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Linking ecosystem changes to their social outcomes: Lost in translation

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ABSTRACT

Ecosystem degradation represents one of today's major global challenges, threatening human well-being and livelihoods worldwide. To reverse continuing degradation, we need to understand its socio-economic consequences so that these can be incorporated into ecosystem management decisions. This requires links to be made between our understanding of how ecosystems function and change, with socially meaningful representations of those changes. While increasing attempts are being made at such integration, the interface or translation between those two strands remains largely undiscussed. This carries the risk that key aspects of the socio-ecological interactions become 'lost in translation'. In this paper, we document and discuss how models of ecosystem change may be combined with socially meaningful outcomes exposing and discussing the translation process itself (i.e. the 'translation key'). For this, we use an exemplar based on peatland condition. We employ a process-based model, DigiBog, to simulate the effects of land use on blanket peatlands, which we relate to estimates of changes to the public's well-being derived from peatland degradation and restoration, obtained as monetary values from a choice experiment survey in Scotland (UK). By quantifying linkages between environmental conditions and social values, we make the translation between these system components transparent and allow value estimates to be recalculated under different ecological scenarios, or as new evidence emerges. This enhances the replicability of the research and can better inform decision-making. By using peatlands as the exemplar ecosystem, this paper also contributes to a limited body of evidence on the socio-economic impacts of changes to the most space-effective carbon store in the terrestrial biosphere.

1. Introduction

With over 70% of the Earth's land area being significantly altered, ecosystem degradation represents one of today's major global challenges, threatening human well-being and livelihoods worldwide (Díaz et al., 2019). There is widespread consensus that, to counter ongoing degradation, we need to understand its socio-economic consequences to inform the design of effective management and conservation strategies, and to gain public and financial support for mitigation policies (CBD, 2011; Díaz et al., 2019; MA, 2005; Olander et al., 2018). Understanding the socio-economic consequences of ecosystem degradation requires knowledge about how an ecosystem works (i.e. the biophysical underpinnings of ecosystem processes and functions); how ecosystem processes are affected by land use and other drivers such as climate change; and how these changes affect people and society. Building this understanding therefore requires that the effects of changes in ecosystem processes and functions are meaningfully translated into outcomes that define impacts on society (Barkmann et al., 2008; Carpenter et al., 2009; Martin-Ortega et al., 2017).

Following the release of the Millennium Ecosystem Assessment (MA, 2005), the interplay between ecosystem change and human-well-being has been explored in many publications, often using the ecosystem services concept (Bateman et al., 2011; Costanza et al., 2017; Haines-Young and Postchin, 2010; Liu et al., 2007; Yang et al., 2015). As a result of this development, integrated interdisciplinary approaches that couple both ecological and economic knowledge are now firmly

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established in academic and environmental management agendas (Bateman et al., 2016; Martin-Ortega et al., 2015a). This integration has been attempted using a variety of approaches, often relying on the development of models to establish and map the services delivered by ecosystems under different management scenarios (Maes et al., 2012) in combination with economic data elicited via various valuation methods (Elwell et al., 2018). Some of these assessments are based on global models, such GLOBIO, which was used as the basis of The Economics of Ecosystems and Biodiversity (TEEB) Assessment (Hussain et al., 2011). More detailed landscape scale models run at finer scales, often with local data, are also used to show more realistic changes in ecosystem service supply than global models (Maes et al., 2012). Such models are used in, for example, the InVEST tool (Sharp, 2014), which was explicitly designed to provide information on ecosystem change in terms of human well-being. Quantification of well-being impacts in these assessments often focus only on changes in agricultural/land use gross margins (through yield changes) (e.g., see Schönhart et al. (2018) and further references therein). Other studies include assessments of impacts on a broader range of sources of social well-being. For example, Martin-Ortega et al. (2015b) used hydro-chemical models to simulate the effectiveness of interventions to reduce dissolved phosphorous reduction loads in water bodies in Scotland and related the changes to the non-market benefits derived from improving the ecological status of a catchment. Grêt-Regamey et al. (2008) also combined various process-based models for characterising avalanche protection, scenic beauty, timber production and habitat provided by an Alpine region to establish public values for these ecosystem services.

Spatially explicit statistical models relating land use to economic outputs have also been developed. One example is Bateman et al. (2016), in which monetary valuation of climate driven land-use change is underpinned by land-use modelling. The model predicts climate-driven shifts in the profitability of alternative uses of agricultural land, including farm gross margins and monetary values for water quality and recreation, at the individual and catchment scale. Other approaches have integrated ecological and economic elements using Bayesian Belief Networks. McVittie et al. (2015) used this method to assess and value the delivery of ecosystem services from riparian buffer strips under alternative management options. Whereas Juutinen et al. (2020) combined various biophysical models with an economic analysis of biodiversity, climate impact and water emissions to identify cost-effective land-use options of drained peatlands.

The approaches mentioned above have certainly represented substantial knowledge advancement. However, producing a set of model outputs that can be linked in one way or another to one or more ecosystem services does not guarantee the most appropriate representation of ecosystem change for assessing its societal impact (Elwell et al., 2018). This link is generally loosely specified, since there is often a mismatch between typical outputs of ecosystem models and the representation of outcomes that are perceived to be relevant by the general public (Martin-Ortega et al., 2017; McVittie et al., 2015). Furthermore, models should be relevant to the scale at which changes in ecosystem services delivery are relevant for the people who benefit from it (Hein et al., 2006).

To address the mismatch between how ecosystem change is representated and the assessment of related social outcomes, recent suggestions emphasise the need to place people's perceptions at the centre of the assessment process (Elwell et al., 2018; Jones et al., 2016; Martin-Ortega et al., 2017). However, there is little evidence that this insight is then used to help improve ecosystem services modelling in assessments of changes to social well-being (Elwell et al., 2018), leaving the values poorly supported by biophysical measures (Olander et al., 2018).

This remaining disconnect between the ways in which we address our understanding of how ecosystems work and respond to change, and our estimates of how this affects people, carries the risk that key aspects of the socio-ecological interactions are 'lost in translation'. Published work typically contains a great level of detail on one or both aspects (i.e., ecosystem modelling or valuation of social outcomes), but often neglects to report and discuss sufficiently the translation between the two, with the interface remaining a 'black box'. Or, as Olander et al. (2018) note, "what is less clear is the hand-off between the biophysical measures and valuation – the link between the biophysical measure and a measure of what that biophysical entity means to (or how it affects) people". Here, we postulate that building, articulating and exposing this interface is critical to enhance the robustness and usefulness of integrated assessments of ecosystem change (Evans et al. 2014). That translation should be a clearly identifiable step in the research process that is open to scrutiny, thus facilitating continued knowledge improvement and more robust support to decision-making.

In this paper, we document and discuss how models of ecosystem change may be combined with socially meaningful outcomes, making a point of exposing and discussing the translation process itself. We use an exemplar based on change in peatland condition, applying the DigiBog development model (Baird et al., 2012; Young et al., 2017) to simulate the effects of land use on the ecological functioning of blanket peatlands. We categorise DigiBog model outputs describing peatland condition according to public perceptions of, and preferences for, key ecosystem services. Model outputs are linked to estimates of public values (in monetary terms) derived from peatland restoration, obtained from a choice experiment survey in Scotland. We highlight the additional processing step used to make the quantitative link between direct model outputs and aspects of peatland condition with their socially meaningful outcomes. And we emphasise how the link was built and articulated: what we refer to here as the 'translation key'.

