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Reviews and Syntheses: Evaluating the Potential Application of Ecohydrological Models for Northern Peatland Restoration: A Scoping Review

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Abstract. Peatland restoration and rehabilitation action has become more widely acknowledged as a necessary response to mitigating climate change risks and improving global carbon storage. Peatland ecosystems require restoration timespans on the order of decades and thus cannot be dependent upon the shorter-term monitoring often carried out in research projects. Hydrological assessments using geospatial tools provide the basis for planning restoration works as well as analysing associated environmental influences. “Restoration” encompasses applications to pre- and post-restoration scenarios for both bogs and fens, across a range of environmental impact fields. The aim of this scoping review is to identify, describe, and categorise current process-based modelling uses in peatlands in order to investigate the applicability and appropriateness of eco- and/or hydrological models for northern peatland restoration. Two literature searches were conducted using the Web of Science entire database in September 2022 and August 2023. Of the final 211 papers included in the review, models and their applications were categorised according to this review’s research interests in 7 distinct categories aggregating the papers’ research themes and model outputs. Restoration site context was added by identifying 234 unique study site locations from the full database which were catalogued and analysed against raster data for the Köppen -Geiger climate classification scheme. A majority of northern peatland sites were in temperate oceanic zones or humid continental zones experiencing snow. Over one in five models from the full database of papers was unnamed and likely single-use. The top three most-used of these models, based on the frequency of their use on distinct site locations, were LPJ, ecosys, and DigiBog, in that order. Key themes emerging from topics covered by papers in the database included: modelling restoration development from a bog growth perspective; the prioritisation of modelling GHG emissions dynamics as a part of policymaking; the importance of spatial connectivity within or alongside process-based models to represent heterogeneous systems; and the emerging prevalence of remote sensing and machine learning techniques to predict restoration progress with little physical site intervention. This review provides valuable context for the application of ecohydrological models in determining strategies for peatland restoration and evaluating post-intervention development over time.

1 Introduction

Peatlands play a vital role in global carbon (C) storage and climate regulation. However, their millennia-long cooling influence is now undermined through human activity, not least the active degradation of extensive areas of peatland and subsequently the effects of climate change (Helbig et al., 2022). In response, northern peatland restoration and rehabilitation activity has increased significantly with large-scale projects on industrial and governmental scales. Restoration projects and related research often occur in "bursts" with typical spans of 4-5 years based on funding availability (e.g., the European Union LIFE projects), or collaborations between academic institutions and other organizations. However, peatland ecosystems take decades to millennia to develop and as such, their impact cannot be perfectly extrapolated from the shorter spans within which these projects are carried out (Bacon et al., 2017).

Restoration plans will need to vary in their responses according to the type of peatland degradation that has occurred. Examples of activities having contributed to peatland degradation include drainage for livestock agriculture, especially in northwestern (NW) Europe, and the creation of oil palm plantations in tropical regions, especially Indonesia. Another example is peat harvesting for fuel or horticulture (where mining can extend down to the mineral soil in places), along with manual cutting along bog margins, which makes site-by-site hydrology extremely variable, especially where not well monitored. Frequently practised restoration strategies arising from peatland research and industrial action include: (1) inundation, achieved by efforts such as drain blocking, bunding, or cessation of pumping, favoured in its simplicity as a direct re-wetting approach; (2) topsoil removal, achieved by removing of the top layer of degrading soil (often less than 30 cm) and vegetation to mitigate nutrient export/minimise nutrient availability for the formation of new biomass; and (3) slow rewetting, a more controlled and progressive alternative to spontaneous inundation of long-term drained peatlands or costly topsoil removal, which diverge from standard restoration practices (Zak & McInnes, 2022).

Once the hydrological conditions of peatland ecosystems are disturbed, they react very sensitively, with consequences for catchment hydrology, soil properties, water quality and biodiversity (Dettman et al., 2014). Environmental impacts of degraded or restored bogs (in their biodiversity, nutrient transport, or C emissions) also depend on site hydrology (Strack et al., 2022). There is an ecological link in the net impact of hydrology on climate change mitigation (as C-storage or C-sinks) which is a primary goal of restoration, alongside efforts to improve regional and nationwide biodiversity: from policy and management perspectives, peatlands are more often considered as nature-based solutions to climate issues based on greenhouse gas (GHG) emissions, which have concomitant "co-benefits" for biodiversity and water quality (Strack et al., 2022). To reflect this, ecohydrological models include interactions between climate, hydrology, and landscape characteristics, producing outputs describing soil moisture, water level and flow, soil nutrient quantities, sediment transport, or vegetation community patterning/growth (Acharya et al., 2017).

