to incorporate results of recent or ongoing large-scale rewetting projects in Indonesia (BRG 2016, Crump 2017) and Russia (Succow Stiftung 2019).

Finally, note that the intervention is phrased as "rewet peatlands" rather than, say, "build dams" because the synthesis focuses on the effects of interventions when successfully implemented (i.e. the effects of a raised water table on vegetation) rather than whether interventions were implemented successfully (i.e. whether dams were constructed in a way that actually raised the water table).

Prescribed burning

As for all actions involving disturbance regimes, prescribed burning was split into two separate interventions. One addressed burning in traditionally or historically disturbed peatlands that were still in a semi-natural state. The natural fire return interval in peatlands is in the order of hundreds of years (Turetsky & St. Louis 2006, Cole *et al.* 2015). The other intervention addressed burning to control problematic plants in peatlands without a clear historical regime of frequent disturbance. The effect of managed disturbance may depend on the history (presence, frequency and intensity) of disturbance in a system (Franklin *et al.* 2000).

Based on the collated evidence, both burning interventions received relatively low effectiveness scores (40–45 %). These scores imply that burning can benefit peatland vegetation, but that the benefits are moderate or occur only in some situations. However, the certainty in these assessments of effectiveness was low (35–40 %), reflecting: (a) the limited number and distribution of independent studies; (b) methodological differences between studies (e.g. number of burn events and length of monitoring); (c) the fact that the effects of burning were sometimes not separated from the effects of other interventions; and (d) inconsistent results within and between studies, such as different effects on graminoids and forbs in different sites (Hochkirch & Adorf 2007). The score for harm was relatively high (20 %) for both interventions, and this reflects impacts on vegetation only. Other negative effects of prescribed burning not captured in the Peatland Evidence Synthesis include those on animals such as birds and amphibians, peat structure and biogeochemistry, greenhouse gas emissions, neighbouring habitats (e.g. from escaped fire or altered hydrology) and human health (Brown *et al.* 2014, Page & Hooijer 2016, Sutherland *et al.* 2018).

Expert assessors were instructed only to consider habitat types (Table 1) where each intervention might be appropriate (guided by the synthesis). Thus, the assessment scores for prescribed burning generalise across bogs and fens, but not tropical peat swamps where fire is not generally accepted as a conservation intervention - or is even banned (e.g. by Indonesian Government Regulation No. 71/2014).

Overall, we suggest that prescribed burning should not be used as a routine management tool to conserve peatland vegetation. There is limited published evidence of the effects on peatland vegetation, and that evidence suggests there are trade-offs between benefits and harm. Furthermore, there is potential for harm to the wider environment and a need to consider legal issues and conflicting values of land users (Figure 6). Thus, the feasibility and likely effects of prescribed burning should be considered carefully on a case-by-case basis, noting the context of the peatland to be managed and the context of each published study (e.g. habitat type, season, burning technique).

Liming

Based on the published evidence, adding lime to complement planting (usually intending to improve the survival or growth of planted peatland vegetation) was the only intervention assessed as *likely to be ineffective or harmful*. As a corollary, published evidence of ineffectiveness or harm was limited for all other interventions.

In theory, lime can increase the pH of peat to make overly acidic bog peat (resulting from acid rain, for example) more suitable for bog plants or to make naturally acidic bog peat more suitable for fen plants. By increasing pH, liming can also affect nutrient availability (Bragazza & Gerdol 2002, Weil & Brady 2016). However, there is little evidence that liming to complement planting actually benefits peatland vegetation. Five of six studies in the synthesis report insignificant or negative effects of liming on peatland vegetation (specifically planted fen herbs, fen vegetation overall, *Sphagnum* mosses in bog pools or peat swamp tree seedlings). Lime may be genuinely harmful in naturally acidic bogs and peat swamps (Posa *et al.* 2011), and ineffective if applied at the wrong dosage or time. One of the studies that reported a small and insignificant effect on fen vegetation (spread onto a degraded bog) added lime 2.5 years after spreading vegetation fragments. Thus, this intervention is another reminder that it is important to consider context when interpreting the individual studies and assessment scores, digging into the details of each study when necessary. It also remains possible that liming planted areas benefits peatland vegetation, especially in fens, and we encourage expansion of the evidence base to show whether this is indeed the case.

