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Peatland core domain sets: building consensus on what should be measured in research and monitoring

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SUMMARY

It is often difficult to compile and synthesise evidence across multiple studies to inform policy and practice because different outcomes have been measured in different ways or datasets and models have not been fully or consistently reported. In the case of peatlands, a critical terrestrial carbon store, this lack of consistency hampers the evidence-based decisions in policy and practice that are needed to support effective restoration and conservation. This study adapted methods pioneered in the medical community to reach consensus over peatland outcomes that could be consistently measured and reported to improve the synthesis of data and reduce research waste. Here we report on a methodological framework for identifying, evaluating and prioritising the outcomes that should be measured. We discuss the subsequent steps to standardise methods for measuring and reporting outcomes in peatland research and monitoring. The framework was used to identify and prioritise sets of key variables (known as core domain sets) for UK blanket and raised bogs, and for tropical peat swamps. Peatland experts took part in a structured elicitation and prioritisation process, comprising two workshops and questionnaires, that focused on climate (32 and 18 unique outcomes for UK and tropical peats, respectively), hydrology (26 UK and 16 tropical outcomes), biodiversity (8 UK and 22 tropical outcomes) and fire-related outcomes (13, for tropical peatlands only). Future research is needed to tackle the challenges of standardising methods for data collection, management, analysis, reporting and re-use, and to extend the approach to other types of peatland. The process reported here is a first step towards creating datasets that can be synthesised to inform evidence-based policy and practice, and contribute towards the conservation, restoration and sustainable management of this globally significant carbon store.

KEY WORDS: evidence-based policy and practice, evidence synthesis, outcomes, standardisation

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INTRODUCTION

The use of evidence to inform policy is often limited by the availability of comparable data that can be integrated across studies and sites. It is rare to find individual studies that conclusively resolve a major knowledge gap or controversy relevant to policy, whose findings are consistently reproduced by others; what Platt (1964) described as "crucial experiments". Instead, knowledge mostly tends to advance through the accumulation of sometimes conflicting evidence via multiple studies of the same phenomena using different methods in different contexts (Poincare 1905, Forscher 1963, Nelder 1986, Pickett 1999, Kemp & Boynton 2021). The most robust and unbiased inferences about the

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phenomena under consideration are best derived when different findings can be compared using synthesis methods (e.g. see Norris *et al.* (2012), Sutherland *et al.* (2012, 2019) and Shackelford *et al.* (2021) for some contemporary approaches to evidence synthesis in environmental science and conservation).

Decision-makers who use the results of scientific studies need robust evidence to inform policies across a range of contexts. However, it is difficult to combine insights from different studies about the same subject when different outcomes have been measured in different ways or when datasets or models are not fully or consistently reported (Kadykalo *et al.* 2020). Without standardised information about the outcome of interest, measured on scales that map to combinable statistical distributions, it is difficult to synthesise findings (Hennessy *et al.* 2022). As a result, policy-makers confronted with conflicting findings may lack the information they need to make decisions about policy goals. Such problems are particularly prevalent in environmental and some social sciences, where effect sizes are not routinely reported or published, and pre-publication analyses are not independently replicated (Kieffer *et al.* 2001, Fidler *et al.* 2005, Callahan & Reio 2006, Freese & Peterson 2017). Furthermore, scientists in these disciplines are not usually given training in the methods needed to inform their peer review work or literature reviews. Selective reporting and publication bias further hamper attempts to synthesise findings across multiple studies to determine whether there is sufficiently robust evidence to support a policy intervention (Dwan *et al.* 2008, Parker *et al.* 2016). It may also be difficult to directly compare policy options because researchers often evaluate options in different ways, e.g. using different metrics to assess whether an option enhances biodiversity or mitigates climate change. As a result, some decisions in policy and practice are informed by the results of individual studies, which are often contradicted by the findings of subsequent research, undermining policies as well as public trust in research (Cairney 2016, 2021).

For these and other reasons, a large proportion of research (estimated at 85 % in the field of health; Glasziou & Chalmers 2018, Yordanov *et al.* 2018) may never be used in practice, or cannot be applied beyond the narrow context in which the data were collected. This is a particular challenge for national governments, research funders, and international programmes that seek to use evidence to inform policy and practice at geographical population scales and timescales far beyond the scope of most individual research studies. As a result, there are growing calls to standardise how data are collected and reported, so they can be included in syntheses that can better inform policy and practice (Gurevitch *et al.* 2018, Nichols *et al.* 2021).

In an attempt to consolidate and standardise the data used in policy processes, a number of initiatives have set out to create standardised sets of criteria and indicators that can be used to inform and monitor policy outcomes, e.g. Pereira *et al.*'s (2013) Essential Biodiversity Variables, pan-European criteria and indicators for sustainable forest management (Baycheva-Merger & Wolfslehner 2016) and desertification (Zucca *et al.* 2021), and the standardised approach of the European Commission Align project (https://ec.europa.eu/environment/biodiversity/business/align/) to biodiversity measurement for the accounting sector (Align Project 2022). However, these tend to be highly prescriptive, based on the needs and purpose of specific policies and sectors, and there are few examples of these being adopted more widely by the research community to rationalise and standardise research and monitoring effort.

Standardisation of data collection and reporting has some exemplars beyond monitoring programmes. For example, the Global Biodiversity Information Facility (GBIF) is an international network and data infrastructure providing open access to biodiversity data (Flemons *et al.* 2007). Several United Nations agencies collaborated to set up the Global Terrestrial Observing System (GTOS) and proposed datasets and approaches for essential terrestrial climate variables for climate change assessment (Sessa & Dolman 2008). There are a number of global data collection initiatives, such as the Amazon Forest Inventory Network (RAINFOR; http://www.rainfor.org) (Malhi *et al.* 2004), ForestPlots (http://www.forestplots.net; Lopez-Gonzalez *et al.* 2011), the FLUXNET Network (https://fluxnet.org/; Baldocchi *et al.* 2001), the Food and Agriculture Organization of the United Nations (FAO) Global Forest Resources Assessment (Keenan *et al.* 2015), the TRY Plant Trait Database (https://www.try-db.org/; Fraser 2020), a database of northern peatland soil properties and Holocene carbon and nitrogen accumulation (Loisel *et al.* 2014), the newly established PeatDataHub (https://peatdatahub.net; Young *et al.* 2016) and the Eyes on the Bog citizen science initiative (https://www.iucn-uk-peatlandprogramme.org/get-involved/eyes-bog; Lindsay *et al.* 2019).

By agreeing what to measure and how to measure, quality assure and report it, initiatives like ForestPlots have facilitated global syntheses on forest ecology within and across tropical regions

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(e.g., Draper *et al.* 2021, ForestPlots.net *et al.* 2021). Similarly, Long-Term Ecological Research networks have used common methods to facilitate cross-site syntheses to measure environmental change in a number of countries (Knapp *et al.* 2012). Attempts have been made to extend this work to include socio-economic variables (Redman *et al.* 2004). FAO has done decades-long work on refining forest-related definitions (FAO 2002a, 2002b, 2018) and used them to produce the most comprehensive data covering all countries in the series of Global Forest Resources Assessment reports (FAO 2020a). Similar approaches have been advocated for standardisation of biodiversity data to inform progress against global targets (Pereira *et al.* 2013) and there have been repeated pleas for standardised reporting of the costs of conservation interventions to facilitate decision analysis (Pienkowski *et al.* 2021). Shared vocabularies and shared standards that facilitate data sharing and reuse have been developed for databases of species traits in some taxa (Schneider *et al.* 2019) and for species occurrence data (e.g., the Darwin Core standard used by GBIF; Wieczorek *et al.* 2012). A number of similar approaches have also been developed in wider soil and water contexts. For example, Holmquist *et al.* (2018) developed a standardised approach to data collection in tidal wetland soils, and Diefenderfer *et al.* (2011, 2016) developed a levels-of-evidence approach to integrate river restoration knowledge and evidence that facilitates assessment of the cumulative landscape effects of restoration actions at multiple locations, incorporating data from restoration and reference sites, hydrodynamic modelling, geographic information systems and meta-analyses, in a five-stage process.

However, environmental science lacks a unified process that can be used by researchers in different disciplines to propose, agree and prioritise what should be measured and how it should be measured. In medicine there are communities of practice that have created such processes to develop sets of variables, or “core domain sets”. These provide an agreed standardised collection of target domain outcomes for measuring and reporting in a specific area of research. Core domain sets define the minimum number of outcomes that should be measured in a study. The ‘Outcome Measures in Rheumatology (OMERACT)’ initiative pioneered this movement in 1992 and developed an extensive methodology that we applied in our current study (Boers *et al.* 1998, Tugwell *et al*. 2007, Boers *et al.* 2014). More recently, the need for core outcomes in medicine has resulted in the establishment of the COMET (Core Outcome Measures in Effectiveness Trials; Williamson *et al.* 2017, 2020) initiative, which brings together people interested in the development and application of agreed standardised sets of outcomes and provides methodological guidance on developing them (Gargon *et al.* 2014).