The value of this paper lies in the exposure and discussion of the translation process and on how the process model was adapted to match socially meaningful outcomes. Our intention is to encourage reflection rather than prescription. The ultimate aim is not an ontological simplification of the problem – i.e. socio-ecological interactions are and will always be complex and there will always be limits to how much of that complexity we can disentangle, or represent in models (Martin-Ortega et al., 2017). Instead, the aim is to improve the development of tools and processes that can support decision-making to reverse the current degradation trend (Olander et al., 2018).

2. Methodology

We followed proposals by Elwell et al. (2018), Jones et al. (2016) and Martin-Ortega et al. (2017) to place the identification of socially meaningful outcomes at the core of the process via a transdisciplinary process involving key stakeholders and the public, through which we elicited public values of the ecosystem services provided by peatland restoration as measures of well-being. The peatland model (DigiBog) was adapted so that its functional representation of the biophysical changes in the ecosystem could be linked explicitly to those socially meaningful outcomes, establishing the 'translation key'.

This approach differs from the practice of describing social outcomes as the endpoints of a linear process that starts with the characterization of ecosystem change, followed by quantification of changes in the provision of ecosystem services in biophysical terms and ultimately their valuation. An approach that is implicit in the widely referred to framework of the ecosystem services cascade (Haines-Young and Potschin, 2010), and the main large ecosystem assessments carried out so far (e.g. Bateman et al., 2011; Kumar, 2010; MA, 2005). Fig. 1 highlights the differences between approaches that use this implicit/un-managed translation between biophysical outputs and social outcomes (Fig. 1a), and the one used here, where the translation key is explicit and managed (Fig. 1b).

We chose DigiBog for our biophysical model because it simulates peatland development over different underlying landscape scale features (e.g., slopes of varying gradients, plateaus, and hollows). The model can be configured in either 2-D or 3-D to represent sections of a landscape comprising some or all these features with contiguous,

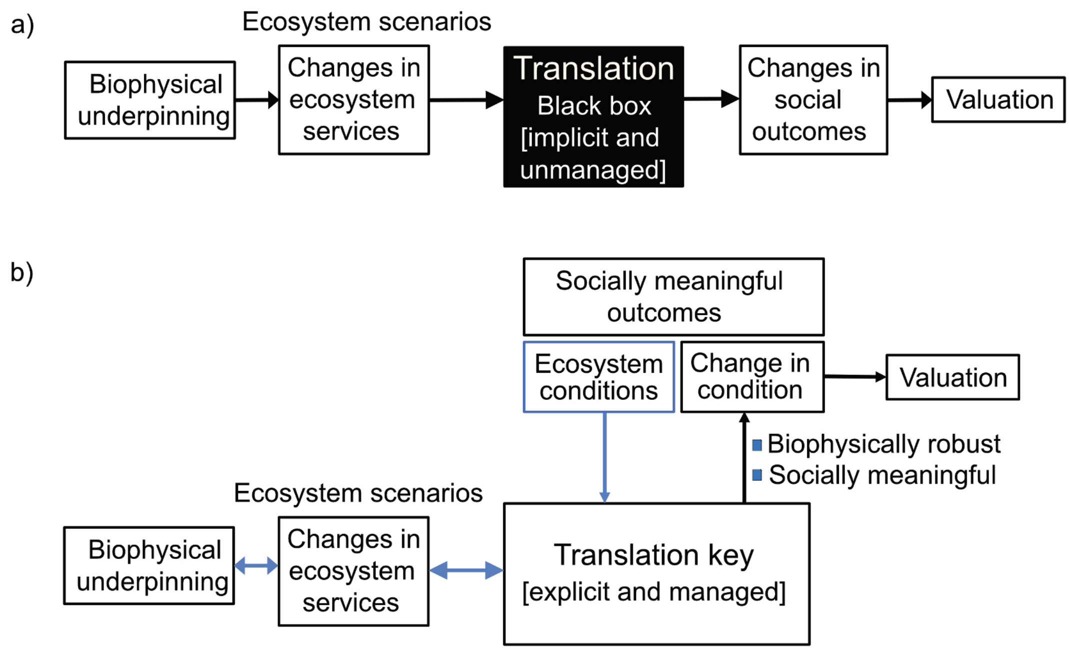


Fig. 1. (a) conventional linear approach to linking the understanding of ecosystem change and social outcomes in which biophysical outputs are linked to social outcomes in an implicit unmanaged way (or in any case, under-discussed), creating a 'black box' at their interface; (b) alternative approach (used in this research) in which social outcomes are placed centrally and the interface or translation is explicitly articulated and discussed. The blue arrows in (b) indicate the matching of the key characteristics of socially meaningful outcomes and a biophysical simulation of the ecosystem (i.e. the translation key based on ecosystem conditions in our case).

hydrologically connected columns that 'talk' to each other. Because of these connections, which are not intrinsic to existing 1-D peatland models (e.g., Frolking et al.,2010), peat properties can vary both vertically and horizontally and can be affected by land uses in other parts of the simulated landscape (see Young et al., 2017). As a result, overall peatland condition can be determined from these smaller-scale interactions.

2.1. Estimating socially meaningful outcomes of peatland restoration

We use blanket peatlands in Scotland as the exemplar of this research. Blanket peatlands are the most common peatland type in Scotland, covering 20% of its land surface (Bain et al., 2011; Bruneau and Johnson, 2014), mainly in the uplands. These peatlands provide several important ecosystem services at global and national scales, such as carbon storage and fresh water supply (Bain et al., 2011). Atmospheric pollution, along with land uses, including drainage, conversion to agriculture, burning for game shooting, and forestry, have caused blanket peatlands to become degraded (Maltby, 2010). In the past, peatlands in Scotland were mainly seen as either a source of peat for fuel or as wastelands to be converted to other productive uses such as forestry or agriculture (Rotherham, 2011). As a consequence, more than two thirds of Scottish peatlands are thought to be damaged or degraded to some degree, and degradation is projected to continue if no action is taken to restore their ecological function (Bain et al., 2011). This has led to a surge in policy interest to restore degraded peatlands in Scotland. In its recent Climate Change Plan, the Scottish Government (2018) laid out ambitious targets to restore 250,000 hectares of degraded peatland by 2030, supporting this aim through grants available to land managers.

Social outcomes from peatland restoration are represented here by monetary values provided by improved ecological condition, as measures of well-being increase. These values were estimated as the public's willingness to pay in a choice experiment (Adamowicz et al., 1998) implemented in an online survey of a representative sample of Scotland's population (Glenk and Martin-Ortega, 2018). In the choice experiment, survey respondents were asked to choose from two peatland restoration alternatives and a third business as usual situation (i.e. no restoration, with no cost). These alternatives were characterized by attributes described as outcomes of a restoration programme in terms of improved peatland condition to be attained at a cost by 2030. This valuation was developed through a transdisciplinary process in a combination of workshops, focus groups and bilateral interactions between natural and social scientists, peatland restoration practitioners and members of the public[1] (Table 1 summarizes the stages of the process and Table 2 shows the organizations involved). Martin-Ortega et al. (2017) provide a more detailed account of the process and the actors involved, but of relevance to the present paper is that it was driven by and shaped from the public's perspective. The process was able to represent restoration outcomes and establish a restoration reference (including temporal and spatial aspects) in a way that was meaningful from the public's perspective and useful in terms of assisting management decisions (see Martin-Ortega et al. (2017) for evidence on these claims).