Liming is considered in two further (subtly different) contexts in the Peatland Evidence

Synthesis. First, there is an intervention that considers the effect of adding lime without introducing peatland vegetation. This may benefit spontaneously colonising vegetation directly, or indirectly by helping nurse plants to establish (Caporn *et al.* 2007, Groeneveld *et al.* 2007). Secondly, there is a section that considers studies in which more than three interventions were carried out simultaneously and their effects cannot be separated. In these cases, it is very difficult to ascribe the observed effects to single interventions. Liming is part of a multi-intervention restoration strategy used on peatlands in the UK (the other interventions including fertilisation, sowing nurse crop seeds, gully blocking and adding geojute matting). Generally, the synopsis is split into interventions that we considered would provide useful information for practitioners, but the reader may sometimes need to combine information from multiple interventions. Relevant interventions are easily found by searching for key words in any of the synthesis outputs.

The future of peatland conservation

The Peatland Evidence Synthesis, through a large scale and broadly systematic review of the literature, highlights large gaps in the published evidence for effects of interventions to conserve peatland vegetation. It was surprising to find so little published quantitative evidence on certain interventions (insufficient or no evidence for 89/125 interventions; see Results). For example, we found few studies of the effect of removing problematic plants from peatlands. This probably reflects a genuine lack of quantitative (not qualitative) studies focusing on desirable plants or the whole peatland community (rather than just the problematic plant). Our literature searches were thorough although not completely comprehensive (see Methods). Future updates to the Peatland Evidence Synthesis will build on the completed systematic searches, expanding the range of journals / grey literature sources and languages covered. Meanwhile, we encourage the publication of more quantitative evidence for the effects of peatland conservation interventions.

There was also strong geographical bias in the published evidence (Figure 2), with North America and Europe contributing 84 % of the publications in the synthesis. Hardly any studies from Russia (0 publications), Africa (0 publications) and South America (1 publication) were captured despite the presence of large expanses of peatland in these areas (Xu *et al.* 2018). This bias in the literature on testing peatland conservation interventions matches, qualitatively, the geographical bias in papers testing conservation interventions more generally (Godet & Devictor 2018). It may reflect greater rates of intervention in countries with higher human development indices (HDIs) where there is a greater need for conservation owing to high rates of peatland degradation (Chapman *et al.* 2003) and a greater capacity to fund conservation interventions (Waldron *et al.* 2013). Furthermore, results from these countries are more likely to be published in the English-language scientific journals that were the focus of literature searches for the synthesis (Fazey *et al.* 2005, Trimble & van Aarde 2012). Finally, we recognise that additional literature suggested by the advisory board contributed to the geographical bias in the synthesis. Although the board represented five continents, most advisors (6 of 11) were based in Europe or North America and 69 % of publications included in the synthesis based on advisors' suggestions were from Europe or North America.

Ideally, updates of the Peatland Evidence Synthesis will include tests of interventions from a wider geographical area. In the coming years, studies from countries with lower HDIs may become more prevalent as these countries start to repair the (more recently inflicted) damage to their peatlands (Graham *et al*. 2017). However, publication rates in scientific journals may still be influenced by institutional, linguistic and cultural barriers (Fazey *et al.* 2005). Thus, future updates to the Peatland Evidence Synthesis will reduce methodological bias by screening more grey literature sources and more sources in languages other than English.

We encourage critical thinking about what to monitor in order to best document the effects of interventions. The Peatland Evidence Synthesis reports the current state of knowledge and reflects the metrics used in the literature, but there is considerable scope for improvement. For example, it is often important to know *which* species of *Sphagnum* moss responded to an intervention, because some species are associated with specific environmental conditions or peatland types (Rydin & Jeglum 2013). Currently, many studies just describe the response of *Sphagnum* overall. Similarly, overall species richness can be a useful summary of the vegetation community and is commonly reported, but this should be coupled with an indication of which species are present. This information is less commonly reported. Are the species characteristic of bogs or fens, of peatlands in general, of wetlands in general, or of non-wetland habitats? Are they native or non-native? Where possible, raw data should be made available alongside publications to increase the level of detail available to interested readers.