Modelling peatland restoration is useful in its flexibility and in giving the potential to calibrate against different cases of rehabilitation and revegetation. Spatial hydrological assessments using models like MODFLOW (e.g., Brandyk et al., 2016), SIMGRO (e.g., Jaeincke et al., 2010; Povilaitis and Querner, 2008), SAGA (e.g., Ikkala et al., 2022), FLUSH (e.g., Haahti et al., 2016), TOPMODEL (e.g., Goudarzi et al., 2021), DigiBog_Hydro (e.g., Putra et al., 2022), or unnamed numerical algorithms (e.g., Kennedy and Price, 2004; Luscombe et al., 2016) provide the basis for creating a restoration plan, which often prioritises raising the water table as the key engineering goal with outputs confined to groundwater head/flow, surface water level, or catchment runoff/discharge. Yet, despite decades of research, models of this kind are deficient in addressing the entirety of restoring peatlands (i.e., the degradation, mid-restoration, and long-term impact stages) in an efficient, ecohydrological manner.

1.1 State-of-the-art models available to date

A variety of hydrological modelling approaches can be used in a northern peatland restoration context, including conceptual models, empirical models, and physical (i.e., process-based/numerical) models (Lana-Renault et al., 2020), and more recently, machine learning (ML) models (Shen et al., 2021). These models are not always ecohydrological in nature but can be manipulated to operate to this end.

Belyea and Baird (2006) present R.S. Clymo's theoretical Bog Growth Model (BGM) as the basis for their own conceptual models of peatland development, and called for the consideration of peatlands as Complex Adaptive Systems for future models. The authors found that the primary limitation of the BGM was a lack of accounting for cross-scale coupling of hydrological and ecological processes. They suggested that linking hydrological and ecological processes may provide insight on peatland structure development, while noting that (at the time of publication) feedbacks across temporal and spatial scales could not be properly incorporated (Belyea & Baird, 2006). Other hydrological conceptual models are often developed after extensive site-based monitoring, to inform further predictions of restoration or climate change impacts (e.g., Lhosmot et al., 2023). [MS1][MS2]

Models of peatland dynamics can be specific to climate policy-related outputs rather than providing a full picture of hydrology and ecology. Empirically based statistical GHG estimation models have been developed for C budgeting (van der Snoek et al., 2023; Swails et al., 2022). Van Der Snoek et al. (2023) developed a decision support tool (DST) to produce daily, monthly, or annual GHG budgets and a statistical model (SET) to calculate GHG budgets only annually. Swails et al. (2022) use a multiple regression model to demonstrate responses between soil respiration, soil temperature, and water table depth (WTD) in a restoration context, but only considered these in one site-specific study (in the southeastern United States).

The process-based DigiBog model (Baird et al., 2011; Morris et al., 2012) combines C-accumulation with a hydrology submodule (Young et al., 2017). However, the C-accumulation submodule accounts only for deep peat modification, meaning that there is a discrepancy between rapid near-surface C-accumulation and overall C sinks in a peatland (Young et al., 2019). Recent studies also use ML instead of process-based models, as researchers such as Koch et al. (2023) claim that site-specific knowledge for hydrology, topography, and soil properties makes process-based modelling difficult in large-scale applications. Active development of new ML models is occurring with increased specificity, as well, such as one developed by Horton et al. (2022) to describe the distribution of fires in tropical peatlands for testing the potential impact of management and restoration scenarios.

Recent efforts have been made to identify available models for peatland dynamics in a review by Mozafari et al. (2023), though the review made little explicit reference to peatland restoration. Additionally, a scientometric review was completed by Apori et al. (2022) to identify papers that examine the restoration of degraded peatland in the current body of literature, but neglects a focus on modelling.

1.2 Knowledge gaps

Restoring site hydrology (i.e., raising WTD) is often considered by engineers and policymakers as the landmark for restoring an ecosystem. When considering ecohydrology, desirable model outputs will depend upon (but likely go beyond) detailed hydrology which, in the case of restoration, may create distinct zones of varying hydraulic behaviour contingent upon the scale of degradation or the restoration technique applied. Additionally, process-based models have infrequently been calibrated to describe degraded scenarios or a transition from a degraded to a restored scenario.