The design of the choice experiment included three ecosystem conditions: bad, intermediate and good. The conditions were associated with varying levels of ecosystem service provision related to climate change mitigation (carbon storage), water quality improvement and changes to wildlife habitat. These ecosystem services were chosen following the transdisciplinary process. We also introduced productive uses – and related provisioning services including forestry, field sports (shooting) and livestock grazing – in the contextual description of the valuation scenario (rather than as attributes of the choice experiment). Specifically, respondents were reminded that *"some peatlands are currently unused, while others are used for sheep grazing and deer*

[1] Three focus groups with members of the general public were conducted in two locations in Scotland chosen due to their contrasting characteristics in relation to peatlands and the different relationships and experiences that we assumed people would have with peatlands. The focus groups were attended by a total of 37 participants, covering both genders (over half were female), and a wide range of ages (early 20s to 70s), socio-economic backgrounds, and reasons for wanting to attend the focus groups (from a general interest in the environment and outdoor recreation to being offered some food at the workshop or "having nothing better to do that day").

Table 1
Stages of the transdisciplinary process.

Stage[a]	Aims	Strands of interaction[b]	Format of interaction
1	Understand the current knowledge base of peatlands processes, functions and ecosystem services delivery Identification of the policy agenda	Natural scientists Practitioners and policy-makers	Workshops
2	Define the potential challenges associated with understanding peatland restoration and its public perceptions	Natural scientists	Bilateral dialogue
3	Development of a tool for conveying simplified restoration information	Natural scientists Practitioners and policy-makers	Bilateral conversations Policy makers and practitioners' workshop
4	Testing and refining the tool with the public	Public	Focus groups Survey
5	Validation and uptake	Natural scientists Practitioners and policy-makers Public	Experts' focus groups Bilateral dialogue Policy events Learning module and condition assessment support tool

[a] Although stages are somewhat consecutive, there was some level of overlap between them and some of the tasks were interspersed (e.g. focus groups with the public also took place as part of stage 3). [b]The process is presented from the perspective of the social scientists leading this research, and therefore should be read as 'strand of knowledge with which the social science strand interacts'.

Table 2
Main organizations involved in the transdisciplinary process.

Name	Type of organization
The James Hutton Institute	Research (including hydrologists, ecologists, soil scientists, economists, environmental social scientists)
Scotland's Rural College (SRUC)	Research (economists)
University of Leeds	Research (including hydrologists, wetland and peatland scientist, economists)
University of Birmingham	Research (social and natural sciences)
Centre for Ecology and Hydrology	Research (including water ecologists, hydrologists and peatland scientists)
Scottish Natural Heritage (SNH)	Practice (peatland restoration practitioners)
Scottish Government	Policy-making (environmental and strategic research managers)
International Union for the Conservation of Nature (IUCN) – UK National Committee	Practice (nature conservation)
Scottish Environmental Protection Agency (SEPA)	Policy-making (environmental management)
ClimateXChange	Science-practice interface (climate change)

management, forestry or field sports like grouse shooting". Respondents were also informed about the relation between condition and scope for productive uses. Specifically, they were told that *"peatlands which are in intermediate condition can be used for livestock grazing and field sports (grouse), but if they deteriorate to poor condition all of these uses and activities are severely impaired. Peatlands in good condition are not suitable for livestock grazing and field sports"*. The normative labelling of the peatland conditions (i.e., bad, intermediate and good) were intentional in its reference to the ecological condition of the ecosystem so that it can be understood by the public.

Three stylized landscape representations (drawings) and descriptions (narratives) portraying the three conditions were developed in an iterative process with stakeholders and the general public. They describe in simple terms how changes in ecosystem condition lead to changes in ecosystem service provision for each of the peatland conditions. The narratives served as mechanisms for conveying (at least in part) the complexity of the ecosystem processes that lead to the delivery of the ecosystem services mentioned above (Martin-Ortega et al., 2017) and are shown in Table 3. This approach also allowed a straightforward quantification of restoration monetary benefits on a per hectare basis (i.e. £/hectare/year), making it appealing to use for decision makers, and facilitating further spatial analysis of benefit estimates (Glenk and Martin-Ortega, 2018).

The survey was implemented online using a professional market research company with 585 adult Scottish citizens between February and March 2016. A quota-based approach was used to sample from the online panel with age and gender quotas. The sample was representative of the population of Scotland in terms of gender, age, and the rural/urban split. In terms of educational attainment, higher educational levels are slightly over-represented, as well as respondents with higher employment-based social grade (see Supplementary Material S1).

Further details of the choice experiment application (e.g., sampling procedure and recruitment, survey structure, experimental design, etc.) and detailed monetary estimations can be found in Glenk and Martin-Ortega (2018). Of relevance here is that this process allowed us to understand what it means to people if peatlands become degraded and restored, expressed as the trade-off that these changes represent in terms of their well-being (in this case: the monetary value they ascribe to these changes measured in £/ha/year).

2.2. Peatland model description

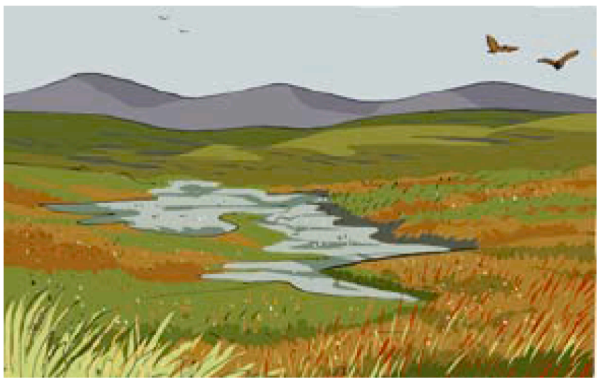
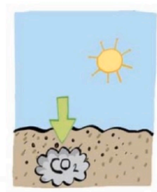
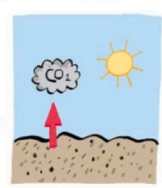
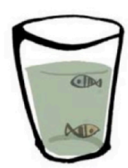
DigiBog simulates the development of a peatland in 2-D/3-D over centuries, building up layers of peat within hydrologically connected columns. Simulations begin with a mineral soil base and individual peat layers are added to each model column on an annual basis. The processes of peat formation, peat decomposition, and water movement in the model can be summarized as follows: (1) the mass of each new layer is determined by a plant litter productivity function. Peat formation occurs as an annual addition of new plant litter to the top of each model column, with the thickness of the new layer varying according to annual average air temperature and the annual average water-table depth for the column; (2) on a sub-annual basis, the peat in each layer of a column is decomposed depending on its position relative to the water-table and the annual air temperature; and (3) also on a sub-annual basis, water is moved horizontally between columns to simulate water-table behaviour (driven by net rainfall and the hydraulic properties of the peat). Therefore, the addition of new peat varies from column to column, and peat decomposition varies both horizontally (between columns) and vertically (within a column). The degree of decomposition of a peat layer determines its saturated hydraulic conductivity, which in turn determines water movement between columns. These interactions mean that there are feedbacks between peat accumulation, decomposition, changes in hydraulic properties, and water movement.