Echoing a general call in ecology (Kuebbing *et al.* 2018), we also encourage more long-term studies of the effects of peatland conservation interventions. Short-term monitoring, up to around four years post-intervention, was common in publications captured for the Peatland Evidence Synthesis (Figure 4). This can generate misleading conclusions about the effects of an intervention based on responses during transitional periods. For example, burning was carried out to control heather (*Calluna vulgaris*) on a bog in Moor House National Nature Reserve, UK. Cover of cottongrasses (*Eriophorum* spp.) increased in the short term (within ca. 12 years of burning) but heather resumed its dominance over the longer term (after more than 12 years without burning) (Hobbs 1984, Taylor *et al.* 2018a). Long-term monitoring is especially important in peatlands and other ecosystems that may undergo extended periods of re-adjustment following conservation interventions. Vegetation can take decades to colonise peatlands and a fully functioning peatland ecosystem can take millennia to develop (Joosten 1995, Lavoie *et al.* 2003). Long-term monitoring is also important to record the effects of interventions under a changing climate. Novel methods such as satellite and drone imaging may reduce the cost of, and effort required for, long-term peatland monitoring.

The Conservation Evidence project continues to synthesise available evidence for the effects of interventions. Alongside other topics, progress is underway on evidence syntheses to cover vegetation in non-peat wetlands. In the coming years the Peatland Evidence Synthesis will be refined and updated. We welcome constructive feedback, particularly suggestions of quantitatively monitored tests of conservation interventions and especially from practitioners and managers - who we hope will be some of the primary users of, and contributors to, evidence-based conservation.

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NGT, PG and WJS were authors of the original synthesis which provided the data for this article. MSF, EG, LLBG, AR, RvD and JW were on the advisory board for the synthesis; and NGT, EG, LLBG, EK, RAL, DAL, NO, AR and JW contributed to the expert assessment. NGT conceived, designed and performed the analyses for this article, and wrote the first draft. All authors commented on the first and subsequent drafts.

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Appendix

List of all 125 interventions in the Peatland Evidence Synthesis. Interventions are generally grouped by the IUCN threat category (Salafsky *et al*. 2008) that they could be used to address. There are additional groups for interventions that could be used to address a variety of threats (i.e. habitat creation and restoration, habitat protection, education and awareness) and interventions used to complement planting of desirable peatland vegetation. The interventions are explained in more detail in the Peatland Evidence Synthesis.

The coloured points indicate the overall effectiveness category for the intervention, based on expert assessment: Beneficial; Likely to be beneficial; Trade-off between benefit and harms; Unlikely to be beneficial; Likely to be ineffective or harmful; Unknown effectiveness (limited evidence); No evidence (not assessed). We stress that these are generalised scores, and that Peatland Evidence Synthesis should be consulted for further details of the effects of the interventions.

1. Threat: Residential and commercial development

- Remove residential or commercial development from peatlands
- Retain/create habitat corridors in developed areas

2. Threat: Agriculture and aquaculture

Multiple farming systems

- Implement 'mosaic management' of agriculture
- Retain/create habitat corridors in farmed areas

Wood and pulp plantations

- Cut/remove/thin forest plantations
- Cut/remove/thin forest plantations and rewet peat

Livestock farming and ranching

- Use barriers to keep livestock off ungrazed peatlands
- Exclude or remove livestock from degraded peatlands
- Reduce intensity of livestock grazing
- Change type of livestock
- Change season/timing of livestock grazing

3. Threat: Energy production and mining

- Replace blocks of vegetation after mining or peat extraction
- Retain/create habitat corridors in areas of energy production or mining

4. Threat: Transportation and service corridors

- Backfill trenches dug for pipelines
- Maintain/restore water flow across service corridors
- Retain/create habitat corridors across service corridors

5. Threat: Biological resource use

- Reduce frequency of harvest
- Reduce intensity of harvest
- Use low impact harvesting techniques
- Use low impact vehicles for harvesting

- Implement 'mosaic management' when harvesting wild biological resources
- Provide new technologies to reduce pressure on wild biological resources

6. Threat: Human intrusions and disturbance

- Restrict vehicle use on peatlands
- Physically exclude vehicles from peatlands
- Restrict pedestrian access to peatlands
- Physically exclude pedestrians from peatlands
- Install boardwalks/paths to prevent trampling
- Wear snowshoes to prevent trampling
- Adopt ecotourism principles/create an ecotourism site

7. Threat: Natural system modifications

Modified water management

- Rewet peatland (raise water table)
- Irrigate peatland
- Reduce water level of flooded peatlands
- Restore natural water level fluctuations

Modified vegetation management

- Cut/mow herbaceous plants to maintain or restore disturbance
- Remove plant litter to maintain or restore disturbance
- Cut large trees/shrubs to maintain or restore disturbance
- Use grazing to maintain or restore disturbance
- Use prescribed fire to maintain or restore disturbance