Here we adapted the OMERACT approach and applied it to environmental science and conservation, using peatlands as a case study. We chose peatlands because they are amongst the world’s most carbon-dense terrestrial carbon stores and are important for the livelihoods of some of the most remote and impoverished populations in the tropics (UNEP 2017). Peatlands are made up of partially decayed plants that accumulate under waterlogged conditions. Intact peatlands have been long-term carbon sinks but, if their structure is damaged, they become a major source of greenhouse gases (GHGs). Globally ~11 % of peatlands have been modified and drained, and despite covering less than 0.4 % of the global land area, these peatlands are responsible for ~5 % of global anthropogenic GHG emissions (Leifeld & Menichetti 2018, Leifeld *et al.* 2019). In the last three decades, peatland conservation and restoration has emerged as a key solution to fight climate change and global biodiversity declines (Tanneberger *et al.* 2021). However, a key challenge remains the scaling up of global efforts in a cost-effective way, which should be underpinned by robust evidence (Rochefort & Andersen 2017). This challenge is compounded by a lack of consistent data on peatland, climate, hydrological and biodiversity outcomes. Although FAO (2020b) proposed examples of metrics for monitoring different types of peatlands for climate change reporting, it was limited to climate-related outcomes and there remains a lack of consensus in the research and monitoring community about which of these outcomes are most important to measure and report.

We therefore propose a methodological framework, based on the process defined by OMERACT, for identifying, evaluating, and prioritising the core outcomes to be measured, and discuss subsequent steps towards achieving standardised measurement methods and reporting. We used the framework to select core domain sets focused on the core areas of climate, hydrology and biodiversity for UK blanket and raised bogs. In tropical peat swamps we focused on the same core areas as for the UK but with the addition of fire, given that many tropical peatlands are forested and prone to wildfire. The UK peatlands were selected to develop and refine our approach, following calls to standardise monitoring from the policy community (Bain *et al.* 2011, Reed *et al.* 2020, DEFRA 2021). We then applied what we had learned to tropical peat swamps, which are responsible for most peatland GHG emissions (Crump 2017).

In this first stage, our aim was to focus on *what* to measure and not *how* to measure or report it. While future research is required to define the measurement instruments and reporting procedures needed to improve our ability to synthesise data from peatlands, we hope that the process and core domain sets identified in this article will be used as a starting point to direct research and monitoring that seeks to achieve climate, hydrological or biodiversity objectives, so that these data collection efforts will converge on a more standardised set of outcomes. Thus it should become possible to use meta-analysis and other forms of evidence synthesis to better inform decision making on the protection, restoration and sustainable use of peatlands (Carmenta *et al.* 2021).

METHODS

Definitions

We use the following definitions, adapted from Boers *et al.* (2014) and D'Agostino *et al.* (2021):

- A "core area" is an aspect of the natural environment that needs to be measured to understand peatlands. An example would be climate.
- Core areas are broad concepts consisting of a number of more specific concepts called "broad domains", for example GHG flux.
- Broad domains can be sub-divided into "(sub)domains" (Boers *et al.* 2014) or "target domains" (D'Agostino *et al.* 2021): the most specific concepts to be measured. When measured, these give rise to quantitative or qualitative "outcomes", which Boers *et al.* (2014) define as "any identified result in a target domain arising from exposure to a causal factor or … intervention". In this article we refer to target domain outcomes, sometimes abbreviated to core outcomes, or just outcomes. An example would be methane flux.
- The "outcome measurement instruments" used to assess each outcome can then be specified, e.g. closed chambers or micrometeorological towers.
- The "core domain set" is the minimum set of broad and target domains necessary to study a core area. These provide a standardised set of outcomes that should be measured for any given core area of peatland research or monitoring (e.g. by researchers, practitioners, managers or citizens).
- A "contextual variable" is one that is not an outcome in a study, but needs to be recognised and measured to interpret the study results, for example site location or site history.

For each core area, the core domain set defines '*what*' outcomes to measure and is coupled to the agreed methods of '*how*' they should be measured (the outcome measurement instruments) (Figure 1). There could be several broad domains within each core area, several target domain outcomes within each broad domain, and many alternative measurement instruments related to each target domain outcome, the use of which would depend on a project's objectives and resources.

Methodological framework

We used four steps to generate, agree and vote on core domain sets:

1. Expert identification through citation analysis (using Elsevier's SciVal tool), stakeholder analysis (Reed *et al.* 2009) and snowball sampling, in which experts help define additional experts based on their knowledge and networks (Goodman 1961).
2. Pre-workshop questionnaire to identify preliminary broad and target domains, inductively clustered into related core areas (biodiversity, hydrology and climate).
3. Deliberation over broad and target domains in a workshop setting to supplement and amend these and decide on the most appropriate clustering of target domains into broad domains.
4. Post-workshop questionnaire to identify core domain sets by voting on the relative importance of each target domain outcome in relation to their relevance for assessing common research and policy objectives.

In the methodological framework depicted in Figure 2, two additional steps (not undertaken in this project) are needed to ensure that data are generated and reported in ways that can be effectively synthesised:

1. The methods required for each target domain outcome, seeking methods that range from highly accurate (but potentially time-consuming, costly, and requiring high levels of expertise) to proxy methods (which may be less accurate but may be more feasible for those with limited resources and expertise).
2. Reporting protocols and platforms identified to standardise open data reporting and allow the capture of contextual data (e.g. site location, habitat and environmental condition).

As evidence grows and methods evolve, it is important to revisit the steps above on a regular basis,

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to ensure the core domain sets and their associated outcomes and measurement instruments remain up-to-date.

The research steps above are designed around the following questions (Figure 1):

- What is the scope - what do we want to know about the peatland habitats of interest?
- What are the broad domains within which we might define outcomes in these peatlands?
- What target domain outcomes should be measured in each type of peatland? Which of these outcomes are the most important to measure?
- How should each outcome be measured?
- How and when should the data be reported so that they can be synthesised and interpreted effectively?

Data collection

UK blanket and raised bogs

We used stakeholder analysis (Reed *et al.* 2009) to identify peatland experts (from research, policy, and practice), followed by a snowball sample (Goodman 1961). In the snowball sample we asked those identified in the stakeholder analysis to recommend other experts for consideration. We used the Delphi approach (Moseley & Mead 2001) to conduct two expert questionnaire surveys, with the aim of seeking consensus on core outcomes. In the first questionnaire, experts were asked to identify broad domains and their associated target domains or outcomes, relevant to blanket and raised bogs. A total of 49 participants were invited to complete the first questionnaire (which received 22 responses) to identify potential outcomes in three pre-defined core areas. Given differences in the functioning of blanket and raised bogs versus fens (fens have greater water exchange and are less acidic), the study focused only on blanket and raised bogs to avoid confusion in the prioritisation of outcomes, which may differ between these habitats.

We decided to focus on biophysical domains, which we represented in three core areas to cover the main functions of peatlands; climate, hydrology, and biodiversity. The identification of social, economic and cultural domains (e.g. place identity or attachment outcomes) was left for future work, given the complexity of these additional areas.

In the first questionnaire, participants were invited to propose outcomes within each of the three core areas. In each case, two examples of outcomes were provided and respondents were asked to add additional outcomes. We also included three broad questions about the existence or future use of core outcomes within peatland science (see SUK1 in the Supplementary Material).

We used the questionnaire results as a starting point for a workshop to which questionnaire participants were invited (Newcastle-upon-Tyne, UK, March 2018; attended by 32 participants; Figure 3). Participants worked in three discussion groups (one for each of the core areas), which they self-selected based on their expertise.