We used a modified version of the 2-D/3-D DigiBog peatland development model (Young et al., 2017) to simulate the accumulation of blanket peat in response to land use. The model used by Young et al. (2017) now includes an algorithm to reduce simulation times. The algorithm aggregates neighbouring layers when below a user-defined thickness, allowing virtual peatlands to be grown over significantly increased spatial scales (thousands of metres rather than tens of metres), which enabled the use of the model for this study (also see Young et al. (2019)).

2.3. Linking DigiBog outputs to monetary values of peatland restoration

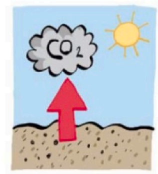
We used three steps to link the monetary values of peatland restoration into parameters for our peatland development model (Fig. 2). The

Table 3
Socially meaningful description of peatland ecological conditions elaborated in a transdisciplinary process, including pictorial representation and accompanying narratives. These were shown to the public in an interactive manner through an online survey (i.e. fragments of the narrative appeared as participants clicked at relevant features in the drawings).

Peatlands Categories	Ecosystem Services Representation	Accompanying Narratives
 **Good Ecological Condition**	  	In good condition, there is plenty of water, so it is visible on the surface, slowly flowing through larger and smaller pools.You will see small grasses and especially the peat moss that grows well in wet conditions. The moss stores lots of water and makes the peatland appear in a typical red-green–brown mosaic.Peatlands in good condition continue to grow by adding more and more layers of peat. While growing, carbon is taken up from the atmosphere as carbon dioxide (CO_2) and stored as peat.Water that flows from peatlands that are in good ecological condition is usually clear and of good quality. This means less need for water treatment. The water quality is also good for fish living downstream, especially salmon and trout.Peatlands in good condition are home to various birds and wildlife species.This includes waterfowl and wading birds such as curlew, and predators such as hen harrier and red kite.
 **Intermediate Ecological Condition**	  	In peatlands in intermediate condition, water has been taken off the land by creating channels for drainage. This allows activities such as livestock grazing. Surface water is rarely visible.With less water on the land, taller plants can grow, like cotton grass, or small bushes like heather.Peatlands in this condition are not very colourful. However, if heather grows in the area and is in bloom, its purple colour stands out. Signs of bare peat start to appear as dark patches. Sometimes peatland of intermediate condition is burned regularly, to create conditions for grouse shooting. This leaves characteristic patterns of burned and unburned land in the landscape.Peatlands in intermediate condition have stopped growing. No additional peat layers are added. Instead, peat layers gradually shrink, releasing a moderate amount of carbon to the atmosphere, where it contributes to climate change.Water flowing from such peatlands can be of lower quality. Water can be slightly murky, especially after a heavy rainfall. This can affect the fish population downstream, including salmon and trout, and increase the need for water treatment.Peatlands in intermediate condition may still harbour some of the wildlife that is present in peatlands in good condition. However, it is less abundant and some of the wildlife may not be found any more.It is also more likely that you will see managed species such as deer, sheep and grouse.

(*continued on next page*)

Table 3 (*continued*)

Peatlands Categories	Ecosystem Services Representation	Accompanying Narratives
 **Bad Ecological Condition**	  	Peatlands in bad condition have been drained for a longer time. The forces of water and wind (erosion) have now exposed larger areas of bare peat. Deep gullies and trenches are formed.Rarely any plant grows on the areas that are exposed. Patches of grasses or heather are still found on ‘islands’ in between exposed bare peat. The exposed bare peat areas will continue to grow, leaving less plant cover as protection on the surface. Peat will continue to be lost until the solid rock surface emerges.Peatlands in bad condition lose carbon at a high rate. They have turned into a severe ‘source’ of carbon to the atmosphere, where it contributes to climate change.Water that flows downstream is of bad quality. It is often murky and can be dark brown from soil components in the water, especially after heavy rainfall events. The bad water quality will affect fish downstream. It is not suitable for human consumption and therefore needs a lot of treatment.Peatlands in this condition are home to little wildlife. Not many plant and animal species can be found.

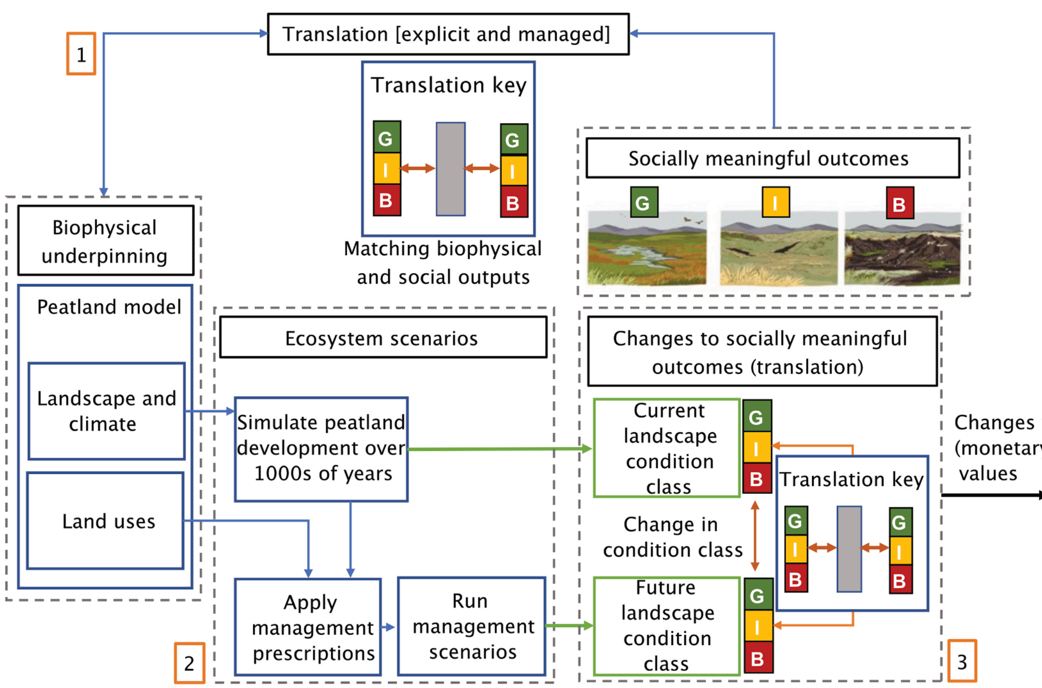


Fig. 2. The three-step process used to link the peatland development model with the socially meaningful outcomes – as defined here in terms of monetary values for changes in peatland condition (G: good; I: intermediate; B: bad). The numbered steps are shown to indicate the overall order of the steps we took (although in reality the process was often iterative): [1] Translating descriptions of peatland conditions into model outputs, i.e. establishing the ‘translation key’ (see Table 4 for a detailed description); [2] simulating ecosystem scenarios; and [3] assessing the impact of scenarios in terms of changes in well-being.

objective of this process was to: 1) identify the key characteristics of peatland condition that are socially meaningful (as defined in Section 2.1) and match them to DigiBog model outputs, i.e. establishing what we refer to here as the ‘translation key’; 2) model a scenario of peatland degradation (e.g. following drainage) and restoration intervention as an exemplars; and 3) use the key characteristics defined in the matching (translation) process, to assess the impact of the scenario on the change in monetary values of peatland condition. This process (and Fig. 2) represent the detailed version of the broad research approach proposed in Fig. 1(1b).