Modified wild fire regime

- Thin vegetation to prevent wild fires
- Rewet peat to prevent wild fires
- Build fire breaks
- Adopt zero burning policies near peatlands

8. Threat: Invasive and other problematic species

All problematic species

- Implement biosecurity measures to prevent introductions of problematic species

Problematic plants

- Physically remove problematic plants
- Physically damage problematic plants
- Use cutting/mowing to control problematic herbaceous plants
- Change season/timing of cutting/mowing
- Use cutting to control problematic large trees/shrubs
- Use grazing to control problematic plants
- Use prescribed fire to control problematic plants
- Use covers/barriers to control problematic plants
- Use herbicide to control problematic plants
- Introduce an organism to control problematic plants

Problematic animals

- Exclude wild herbivores using physical barriers
- Control populations of wild herbivores

9. Threat: Pollution

Multiple sources of pollution

- Clean waste water before it enters the environment
- Divert/replace polluted water source(s)
- Slow down input water to allow more time for pollutants to be removed
- Retain or create buffer zones between pollution sources and peatlands
- Use artificial barriers to prevent pollution entering peatlands
- Reduce fertilizer or herbicide use near peatlands
- Manage fertilizer or herbicide application near peatlands

Agricultural and aquacultural effluents

- Convert to organic agriculture or aquaculture near peatlands
- Limit the density of livestock on farmland near peatlands
- Use biodegradable oil in farming machinery
- Remove oil from contaminated peatlands

Airborne pollutants

- Remove pollutants from waste gases before they enter the environment
- Add lime to reduce acidity and/or increase fertility
- Drain/replace acidic water

10. Threat: Climate change and severe weather

- Add water to peatlands to compensate for drought
- Plant shelter belts to protect peatlands from wind
- Build barriers to protect peatlands from the sea
- Restore/create peatlands in areas that will be climatically suitable in the future

11. Habitat creation and restoration

General habitat creation and restoration

- Restore/create peatland vegetation (multiple interventions)
- Restore/create peatland vegetation using the moss layer transfer technique

Modify physical habitat only

- Fill/block ditches to create conditions suitable for peatland plants
- Excavate pools
- Reprofile/relandscape peatland
- Roughen peat surface to create microclimates
- Remove upper layer of peat/soil
- Bury upper layer of peat/soil
- Disturb peatland surface to encourage growth of desirable plants
- Add inorganic fertilizer
- Cover peatland with organic mulch
- Cover peatland with something other than mulch
- Stabilize peatland surface to help plants colonize

- Introduce nurse plants
- Build artificial bird perches to encourage seed dispersal

Introduce peatland vegetation

- Directly plant peatland mosses
- Directly plant peatland herbs
- Directly plant peatland trees/shrubs
- Add mosses to peatland surface
- Add mixed vegetation to peatland surface
- Introduce seeds of peatland herbs
- Introduce seeds of peatland trees/shrubs

12. Actions to complement planting

- Add lime (before/after planting)
- Add inorganic fertilizer (before/after planting)
- Add organic fertilizer (before/after planting)
- Cover peatland with organic mulch (after planting)
- Cover peatland with something other than mulch (after planting)
- Introduce nurse plants (to aid focal peatland plants)
- Rewet peatland (before/after planting)
- Irrigate peatland (before/after planting)
- Reprofile/relandscape peatland (before planting)
- Create mounds or hollows (before planting)
- Remove upper layer of peat/soil (before planting)
- Bury upper layer of peat/soil (before planting)
- Add fresh peat to peatland (before planting)
- Encapsulate planted moss fragments in beads/gel
- Use fences or barriers to protect planted vegetation
- Remove vegetation that could compete with planted peatland vegetation
- Add root-associated fungi to plants before planting
- Protect or prepare vegetation before planting (other interventions)

13.Habitat protection

- Legally protect peatlands
- Create legislation for 'no net loss' of wetlands
- Adopt voluntary agreements to protect peatlands
- Pay landowners to protect peatlands
- Increase 'on-the-ground' protection (e.g. rangers)
- Allow sustainable use of peatlands

14. Education and awareness

- Raise awareness about peatlands amongst the public (general)
- Raise awareness about peatlands amongst the public (wild fire)
- Raise awareness about peatlands amongst the public (problematic species)
- Raise awareness through engaging volunteers in peatland management or monitoring
- Provide education or training programmes about peatlands or peatland management
- Lobby, campaign or demonstrate to protect peatlands