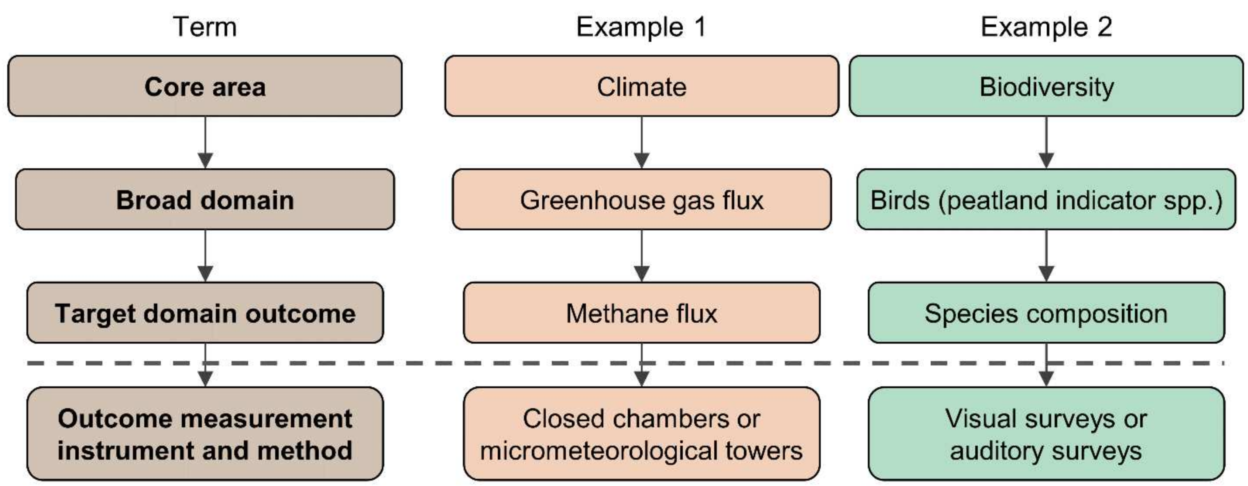

Figure 1. Conceptual organisation of core areas, domains and outcomes - which are prioritised and short-listed to define core domain sets of the minimum set of broad domains and target domain outcomes that should be measured - showing examples from peatlands, based on this research. The scope of the work reported here is shown above the dashed line. Future research could identify the method and outcome measurement instruments for each of the outcomes that this research has prioritised in the core domain sets.

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At the workshop, participants were first invited to review, discuss, amend and add to the lists from the survey of potential outcomes and, if necessary, amend the broad domains into which they were clustered. They were also asked to identify contextual variables that should, where possible, be measured and reported alongside the outcomes for the core area. The work of each group was then presented in plenary for feedback and discussion, paying special attention to points of difference between participants, leading to a final, refined long list of outcomes clustered in broad domains in each of the three core areas.

Finally, to gain consensus on which outcomes should be prioritised as core outcomes within each broad domain, we asked participants to vote on the importance of each outcome. This stage was done via a second questionnaire (see SUK2 in the Supplementary Material), sent post workshop to all workshop participants plus an additional six experts who were unable to attend the workshop, and drew on multi-criteria evaluation methods (Zopounidis & Pardalos 2010). This questionnaire was also made available at the IUCN UK Peatland Programme's 2019 annual conference in Belfast, UK. We received 19 complete responses to the second questionnaire.

Before voting, participants were required to indicate their level of expertise, and were asked to evaluate only the outcomes in the core areas in which they had extensive or expert knowledge:

- Extensive: "I regularly work in this field and have a very good working knowledge of the topic. I have contributed to field guides or the research literature about this topic"; or
- Expert: "I work extensively in this field and have a full working knowledge of the topic. I actively contribute to the research literature about this topic".

Respondents were asked to assign a score to each outcome to indicate if it should be considered low (a score of 1–3), medium (4–6) or high (7–9) priority for research or monitoring projects that sought to achieve climate, hydrological or biodiversity objectives. These data were analysed to identify outcomes that were considered a high priority by 70 % or more of the respondents who scored them (outcomes could be skipped if respondents were unsure about them). The decision to adopt the 70 % threshold was based on the OMERACT methodology (Tugwell *et al.* 2007, Boers *et al.* 2014), but is otherwise arbitrary and could be revisited in future research. For this reason we discuss a number of outcomes that did not reach the threshold, which may merit further consideration.

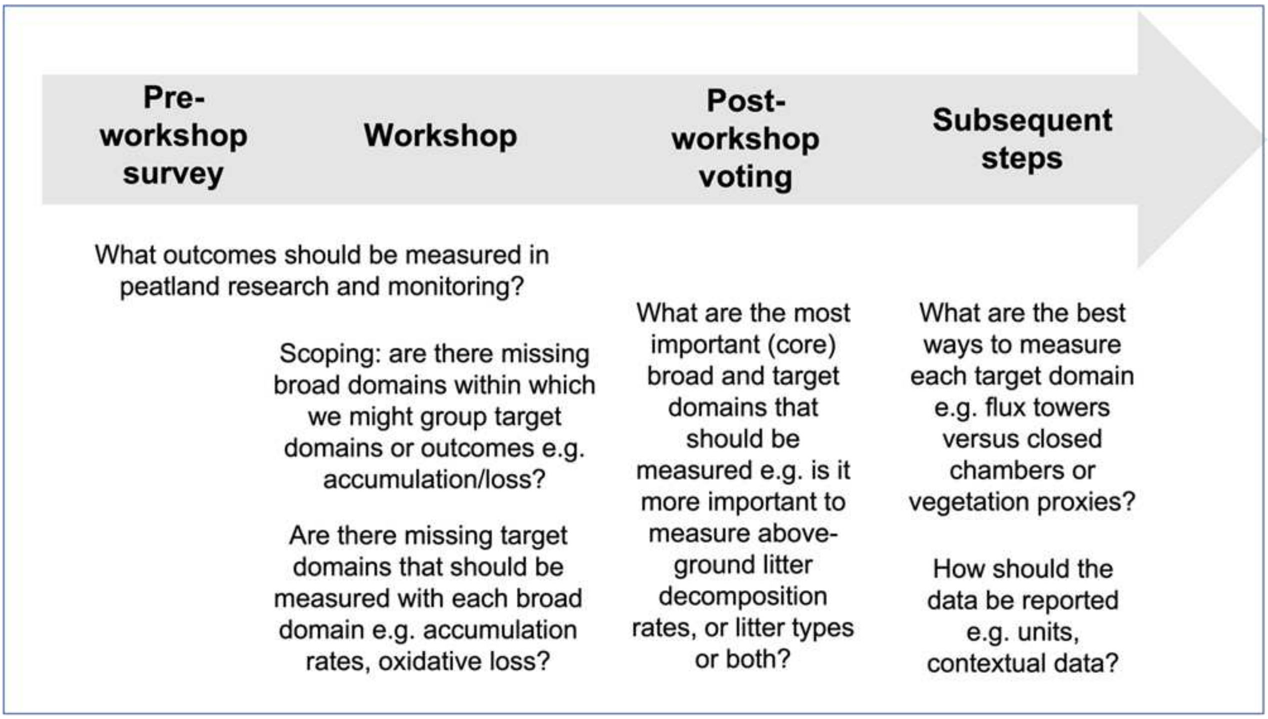

Figure 2. Methodological framework for agreeing core domain sets of standardised outcomes that should be measured in peatland research and monitoring (subsequent steps were not undertaken in the research reported in this article).

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Tropical peat swamps

We refined our approach to apply the above process to tropical peat swamps, using a more objective method for selecting experts and adapting the policy criteria to the tropical context. This included the addition of criterion-based selection of researchers alongside the stakeholder analysis and snowball sampling carried out in the UK. Our aim was to invite researchers and those involved in monitoring peatlands from all continents with tropical peatlands. We identified researchers who had published tropical peatland research in the last five years. We prioritised the 10 % (field-weighted) most cited researchers according to a SciVal analysis, then supplemented this list with less published and cited researchers as necessary to augment the sample in each continent. Although citations are crude indicators of expertise, our goal was to prioritise the peatland researchers from each continent with the most expertise and experience. Other people were identified as part of the stakeholder analysis, recommended by colleagues who could not participate, or as members of the Global Peatlands Initiative Research Working Group (GPI). Members of the GPI were invited to comment on and supplement the invitation list to ensure regional, disciplinary and gender balance as far as possible.

Next, following the UK-based process, participants were given a pre-workshop questionnaire (STR1 in the Supplementary Material) to identify an initial long list of outcomes for prioritisation. The questionnaire was sent to 41 participants and was completed by 17 people. Respondents were asked to identify broad domains and outcomes (or initiatives to do this) for tropical peatlands, along with potential uses for core outcomes arising from the workshop. Outcomes were clustered into broad domains within four broad core areas (climate, hydrology, biodiversity and fire; the latter added by workshop participants to recognise the importance of fire in tropical peatlands). These were discussed at a workshop in Bogor, Indonesia (July 2019) with 31 participants, all with experience working in tropical peatlands in Latin America, Africa and Asia (Figure 3).