Step 1 – Establishing the translation key of socially meaningful peatland condition descriptions into model outputs. The aim of this stage was to identify how the descriptions of peatland condition could be translated into biophysical outputs without being overly constrained by the existing DigiBog set up (Fig. 2[1]). To fully incorporate the key characteristics into DigiBog, we used the model code described in Young et al. (2017) with a modification to reduce simulation times (see Young et al., 2019). To ensure that the model outputs for each peat column of the simulated landscape included, directly or indirectly, the key characteristics for the three condition classes, we reviewed the descriptions of peatland condition defined by Martin-Ortega et al. (2017) both in their diagrams and the associated narratives (Fig. 2and Table 3). In this way, we identified two key characteristics on which the economic valuation had been based, that could be derived either directly or indirectly from DigiBog model outputs. The condition assessment criteria are shown in Table 4.

These two characteristics are the vegetation cover and carbon (C) sink status. We modified DigiBog to include litter fractions of four plant functional types (PFTs) (*Sphagnum* mosses, shrubs, sedges, and grasses), which comprise the mass of peat. The PFTs also indirectly represent the domesticated and wild fauna associated with the narrative descriptions. For example, the narrative for good condition states: "*You will see small grasses and especially the peat moss that grows well in wet conditions … Peatlands in good condition are home to various birds and wildlife species. This includes waterfowl and wading birds such as curlew, and predators such as hen harrier and red kite*" (Table 3).

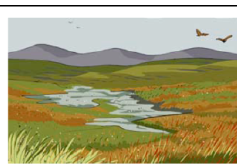
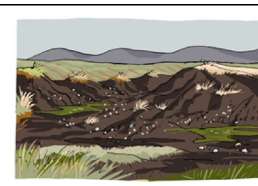
Carbon accumulation is an output of DigiBog (i.e., there is a direct link between the model and the condition classes). However, because C exchange takes place throughout the total depth of a peat column (Clymo, 1984; Young et al., 2019), we could not infer the C sink status of our simulations from the surface vegetation. We, therefore, calculated separately the C sink status of the simulated peatland following the method detailed in Young et al. (2019) and converted the output to CO_2 equivalent (CO_2e). For our purposes, we used a conversion factor of 1 t C equals 3.67 t CO_2e. The last step allowed us to compare our results with the emissions factors for peatlands (minus N_2O) in different condition statuses calculated by Evans et al. (2017).

The vegetation on the surface of a peatland is not simulated by the model (i.e., there is an indirect link between the model and the condition classes). DigiBog simulates the accumulation of layers of peat that are made up of the PFTs described above, but these do not necessarily match the vegetation cover on a peatland's surface. For example, some grasses may be abundant on the surface but undergo significant decay before becoming part of the peat proper, meaning there could be a mismatch between proportion of such a grass that makes up peat and that on the surface. We therefore needed to develop a way of calculating the proportions of surface cover for our PFTs. To link vegetation cover and composition to the condition descriptions from Martin-Ortega et al. (2017), we developed response relationships based on a dataset of field observations of PFTs and their corresponding water-table depths. The set of equations predicts the proportion of cover for the four PFTs according to the model's simulated water-tables. In this two-step approach vegetation composition was calculated using the MultiMOVE set of niche models (Smart et al., 2010; Henrys et al., 2015; Alison et al., 2020), using a relationship between plant composition and mean Ellenberg moisture index. The relationship between moisture index and water table depth was derived from co-located floristic and dipwell data from blanket bog at Moor House, UK (see Supplementary Materials S2 for further detail).

To match the three condition categories with model outputs, we transformed the qualitative descriptions within each condition class into categorical variables (Table 4). We determined the categories for our variables by matching the diagrams and narratives of Martin-Ortega et al. (2017) – Table 3– with previous studies or other published information on how to define the ecological condition of blanket peatlands. For example, the three C sink status categories are described in Table 3 as follows; good condition: "*Peatlands in good condition continue to grow by adding more and more layers of peat.*"; intermediate condition: "*… peat layers gradually shrink, releasing a moderate amount of carbon to the atmosphere, where it contributes to climate change.*"; and bad condition: "*Peatlands in bad condition lose carbon at a high rate*". Therefore, we defined our C sink status categories as ranging from the continued accumulation of C (i.e. a sink – good condition) to losing some C (i.e. a small source – intermediate condition) to losing a significant amount of C (i.e. a large source – bad condition) (see Table 3). We used the emissions factors (EF) (minus N_2O) from Evans et al. (2017, Table 4.1 in there) to determine the C condition status of our simulation. We selected the EF of the 'near natural bog' condition category to be equivalent to our good condition and the mean EF for their 'eroded modified bog' condition category as the boundary between our intermediate and bad conditions (the mean EF of the drained and undrained statuses) (Table 4).

Similarly, for PFTs we assessed the condition status of our model outputs by combining the relative habitat suitabilities of our PFTs into two groups: one where greater suitability is associated with good peatland condition (*Sphagnum* mosses and sedges), which we refer to as favourable PFTs, and a second comprised of grasses and shrubs where greater suitability is associated with bad condition when they are the

Table 4
Translation key used to match the key characteristics of peatland condition defined by the transdisciplinary process with the public (i.e. socially meaningful outcomes as per the narratives in Table 3) with DigiBog outputs. See the text for a description of how each key characteristic was determined.

	Ecological condition Good	Intermediate	Bad
Key characteristic			
Carbon sink status (socially meaningful description)	"While growing, carbon is taken up from the atmosphere as carbon dioxide (CO2) and stored as peat"	"No additional peat layers are added. Instead, peat layers gradually shrink, releasing a moderate amount of carbon to the atmosphere"	"Peatlands in bad condition lose carbon at a high rate. They have turned into a severe 'source' of carbon to the atmosphere"
Fifteen-year mean (t CO2e ha-1 yr-1). Negative values are a sink.	=< 0	[0, 4.1]	> 4.1
Cover of plant functional types (socially meaningful description)	"You will see small grasses and especially the peat moss that grows well in wet conditions"	"With less water on the land, taller plants can grow, like cotton grass, or small bushes like heather"	"Patches of grasses or heather are still found on 'islands' in between exposed bare peat"
Fifteen-year mean (proportion)	Sphagnum and Sedges > 0.40	fx6	Grasses and shrubs > 0.50

dominant vegetation cover (Averis et al., 2004), (Table 4). We refer to this second group as unfavourable PFTs.