Figure 3. Clockwise from top left: Participants discussing UK peatland domains in Newcastle, UK (March 2019); Dr Haruni Krisnawati from the International Tropical Peatland Centre opening the workshop to prioritise tropical peatland outcomes in Bogor, Indonesia (July 2019); participants prioritising policy objectives (Bogor); and deliberation over core outcomes (Bogor).

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We discussed each of the four core areas in parallel (see STR2), with experts self-selecting the thematic discussion that most strongly matched their expertise and experience. The work of each group was then presented to the wider group for feedback and discussion, leading to a final, refined long list of outcomes. In the second phase, a metaplan (clustering similar ideas on walls using sticky notes) and sticky dot prioritisation exercise (each participant was given ten dots; Reed 2018) was designed to elicit and prioritise criteria (against which outcomes could be evaluated via a questionnaire) with participants during the workshop rather than these being selected by the research team (as was done in the first phase).

Participants identified the following objectives for tropical peatland monitoring and research: climate change mitigation; sustainable management, protection and restoration; and social and economic goals. The extent to which each outcome could be used to provide valuable information against each of these objectives was then ranked via a post-workshop questionnaire (STR3; sent to 49 participants, consisting of the group who received the pre-workshop questionnaire and eight additional respondents who attended the workshop but had not participated in the pre-workshop exercise, resulting in 20 responses) using the same approach as the first phase (described above), to prioritise the most important outcomes that should be measured wherever possible in tropical peatland research and monitoring, leading to a core domain set for each core area. As with the UK questionnaire, participants were instructed to score only those outcomes and broad domains with which they were familiar, so the number of participants scoring outcomes differs between outcomes, broad domains and core areas. Given the large number of outcomes identified, participants were asked to evaluate contextual variables separately in relation to how important they thought these were for any of the three policy and research objectives.

In a final step, participants from the workshops in Newcastle and Bogor were invited to comment on the resulting lists of core domain sets. No outcomes were added or removed at this stage, but the wording of a small number of outcomes was edited for clarity and consistency.

RESULTS

For UK blanket and raised bogs, 32 unique climate outcomes were prioritised in six broad domains (Figure 4), 26 unique hydrological outcomes were prioritised in seven broad domains (Figure 5) and eight unique biodiversity outcomes were prioritised in four broad domains (Figure 6). Contextual variables that should be measured, where possible, and reported alongside outcomes for each core area were also identified, and are integrated with Figures 4–6.

For tropical peat swamps, 18 unique climate outcomes were prioritised in three broad domains (Figure 7), 16 unique hydrological outcomes were prioritised in four broad domains (Figure 8), 22 unique biodiversity outcomes were prioritised in four broad domains (Figure 9), and 13 unique fire outcomes were prioritised in a single broad domain (Figure 10). The number of respondents voting on contextual variables for each tropical core area was variable, ranging from three to nine responses. Given low response rates for two of the four core areas, these were combined in Table 1 to show where there was agreement for variables that should be monitored and reported alongside outcomes from all four core areas. Future research could usefully focus on refining agreement on the most important contextual variables to measure and report for each individual core area.

Note that some outcomes appear in multiple broad domains, both within and between the three core areas, and for multiple objectives within the same broad domain (e.g. DOC is relevant for measuring both GHG flux and water quality outcomes in the climate core area, and relevant to monitoring for both climate and hydrology objectives; Figure 4). Figures 4–10 only show outcomes that at least 70 % of participants agreed were important to measure, and the different colours indicate why they were deemed important in terms of the sorts of evidence and policy questions that any data collection initiative might be trying to answer. For example, in the accumulation/loss broad domain in the climate core area for tropical peat swamps (top right in Figure 7), participants thought it was important to measure emissions from fire in projects that focus on social or economic issues, on sustainable management, protection and restoration, and on climate change mitigation. On the other hand, measurements of bulk density and carbon content of peat were deemed important only for projects addressing climate change issues.

Although the lowland raised bogs and blanket bogs of the UK differ significantly from tropical peat swamps in terms of their ecology, hydrology, drivers of change and restoration practices, both shared several outcomes that participants agreed should be measured wherever possible. For example, participants agreed that it was important to measure the following climate outcomes in both UK and tropical peatland: rate of peat accumulation; changes

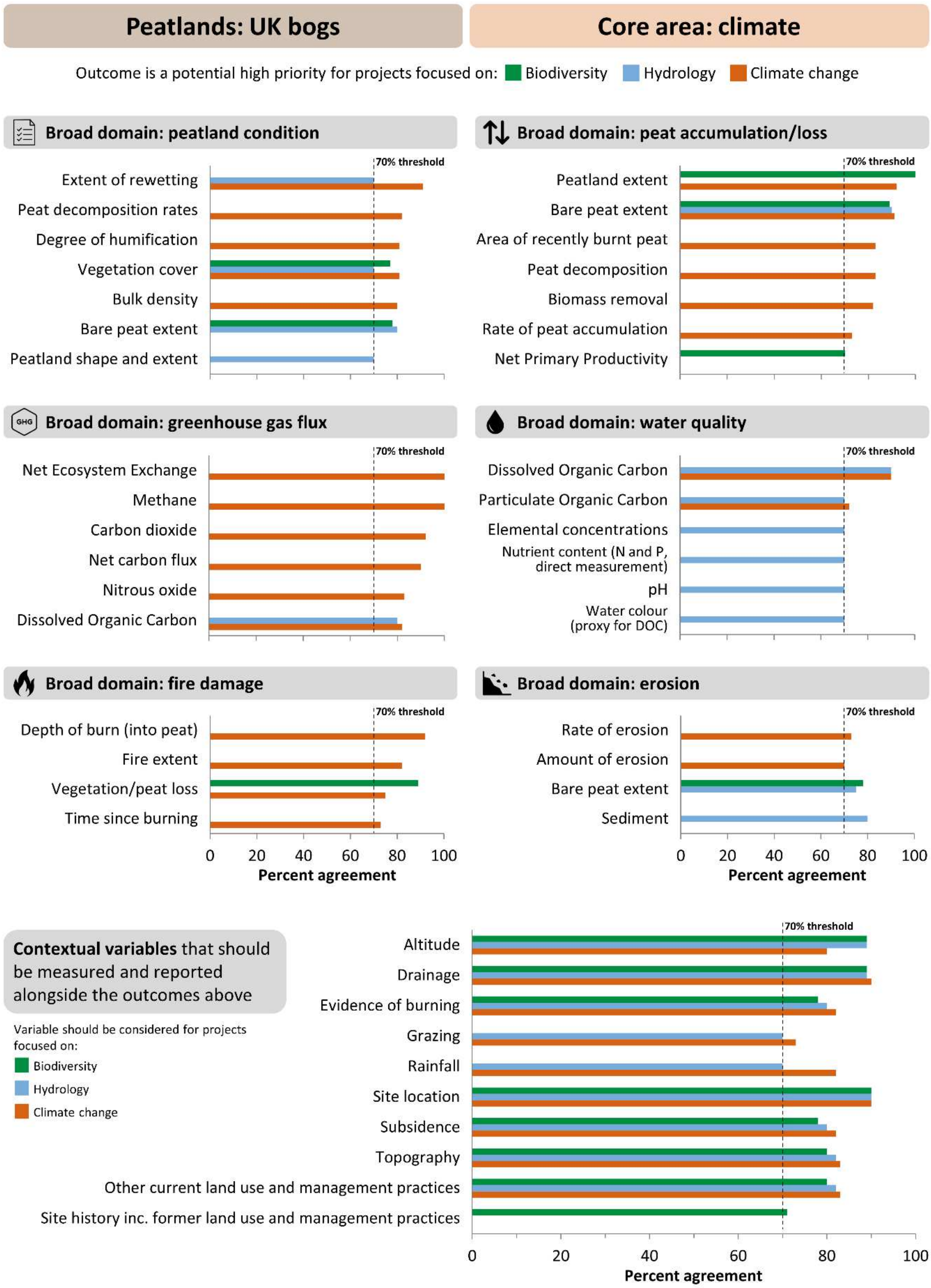

Figure 4. Climate core domain set, and the constituent target domain outcomes agreed by ≥ 70 % of respondents as potential high priorities for measurement in UK peatland research or monitoring, depending on the objective or focus of the research or restoration project (based on 12 expert responses). Scores < 70 % are not shown.

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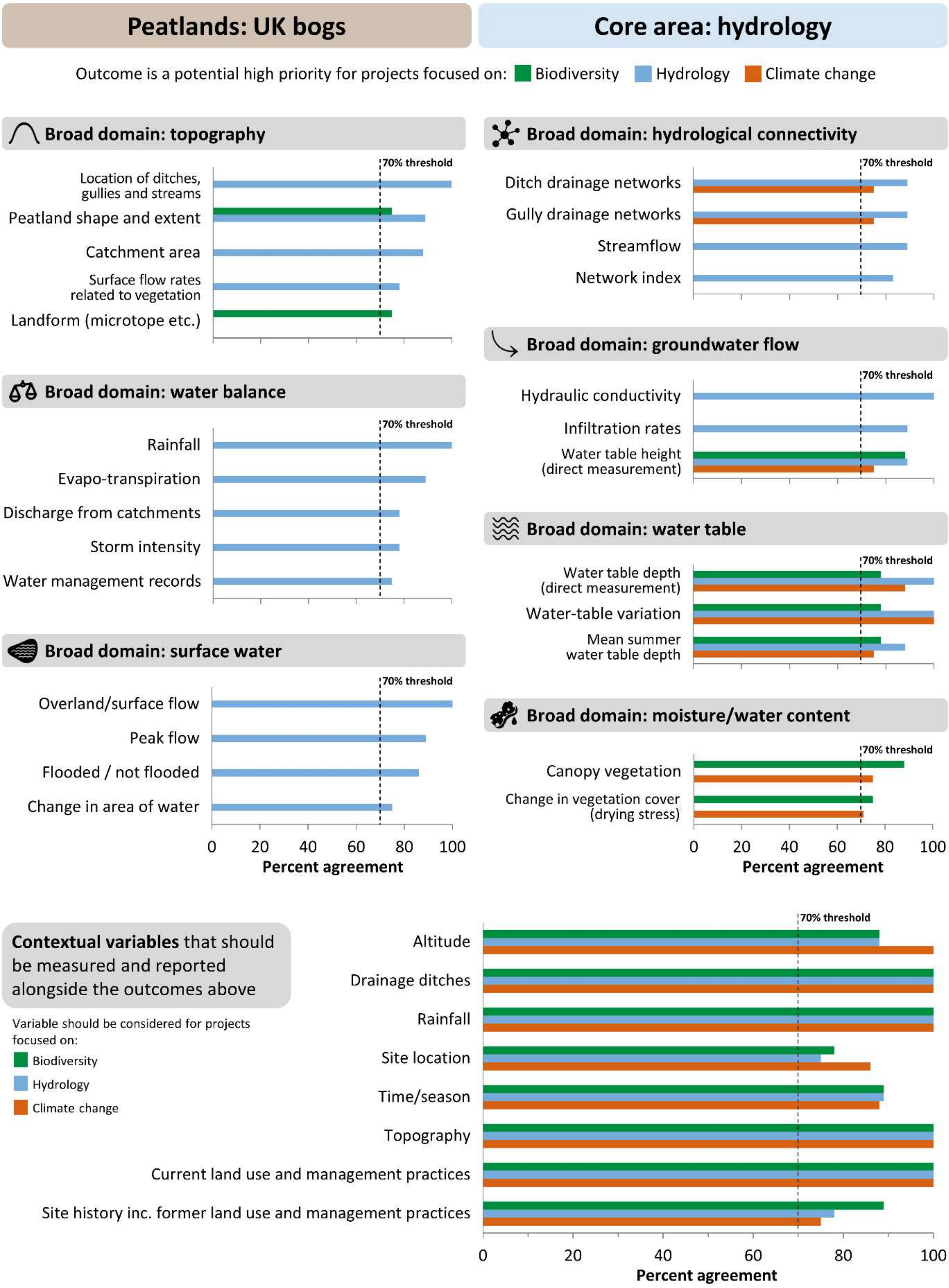

Figure 5. Hydrology core domain set, and the constituent target domain outcomes agreed by ≥ 70 % of respondents as potential high priorities for measurement in UK peatland research or monitoring, depending on the objective or focus of the research or restoration project (based on nine expert responses). Scores < 70 % are not shown.

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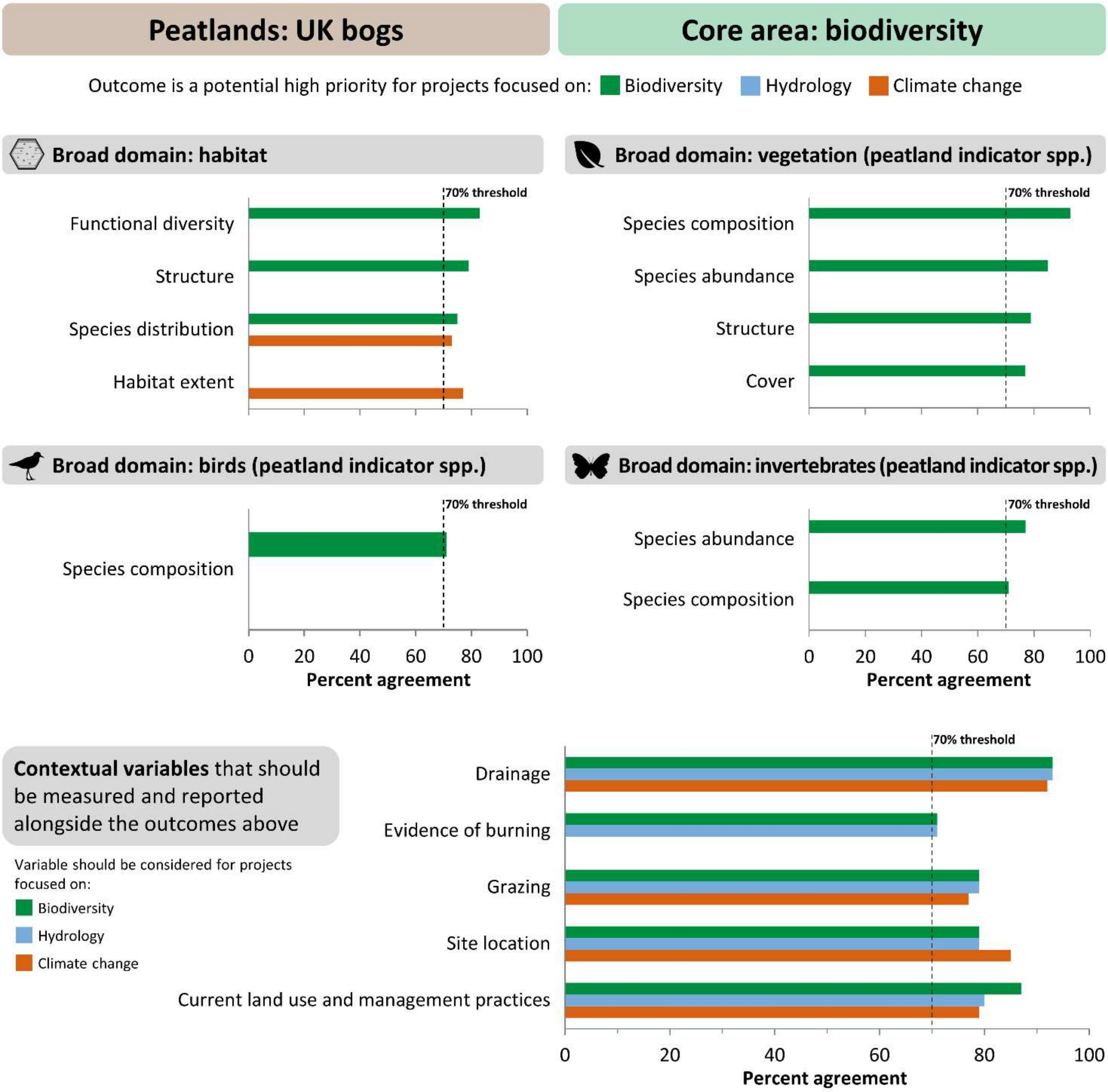

Figure 6. Biodiversity core domain set, and the constituent target domain outcomes agreed by ≥ 70 % of respondents as potential high priorities for measurement in UK peatland research or monitoring, depending on the objective or focus of the research or restoration project (based on 15 expert responses). Scores < 70 % are not shown.

in aboveground biomass (in tropical peatlands this included a range of outcomes related to trees); peat decomposition and oxidative loss; CO_2, CH_4, N_2O emissions and/or fluxes, and net carbon balance. Biodiversity outcomes common to both peatland contexts included: abundance and composition of peatland indicator species; functional diversity; and peatland habitat extent. Common hydrological outcomes included: direct measurements of water table depth; evidence of drainage networks; and hydraulic conductivity. Although there were many more fire-related outcomes identified for tropical peatlands, and an entire broad domain was dedicated to these, some were prioritised for measurement in both UK and tropical peatlands, including: time since burning; fire extent; and depth of burn (into peat).