Step 2 - Simulating ecosystem scenarios. The purpose of this step was to model the effects of our chosen land use and of restoration on the key characteristics defined in step 1 (Fig. 2[2]). DigiBog was set up to simulate peat accumulation over a published transect of blanket bog considered typical for the UK (Tipping, 2008). The transect comprised 100 × 2 m × 2 m columns (400 m^2), which included slopes and plateaus of varying extents and slope angles. Our model was driven with a time series of rainfall and temperature data, typical for UK uplands (see Young et al. (2019) for information about these time series). We ran the model with these driving data for a series of preliminary simulations using different sets of oxic and anoxic decay parameters to ensure that the model produced a plausible peatland. By plausible we mean that peat on slopes was thinner than that on plateaus (for an example see Tipping (2008); page 2104) and that peat thickness on plateaus was similar to that reported for blanket peatlands in the UK (peat built up to a maximum thickness of approximately 3.5 m). Our aim was not to replicate the detailed development history of a specific peatland, but to provide a set of outputs that could be used as an analogue for blanket peatlands.

We identified drainage, grazing, afforestation, and managed burning as the three main land use impacts that are implemented singly or in combination across blanket peatlands in the UK: the reduction or reversal of these activities has also been the focus of recent restoration activities (Parry et al., 2014). Of these activities, we chose to investigate the effects of drainage.

We ran a single simulation for 5100 years. To simulate management, we ran the model for 4900 years and then added six 60 cm deep ditch drains (see Young et al. 2017) at 30 m intervals before allowing the model to continue to run with drainage for a further 100 years. During the 'drainage' phase, the depth of the ditch drains was maintained to simulate active management of water tables. At the end of the drainage period (i.e. after 5000 years) the ditch drains were restored with simulated ditch dams set to a depth of 10 cm (see Young et al., (2017) and the model run continued until 5100 years had elapsed.

Step 3 - Assessing the impact of scenarios in terms of changes in social well-being. We calculated the change in monetary value associated with peatland condition by comparing the classification of our simulated peatland during the final 15 years of each of the stages of our model run (pre-drainage, drained, restored) (Fig. 2[3]). We used these timescales as they matched those originally used to elicit the monetary values in the choice experiment survey, established during the preparatory focus groups of the valuation study (Glenk and Martin-Ortega, 2018). In a reversal of *Step 1*, we used the translation key in Table 4 to classify the simulated peatland into good, intermediate, or bad condition. We first determined the classification of each peat column making up the modelled peatland by categorising the mean values of the peatland condition (good, intermediate, or bad) for the 15-year assessment periods for both drainage and restoration. Then, for each of the changes in peatland stage (i.e., from natural to drained, and from drained to restored), the number of hectares undergoing a change in peatland condition (e.g. from good to intermediate and to bad) was calculated. These hectare changes were then related to per hectare values obtained in the choice experiment survey.

3. Results

3.1. Condition assessment

The addition of ditch drains in our model caused a switch in the surface vegetation from predominantly mosses and sedges (mean cover across the peatland of 56%) to a cover dominated by shrubs and grasses (mean cover of 75%) (Supplementary Material S2). The C balance also reversed from −0.97 t CO_2e ha^{-1} yr^{-1} (negative values are a sink) before drainage to 11.52 t CO_2e ha^{-1} yr^{-1} during drainage (means of all model columns for the last 15 years of each period). During the last 15 years of the restoration period, 69% of surface vegetation was made up shrubs and grasses and the C balance was 2.98 t CO_2e ha yr^{-1} (Supplementary Material S2). During this time, the condition status of the whole peatland changed from good (natural) to bad (drained) to intermediate condition (restored). Fig. 3 shows the whole peatland C sink status for the final 300 years of our simulation. Whilst all peat columns in the pre-drained period of the simulation were classed as in good condition, all three conditions were present to a greater or lesser extent in the drainage and restoration treatments showing a heterogeneous response to land use (Table 5).

Table 6 shows the number of hectares for each of the peatland stages (natural, drained and restored) in the three conditions (bad, good and intermediate). For illustrative purposes, the DigBog results have been scaled up from the simulated 400 m^2 to a hypothetical landscape of 100 ha using the proportions of columns in each category (see Tables 5 and 6). These proportions were then used to establish changes in well-being through measurement of social values quantified in monetary terms (Section 3.2).

3.2. Changes in well-being

For each of the changes in peatland status, i.e. from natural condition to drained and from drained to restored, the number of hectares moving from one ecological condition to another, could then be related to the per hectare values obtained in the choice experiment survey, relating hectare changes from Table 6 to monetary values from Glenk and Martin-Ortega (2018) (Table 7). The move from natural peatland to drained peatlands represents a decrease in well-being, i.e., a decrease in the value that the ecosystem can now deliver. In the case of restoration, the change in value is an increase in well-being, reflecting the value of the increased services delivered.

What these values show us (Table 7) is that there is a clear well-being gain in restoring peatlands; however, the initial loss from draining peatlands in the first place is far greater (by an order of magnitude).

4. Discussion

In this paper we have described an explicit process of linking socially meaningful outcomes, defined in terms of changes to well-being quantified in monetary terms, to the outputs of a process-based model (DigiBog) for three different scenarios (natural, altered and restored ecosystem), placing the emphasis on describing the 'translation key' (Table 4). Such an explicit and articulated translation process increases the replicability of research outputs and makes it possible to scrutinize and update the translation key as new evidence emerges. An example of the potential for updating the translation with new evidence is our calculation of the relationship between water-table depth and vegetation cover of four PFTs. This was based on a robust dataset, but from a single peatland site. Further development of this relationship would benefit from inclusion of data from more sites, and could be used to parameterise a wider set of PFTs for inclusion in Digibog, or other models.

Of greater importance is the potential to challenge, and eventually improve, the translation key itself. For example, a core aspect of this process has been the linkage of ecosystem processes and functions to discrete categories of ecological condition. This meant we had to define 'cut-off' points (boundaries) to establish discrete changes in ecological condition. Although somewhat artificial, the use of discrete categories made it simpler to assess ecological conditions because survey respondents could easily attach well-being trade-offs to such discrete changes. It also greatly helped to define the extent of restoration efforts in the valuation scenarios (Martin-Ortega et al., 2017). However, while rich narratives that try to convey the idea of a gradual process occurring within each of the categories are an improvement over more simplistic descriptions often used in valuation studies, ultimately, the boundaries