A range of contextual variables were prioritised for measurement and reporting alongside these

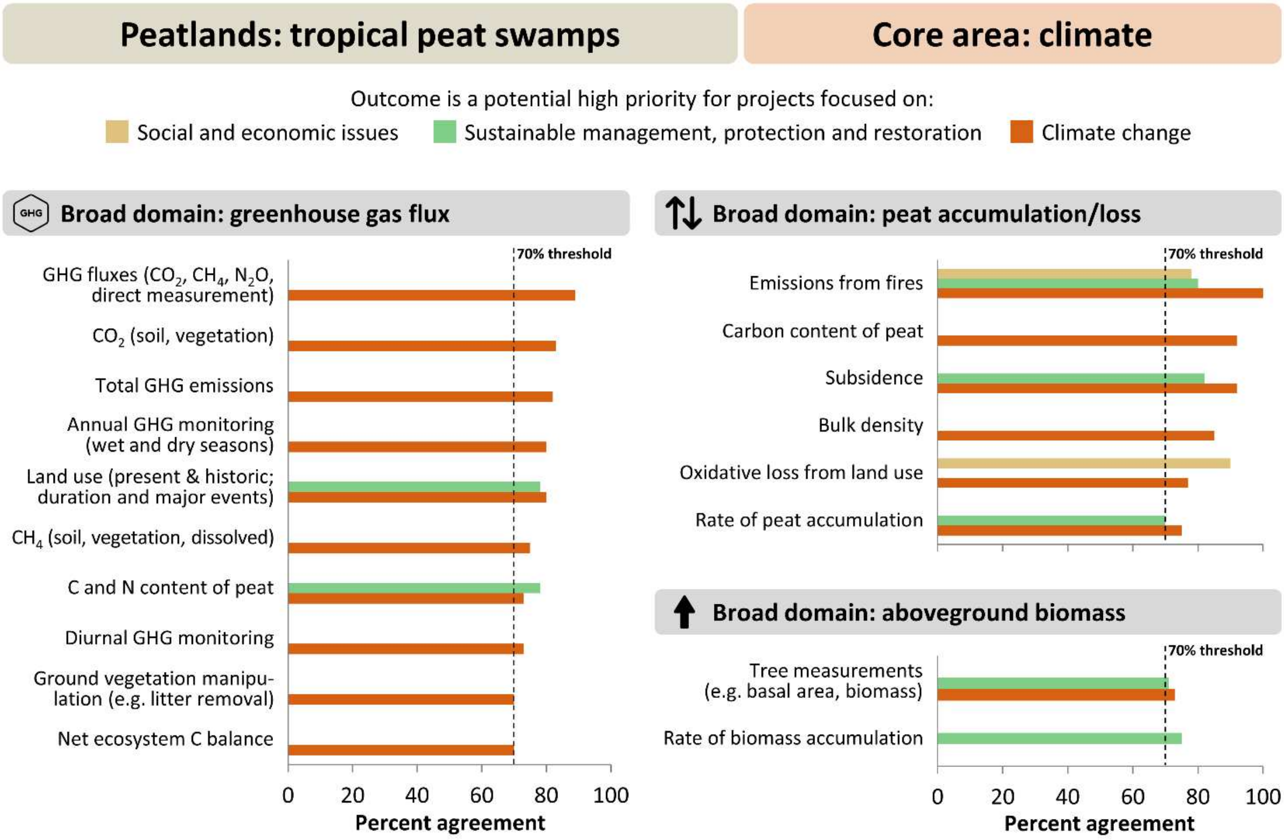

Figure 7. Climate core domain set, and the constituent target domain outcomes agreed by ≥ 70 % of respondents as potential high priorities for measurement in tropical peat swamp research or monitoring, depending on the objective or focus of the research or restoration project (based on 13 expert responses). Scores < 70 % are not shown.

outcomes to enable the user to make interpretations and judgements on the peatland where data were generated. It was universally accepted that location (data/maps) and land use (current and historic) should be reported alongside all climate, hydrological and biodiversity data in the UK and the tropics. Without this information, it would be difficult to assess the comparability of data from different studies. However, the importance of other contextual information varied depending on the core areas being considered, for example evidence of grazing and burning were deemed to be particularly important to report alongside climate and biodiversity data, but less important to report alongside hydrological data, where drainage and rainfall data were deemed more important for context.

It was not possible to evaluate the relevance of contextual variables for different core areas in the tropics, due to insufficient responses in this part of the questionnaire. As many studies and monitoring programmes are likely to draw from multiple core areas, an integrated single list of contextual variables to be collected alongside all other outcome data may be more usable in practice (as was developed for the tropical peatland broad domains in Table 1), with location and previous/historic land use data highlighted as a particular priority.

Given the limited sample of peatland experts engaging in this process, future work could revisit and refine the outcomes (and their definitions) prioritised. When reviewing the outcomes that were prioritised after the workshops (as part of the manuscript writing process), a number of participants commented on omissions of outcomes that had not been prioritised in the ranking process. For example, water table depth scored 64 % agreement in the UK climate core domain set, and so was not prioritised as a core outcome, despite evidence that water table depth has been identified as a key control of GHG fluxes (e.g. Evans *et al.* 2021). Therefore, outcomes that fell short of the consensus threshold would benefit from review and, if necessary, revision. A process for reviewing such outcomes would need to be agreed.

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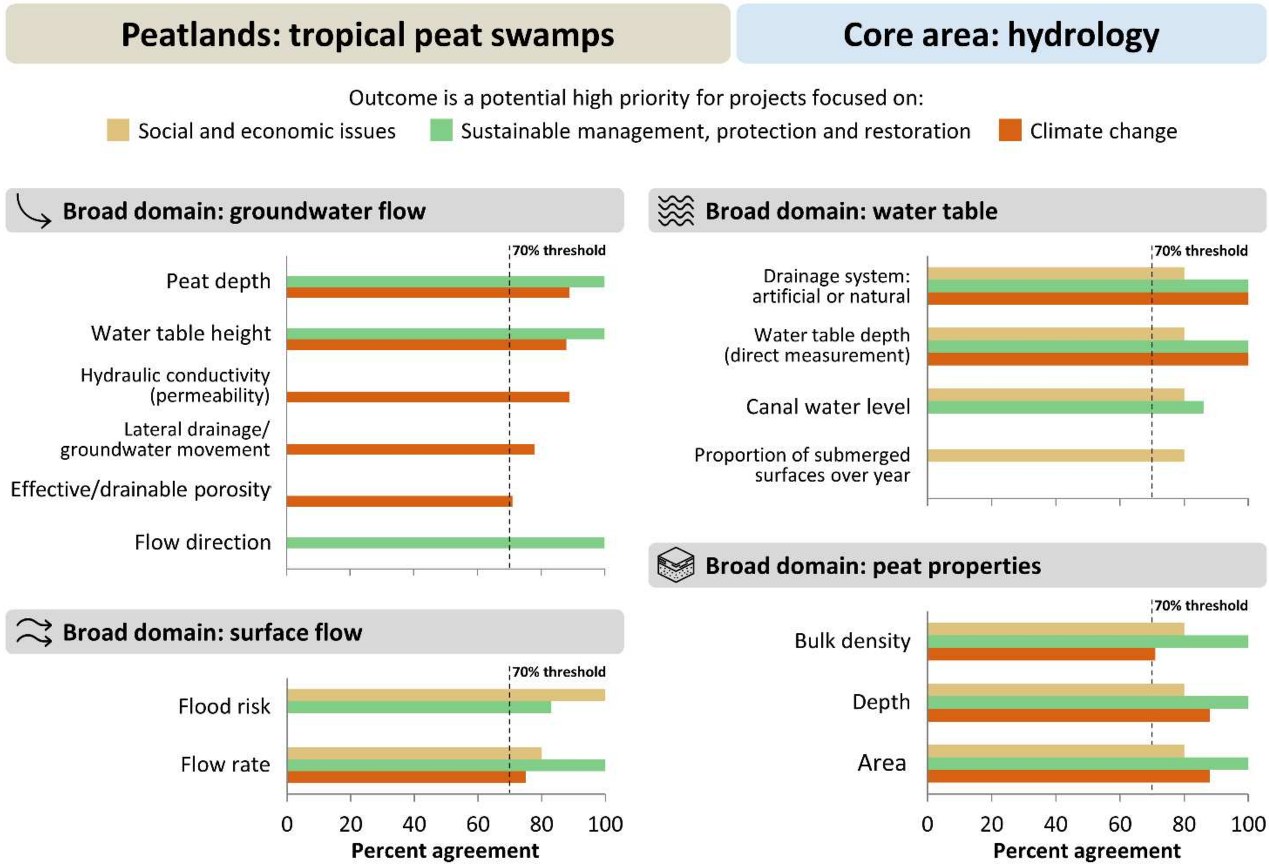

Figure 8. Hydrology core domain set, and the constituent target domain outcomes agreed by ≥ 70 % of respondents as potential high priorities for measurement in tropical peat swamp research or monitoring, depending on the objective or focus of the research or restoration project (based on nine expert responses). Scores < 70 % are not shown.

DISCUSSION

Our results demonstrate how core domain sets could be developed for use in peatland research and monitoring. The methodological framework described in Figure 2 was adapted from a process used in medical science and shows how the development of core domain sets could be replicated across other peatland habitats, and potentially to other fields or topics within environmental science, policy and practice. Our aim was to investigate how to apply this initial step in developing core domain sets (the 'what'). We provide a preliminary list of outcomes that peatland researchers should consider measuring, where relevant and possible, and alongside any additional project-specific outcomes. However, further work is needed on the methods (the 'how') and reporting for the proposed core domain sets. To enable data to be synthesised across studies, agreement is needed on the most appropriate methods to measure the outcomes and to standardise how data are reported, for example by developing controlled data vocabularies (defined lists of terms to systematically organise, categorise or label data) and metadata criteria.

The process of developing core domain sets for UK and tropical peatlands identified a range of limitations and challenges. For example, we focused on biophysical outcomes, and considered their relevance to society by evaluating their perceived importance to different monitoring and research objectives. However, we did not attempt to identify social, cultural, and economic domain sets that might be researched or monitored via methods from the social sciences, economics, arts or humanities.

Obtaining sufficient engagement from across each of the two peatland communities to reach consensus was challenging. One of the reasons was that the multi-criteria evaluation was particularly time-consuming, given the large number of potential outcomes, which when multiplied by the three criteria created hundreds of potential options to choose between (taking up to an hour to complete the survey depending on the expertise of the respondent). In future, this could be simplified by removing or reducing the number of criteria, but discussion at

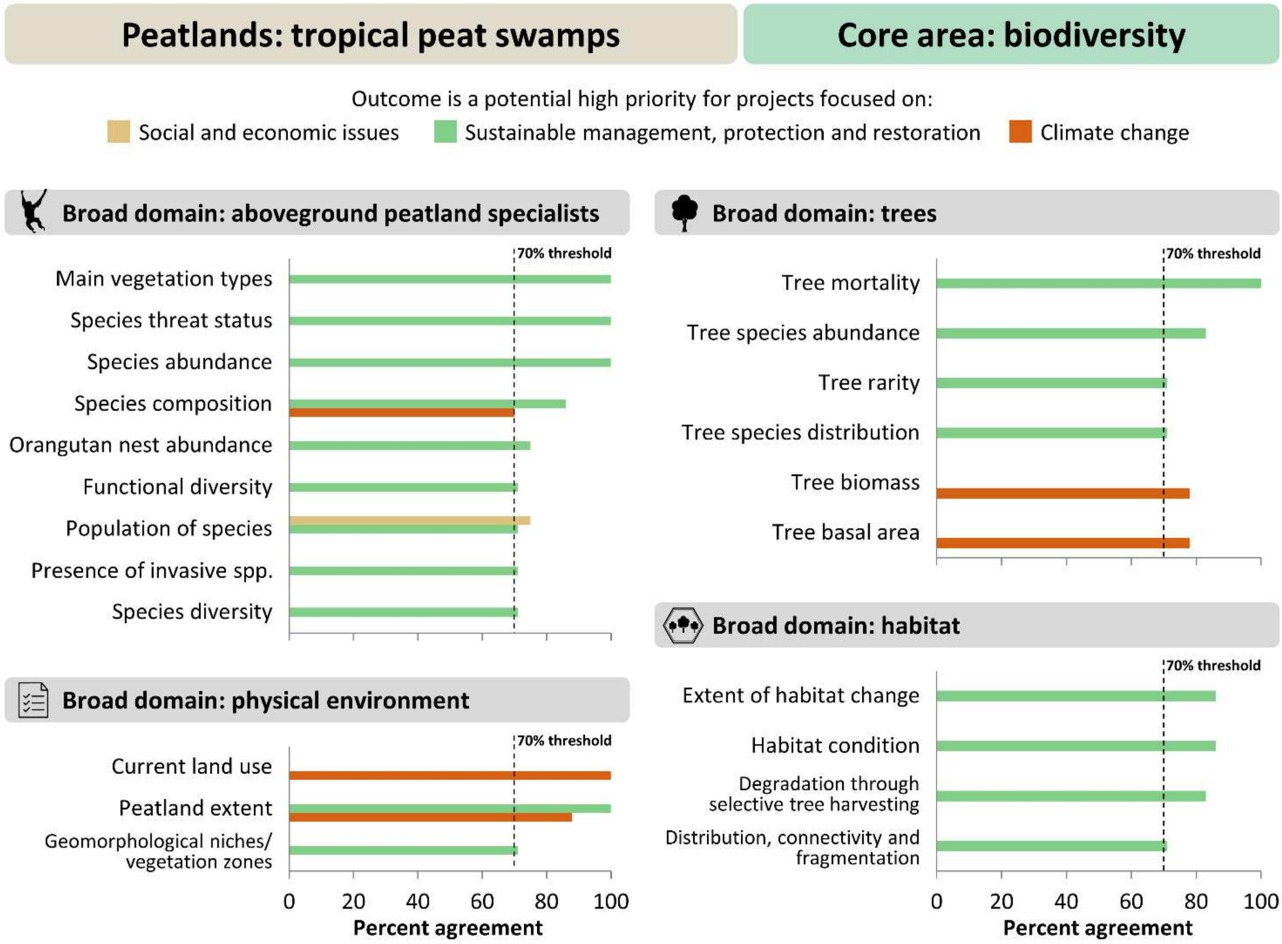

Figure 9. Biodiversity core domain set, and the constituent target domain outcomes agreed by ≥ 70 % of respondents as potential high priorities for measurement in tropical peat swamp research or monitoring, depending on the objective or focus of the research or restoration project (based on 12 expert responses). Scores < 70 % are not shown.

both workshops showed divergence around the implicit criteria people would have used to evaluate and prioritise outcomes, and it was agreed with participants that these should be made explicit and standardised for each of the two processes. Such simplifications could lead to a higher response rate for post-workshop voting in future, leading to a more robust consensus. If the consensus-seeking process is done face-to-face as part of the workshop process, we recommend ensuring an extra day is devoted solely to the multi-criteria assessment.

The main difference between the UK and tropical core domain sets was the focus on fire (including human and non-human ignition) and trees in the tropics - given that tropical peatlands tend to be forested and there are currently significant threats to these habitats from drainage and burning. Purnomo (2021) describes some of the economic and political drivers of fire in tropical peat swamps in Indonesia, but in other countries similar threats are developing as these peatlands are increasingly being cleared for agriculture or resource extraction. Our data suggest that it could be possible to create core domain sets that should be measured across all peatlands, given the overlap between the sets defined for the UK and the tropics. However, it is also clear that additional outcomes need to be prioritised for different peatland types, based on their unique ecology and the drivers of change that they are exposed to. As such, the process that has been tested and refined in this article could be replicated for other peatland types, leading to universal core domain sets for global assessment, in addition to specific core domain sets for each peatland type.