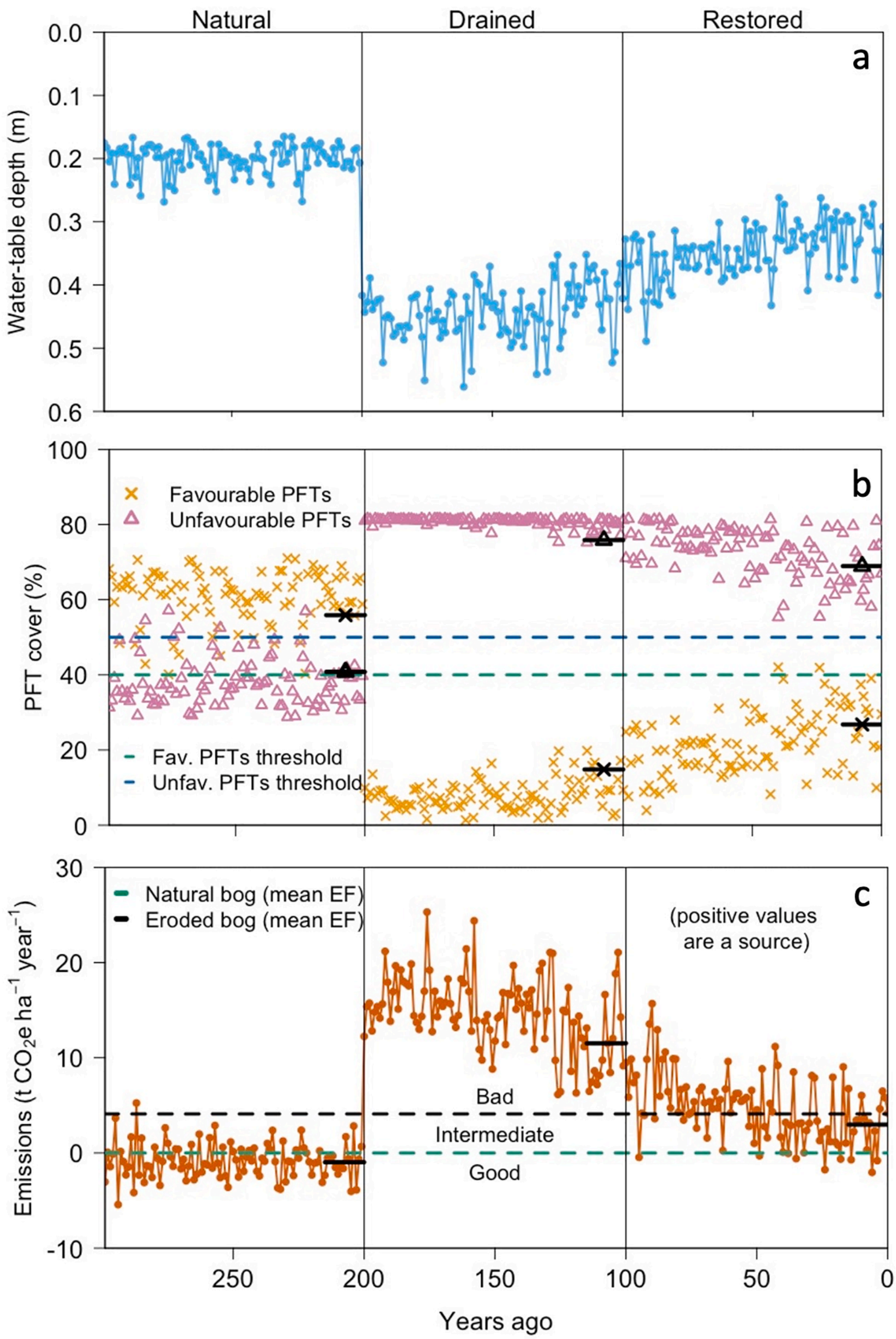


Fig. 3. Condition status assessment inputs for each of the three peatland stages (natural, drained, and restored). Values are the mean of all simulated peat columns. The condition assessment was carried out on all columns in the last 15 years of each period (shown by thick black lines on panels b and c. All panels show the final 300 years of the 5100 years simulation. a) Water-table depth used for predicting the plant functional types (PFTs) on the surface of the virtual peatland, b) Favourable and unfavourable PFTs surface cover, c) C sink status. Mean C emissions (CO_2e) for the three stages of the peatland simulation (natural, drained and restored). The average emission factors for natural, and drained and undrained eroded bog (Evans et al., 2017) were used in the classification of 'good', 'intermediate' and 'bad' C sink status conditions as indicated. The combination of both the criteria for PFTs and C sink status (Table 4) were used to classify the overall condition of the peatland stage.

Table 5
Proportion of peatland in good, intermediate and bad conditions.

Condition	Proportion of peat columns Natural	Drained	Restored
Good	1	0.03	0.04
Intermediate	0	0.29	0.79
Bad	0	0.68	0.17

or cut-off points between condition categories require a value judgement that can thus be questioned. The case for a cut-off point between the good and the intermediate conditions with respect to the C sink status of our virtual peatland is one such example. Only a peatland with a C sink status falls into our good condition category, because the boundary between good and intermediate conditions was explicitly designed to represent the change from carbon sink to carbon source, based on greenhouse gas emissions. But defining the boundary between intermediate and bad conditions was less straightforward and could be challenged. In the socially meaningful description, the intermediate

Table 6
Hectares of peatland in good, intermediate and bad conditions per peatland stage (natural, drained and restored), up-scaled to an hypothetical 100 hectare landscape.

Peatland condition	Hectares
Natural	
Good	100
Intermediate	0.00
Bad	0.00
Total	100
Drained peatland	
Good	3.00
Intermediate	29.00
Bad	68.00
Total	100.00
Restored peatland	
Good	4.00
Intermediate	79.00
Bad	17.00
Total	100.00

Table 7
Changes in well-being (in monetary values) derived from peatland degradation and restoration for an illustrative 100 hectare landscape.

	Change in hectares (as estimated by the simulation, Table 6) (A)	Per hectare value (£/ha, as reported in Glenk and Martin-Ortega, 2018)[a] (B)	Value (£) for a 100 hectare landscape (A × B)
Peatland degradation (from natural to drained)			
Hectares that deteriorate from good to intermediate condition	29.00	−190.90	−5536.10
Hectares that deteriorate from good to bad condition	68.00	−273.05	−18,567.50
Change in well-being			−24,103.40
Peatland restoration (from drained to restored)			
Hectares that improve from intermediate to good condition	1.00	190.90	190.90
Hectares that improve from bad to intermediate condition	51.00	82.15	4189.65
Change in well-being			4380.55

[a] Glenk and Martin-Ortega (2018) report a range of values for each of these changes in peatland category according to changes in some spatial characteristics. For illustrative purposes, here we use the average values. Negative values indicate loss of well-being due to ecosystem deterioration.

condition refers to "*[p]eatlands [that] have stopped growing. No additional peat layers are added. Instead, peat layers gradually shrink, releasing a moderate amount of carbon to the atmosphere*", while the bad condition refers to "*[p]eatlands [that] lose carbon at a high rate. They have turned into a severe 'source' of carbon to the atmosphere*" (Table 3). Establishing when carbon losses are moderate as opposed to high was a judgement based on published information: we chose to define the boundary between intermediate and bad conditions based on peatland emission factors in Evans et al. (2017). As explained in section 2.3, we used the mean of the emission factors for the eroded bog category (drained and not drained) as the limit of the intermediate condition category. Whilst the categories of the emissions factors (e.g., near natural peatland, modified peatland, eroded peatland) were helpful in defining condition boundaries, they are not necessarily socially meaningful. Furthermore, the PFTs are used here as proxies for the attribute "wildlife habitat" that was used in the choice experiment survey, which is another simplification.

An additional complication arises from the fact that the two ecosystem services (carbon emissions and wildlife habitat) are not independent of each other, since they share underpinning ecosystem functions and processes and affect each other. The econometric base of environmental valuation using choice experiments rests on the assumption that attributes reflecting ecosystem service provision can vary independently of each other (Holmes et al., 2017). This makes it implausible to value changes in ecosystem services resulting from peatland restoration on the same site independently if they are causally related (Glenk et al., 2014). For example, water-table position is a key driver of the different plant communities that develop and of the relative abundance of their component species, but it is also an important control of the peatland's C balance (the balance between addition of plant litter and decomposition of peat, Clymo (1984)). Additionally, the ease with which different plant litter decomposes is directly related to the accumulation of C in peatlands. It is therefore unlikely that a peatland with near natural vegetation and wildlife communities will lose significant amounts of carbon (see Fig. 3 and Evans et al., 2017). In cases like this, where ecosystem services are correlated, it is arguably better to bundle correlated services for valuation purposes (Glenk and Martin-Ortega, 2018)[2]. The peatland conditions used here allowed us to derive values for these bundles of services in a way that is more aligned with how ecosystem services are derived in reality. This inter-relation and dependency of service delivery applies to any ecosystem and not just peatlands (Bullock et al., 2011).

There were also socially meaningful outcomes that are not well addressed in our assessment, because they are not provided by DigiBog outputs. Water quality is affected by peatland condition (Martin-Ortega et al., 2014), and was one of the relevant outcomes featured in the narratives used in the valuation study (Table 4). However, DigiBog does not model changes in water quality. This means that in our linking process, water quality remains implicit, i.e. water-table depths and vegetation are expected to affect the water quality levels described in the narratives for the valuation, but this connection remains in the translation 'black box' (Fig. 1). Furthermore, we did not simulate the effect of future climate. This made it easier to visualize the linkage between ecosystem changes related to land management and the social outcomes of such changes, but increasing temperatures due to climate change may worsen peatland condition and affect the recovery time of restored areas (Ferretto et al., 2019; Gallego-Sala et al., 2010; Gallego-Sala and Prentice, 2013). Such climate change effects may translate into different social outcomes, since there might be varying public preferences associated with the timing of the delivery of the restored ecosystem services (Glenk et al., 2018).

Nevertheless, by exposing and discussing the translation key, the understanding of the connection between ecological change and its related social outcomes can be improved. The exposure enhances the possibility of continued improvement of integrated assessments, which provide critical information to decision-makers for the management of ecosystem change. This relates to other emerging suggestions, such as that made by Olander et al. (2018), who introduce the concept of Benefit Relevant Indicators (BRIs) as measures that capture the connection between ecological change and social outcomes by considering what is valued by people. BRIs are intended as indicators explicitly constructed to reflect an ecosystem's capacity to provide benefits to society. Their aim is to support ecosystem service assessments by measuring outcomes

[2] It can still make sense to value ecosystem services individually if the focus is on maximizing the delivery of one particular ecosystem service; for example, for off-setting calculations for that particular service.

that are demonstrably and directly relevant to human well-being by using causal chains to make the connections between ecological conditions and human use and enjoyment explicit. BRIs are a conceptual proposition that resonates with the assertion that we make here that those connections need to be central to and explicitly articulated in the assessment process. Jones et al. (2018) also used a translation focussed approach whereby ecosystem impacts, resulting from atmospheric nitrogen pollution, were linked to willingness to pay to maintain plant species diversity. We argue that much more discussion about the translation processes and keys used is still needed. Without it, the linking of ecosystem change and its social outcomes risks, on the one hand, loosing some of the rigour/scientific accuracy regarding the biophysical processes, rendering the assessments inaccurate or possibly flawed; or, on the other hand, not sufficiently meaningful for the public or useful for policy-making.

Finally, it is worth noting the policy relevance of the specific findings from our example and their implications for peatland restoration. By using peatlands, this paper also contributes to a limited body of evidence on the socio-economic consequences of changes in what is the most space-effective carbon store of terrestrial ecosystems (Yu et al., 2010). Across the world, peatlands are threatened by climate change and have, in some places, been severely degraded by land use, changing from a carbon sink to a carbon source (Joosten, 2009; Swindles et al., 2019). As a result, they are now one of the largest sources of greenhouse gas emissions from the terrestrial biosphere to the atmosphere (Leifeld and Menichetti, 2018). Understanding the socio-economic consequences of peatland degradation is therefore also key to advancing the global net zero emissions agenda. The monetary values presented here for an illustrative 100 hectare catchment are of the order of thousands of pounds for restoration and tens of thousands for degradation (Table 7). Considering that in Scotland alone there are over 1.5 million hectares of blanket bog habitat (Aitkenhead and Coull, 2016), gives a measure of the magnitude of the well-being implications of peatland degradation. Compared with the cost of previous and future public investments into peatland restoration in Scotland, peatland restoration is, overall, well-being enhancing, i.e. it provides overall net benefits (Glenk and Martin-Ortega, 2018). These net benefits strengthen the economic rationale for climate change mitigation through improved peatland management.

5. Conclusions

Ecosystem degradation represents one of today's major global challenges that threatens human well-being and livelihoods worldwide. To reverse continuing degradation, we need to understand its socio-economic consequences so that they can be incorporated into ecosystem management decision-making processes. For this, we need to link our knowledge of how ecosystems function and change to socially meaningful representations of those changes. While attempts are increasingly being made at such integrations, the translation processes required for effective linkage remain largely undiscussed. Therefore, key aspects of the socio-ecological interactions may be 'lost in translation'. We argue that, as we further our understanding of ecosystem change, and in line with the aspiration to understand its social effects, the intricacies of the translation processes need to be made explicit and be made available for others to inspect, so that true advancements can be made.

Here we have described, detailed and discussed a process of establishing the social outcomes (in terms of well-being changes measured quantified in monetary values) of ecosystem restoration, using peatlands as an exemplar of a complex ecosystem of global relevance. This illustration is limited in the extent that it only tests one single translation key, while others could be tested and their various consequences compared. Further, we do not claim that our process was perfect or superior to other attempts (this should be obvious from our discussion of the various unresolved and problematic issues in the previous section). Rather, we suggest that precisely those unresolved and problematic issues should be a focus of discussion in the study of global environmental change, and currently such discussions are not taking place often enough. Improving our ability to tackle the future effects of ecosystem degradation will, to a great extent, depend on the usefulness of the models used to understand ecosystem processes (e.g., models able to cope with many ecosystem parameters and that are relevant at the level of land management interventions), the quality of our valuation methods, and our ability to tailor them to specific cases (Evans et al., 2014). But there will always be a limit to the 'real-world' relevance of these integrated approaches if the relationships between these aspects remain in a black box.

Ideally, these integration processes should be co-developed with stakeholders. Iterative, adaptive, and interdisciplinary processes should help (Reed et al. 2013). For example, we used monetary values that had been obtained prior to engaging with DigiBog modellers (although the process was still transdisciplinary and co-developed with peatland scientists). An iterative DigiBog co-development process would have enabled us to make our narratives more consistent across peatland conditions. Furthermore, rather than using an existing model, we could have created an *ad-hoc* model from scratch – although it is also important to consider how realistic it is to construct new models for every assessment process or to come up with models able to cope with a large range of ecosystem types and conditions. Even so, the development of new bespoke models would still not be sufficient to produce a breakthrough without paying attention to the translation key between the two strands of knowledge. The translation key that we have exposed in this paper provides a way of interrogating the interface between our understanding of ecosystem changes and the estimation of their social outcomes. If these strands of knowledge become more sophisticated without paying attention to how ecological change is translated into socially meaningful outcomes (i.e., without paying attention to the 'translation key'), we risk enhancing the divide between them and hampering the robustness and rigor of integrated assessments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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