Funders of peatland research and/or monitoring might then request (or require) that data collection includes the relevant core domain sets or core outcomes, in addition to any additional variables required to meet specific monitoring or research goals (e.g. COMET has identified funders, research registries, journals and systematic review organisations as having a role in the implementation of core outcomes

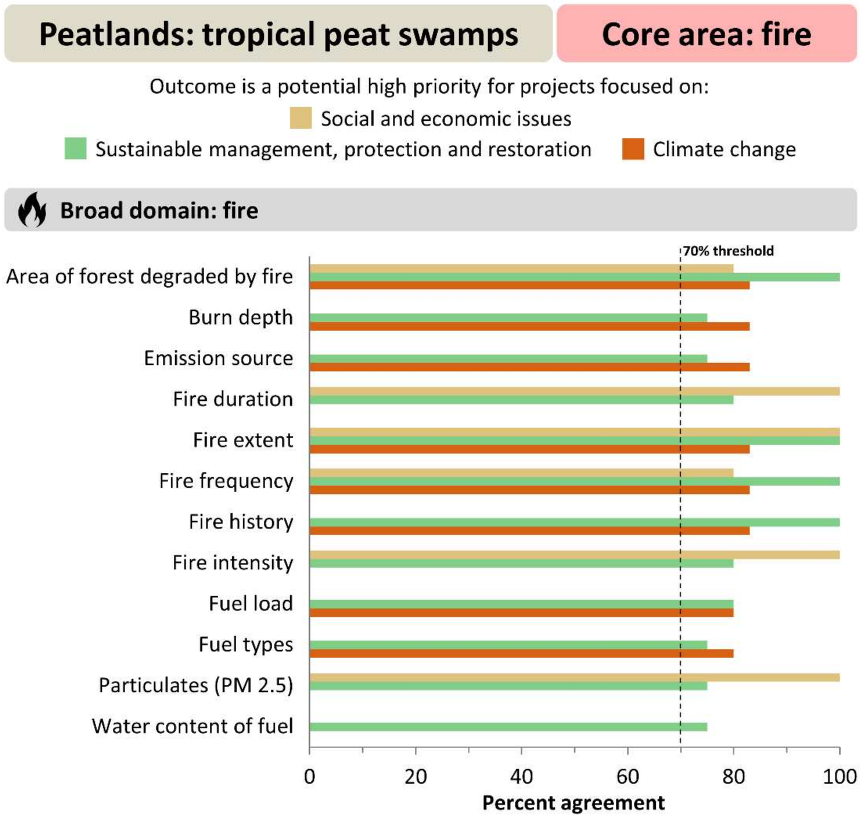

Figure 10. Fire core domain set, and the constituent target domain outcomes agreed by ≥ 70 % of respondents as potential high priorities for measurement in tropical peat swamp research or monitoring, depending on the objective or focus of the research or restoration project (based on six expert responses). Scores < 70 % are not shown.

in medicine; Williamson *et al.* 2017, 2020). Note that the core domain sets that we have published here form a list that researchers can use to determine the most important outcomes they should measure within the broad domains and core areas of most relevance to their work. It is not expected that every project would measure all prioritised outcomes from every broad domain across all three core areas. This contrasts with the use of core domain sets in medicine, which typically define a smaller set of outcomes that should be measured in all studies, but usually for a very specific research question (e.g. acute paediatric diarrhoea; Karas *et al.* 2015).

In the same way that the development of core domain sets does not preclude the collection of other data, any future agreement on methods or reporting protocols would not be binding for research or monitoring unless strongly encouraged by funders (or mandated, as is sometimes the case in medical science). However, the methods could be seen as current good practice. The assessment of the methods for measuring each outcome would need to evaluate the accuracy and reliability of alternatives for both data collection and analysis. Methods are also needed for monitoring programmes with limited access to infrastructure, specialist equipment and expertise (cf. Eyes on the Bog (Lindsay *et al.* 2019) and criteria for evaluating sustainability indicators developed by Reed *et al.* (2006)). This requirement could lead to a decision tree on what methods are suitable under what conditions, or a multi-criteria rating system for methods showing, for example, which methods are highly contested and which are considered sufficiently accurate and reliable, in addition to ratings for their ease of use. Ease of use criteria could include resource intensity and provide options that are sufficiently accurate to inform policy and practice (for example, including methods suitable for citizen science), but that are simpler and less expensive to use than methods typically used by researchers. In addition to the development of new, more accurate and reliable methods for data collection, there is sometimes disagreement over the accuracy or interpretation of data arising from certain methods. It is therefore important that any assessment of methods can be revised as new evidence comes to light, enabling rapid uptake of new methods as they become available.

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Table 1. Contextual variables agreed by ≥70 % of respondents as being important to measure and report alongside all core domain sets (Figures 7–10) for tropical peatlands. Note that although all respondents were asked to vote on every variable, they were advised not to vote on variables they were unsure about, so the total number of votes received differed slightly between variables.

Contextual variable	Total number of high priority votes across all core areas	High priority (% agree)
Previous land use	19	78
Drainage system characteristics and surface area on drained land	17	89
Land cover	23	74
Forest cover	22	77

Reporting and data sharing is just as important an issue, requiring standardisation in line with open science practices (Vicente-Saez & Martinez-Fuentes 2018, Dwivedi *et al.* 2021). The emerging gold standard in ecology is preregistered studies with open data (provision of data) and open methods (provision of all code used in the manipulation and analysis of data) (Nosek *et al.* 2015). As a minimum, summary information sufficient to generate effect sizes and estimates of precision should be reported for all outcomes alongside contextual information (Gerstner *et al.* 2017). These recommendations are generic but those in the environmental field need to take special note of spatio-temporal dependencies, reporting information at or across appropriate scales, and consider unit of analysis issues in relation to pseudo-replication and limitations due to experimental design. Having said this, it is worth noting that there may be ethical questions about a simplistic approach to open data. Open access to data should be the starting point but researchers need to be given options to limit access if necessary - perhaps making their data open at a later date (Dwivedi *et al.* 2021). Using modern data repository systems should enable different levels of data governance whilst adhering to FAIR data principles (Wilkinson *et al*. 2016) and open science practices.

CONCLUSION

Given the importance of peatlands in the global carbon cycle, their provision of other essential ecosystem services, and the significance of peatland research and monitoring in efforts to mitigate climate change, improving the standardisation of data collection and reporting to enable evidence synthesis is of particular importance. While the need for standardised methods of monitoring and reporting outcomes of peatland restoration has been highlighted frequently in the past (Andersen *et al.* 2017, Chimner *et al.* 2017, Graham *et al.* 2017, Rochefort & Andersen 2017), and a range of approaches have been proposed to meet this need (see Introduction), to our knowledge this article documents the first attempt to develop core domain sets, using methods developed in medical science, for an environmental field. Until further research can review, refine, revise and extend (e.g., to social, economic and cultural core areas) these core domain sets, the findings of this research provide the best assessment to date of consensus around core outcomes for peatlands. As such, the results reported here are a first step towards increasing our ability to synthesise data collected in the two types of peatland to which the approach has been applied. In future, this work may also be extended to consider methods and reporting procedures, and to other types of peatland internationally.

Our application of core domain sets to peatlands suggests that the methodological framework could be applied in other fields of conservation, ecology and environmental science. Given the high levels of research waste documented in some disciplines (Yordanov *et al.* 2018, Glasziou & Chalmers 2018), the adoption of core domain sets could significantly increase the likelihood that research is used in evidence synthesis and meta-analyses of studies from multiple locations. This should increase the likelihood that future research employing core domain sets is used to increase decision-maker confidence and reliably inform policies and practices that need to be applied at national or global scales. However, for these benefits to be fully realised, more work is needed to evaluate methodological and reporting options. Although the core domain sets reported in this article may be used to guide research and monitoring efforts towards the most important

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outcomes, widespread uptake of these domain sets would be needed to generate the data needed for synthesis. In medicine, funding is increasingly linked to the measurement of outcomes within core domain sets (in addition to any other outcomes a study might seek to measure); and so, ultimately, funders of both research and restoration monitoring programmes might wish to look more closely at this approach of reducing research waste, to achieve more widespread adoption in the research and monitoring communities (Andersen *et al.* 2017).

Although evidence synthesis is widely regarded as a gold standard for the development of new policy and practice, systematic reviews are often constrained by the availability of synthesisable evidence in the published literature. As a result, the majority of policy briefs, ministerial briefings, oral statements, consultation responses and the like are based on expert opinion and/or narrative review methods (Cairney 2016, 2021), which rely on the judgement of authors to select what they deem to be the most relevant evidence. While such methods may be appropriate for complex and ill-defined issues in which it is not possible to identify specific interventions or outcomes (Greenhalgh *et al.* 2018), the lack of transparency in these methods means that any biases could ultimately lead to poor decision-making in policy and practice. In contrast, we suggest that widespread adoption of reporting guidelines and development of core domain sets for conservation biology and the environmental sector more broadly should be given greater emphasis, and be further explored by research, policy and practice communities.

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AUTHOR CONTRIBUTIONS

MSR was responsible for leading and managing the project, funding, data collection, writing and revising the manuscript; DMY was responsible for data collection, analysis, writing and revising; NGT, RA, NGAB, HCQ, MG, AH, KH, AMG, JK, HK, EAL, GLG, LM, HR, SS and JSW generated data as participants in workshops and/or questionnaires and were involved in writing and revising the manuscript; GS was responsible for research design and contributed to writing.

CONFLICTS OF INTEREST

MSR is Research Lead for IUCN UK Peatland Programme, sits on the Executive Board for the UK Peatland Code and is co-chair of the UNEP Global Peatlands Initiative Research Working Group.

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