Modellers may be required to understand how and when habitats will change, how much new peat may accumulate long-term, and the subsequent C cycle implications of such evolutions, which is difficult to find in any single modelling exercise in literature to date. There are very few state-of-the-art, process-based, ecohydrological models available to date which have been employed in a peatland restoration application (Mozafari et al., 2023). The potential application of existing models to peatland restoration (considering more than single-state scenarios) has, to date, not been explored systematically. Engineers, planners, researchers, and policymakers would benefit from being more informed about what models currently exist not only to describe peatlands, but to describe peatland restoration, which would be favoured over developing one’s own model tailored to a single restoration scenario or location.

Therefore, the aim of this paper is to identify, describe, and categorise current process-based modelling uses on peatlands in order to investigate the applicability and appropriateness of eco- and/or hydrological models for northern peatland restoration. This will unite ecohydrological and restoration modelling interests by interpreting the relevance of different models’ output(s) to peatland restoration projects, with the expected goal to predict the success of restoration measures undertaken in northern peatlands. Hence, the exploratory nature of this review is scoping rather than systematic.

2. Materials and Methods

2.1 Literature searches: September 2022[MS3] and August 2023

A literature search was conducted using the Web of Science entire database in September 2022 and updated for the 2022-2023 period with a second search in August 2023. The following search string was employed in an advanced search: TS= (peat* AND ((model* AND hydrolog*) OR (model* AND GHG))). The combined search yielded 1116 results. These references were downloaded in .ris format and collated in the free, open-source reference management software, Zotero (Corporation for Digital Scholarship, George Mason University). The papers were screened three times in alphabetical order, with each iteration eliminating inappropriate titles and reducing the batch size.

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While some papers in the search overlapped with the previous search, regular comparisons with the existing database were heeded to avoid double-counting. This addition to the full dataset is shown in Table S3.

2.2 Determination of appropriate models

Models were considered for their potential application in an ecohydrological manner, despite differences in the actual processes incorporated in individual model codes, and whether or not they are strictly called ecohydrological (e.g., a purely hydrological model being shown to operate well in a peatland context). As it may be valuable to investigate long-term bog growth for systems so fundamentally changed by mining or degradation that returning to a "former" habitat is not likely, modelling organic matter decomposition and emission over the span of decades or centuries is pertinent for consideration beyond current hydrological and C dynamics. It is unlikely that any single model will be able to encapsulate all these interests for simulating a restored bog or other northern peatland region. Therefore, it was valuable to document which modelling options exist on local to global scales, as well as in different dimensions of space, time, or conceptual structure, and how these models operate in case some can be combined or used in tandem.

A first pass considered all paper titles, and occasionally portions of paper abstracts for clarity. A second pass was made where the methods sections of each article were read in full. This was done to identify which model interfaces are used and discard those papers that do not name any models or whose models' functions do not match the scope of this review. Criteria for the rejection of a number of articles fell into two themes: too much specificity, or a lack of connection with hydrology (Table 1). This review focusses on "northern" peatlands, existing above 50-40°N (with some emphasis placed on NW Europe, given this a region of interest for the authors), as they are distinct enough in climate and land use contexts from "tropical" peatlands such that modelling in these categories is generally known to diverge in literature (Tarnocai and Stolbovoy, 2006). Some tropical peatland hydrology studies were retained that employ restoration-related modelling which may be useful to identify, despite differences in climate and ecosystem characteristics.

A third and final pass was made during which pertinent information from the full articles was gathered to fill a summary table for each paper. A table, created for each model category, included the following subheadings: (1) Sole focus on hydrology (Pure Hydrology); (2) Focus on greenhouse gases and connected biochemistry (GHG Dynamics), with the ideal to prioritise process-based models which went beyond calculating net ecosystem exchange or global warming potential as sole outputs; (3) Description of long-term peat accumulation projections or reconstructions (Peat Accumulation); (4) Regional or national scaled-up models involving northern peatlands looking beyond a site-specific scale (Global Models); (5) Multiple models from previous categories used in tandem or in sequence (Model Combinations); and (6) Models integrating or coupling processes included in previous categories (Coupled Models). Pertinent information from the second literature search was added to a separate table with identical headers to the original database except for an additional column "Category" linking the papers to the previously generated model categories (five papers appeared relevant but did not neatly fit into any of the existing model categories; their sole focus covered restoration-related remote sensing topics and were categorised as (7) "Remote sensing" to

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reflect this). Studies performed by the same first author(s) on the same or similar site(s) were considered together as a "suite" during analysis but remained separate for subsequent tables and figures.

A final total of 211 relevant papers was retained in the database. The database was manually reviewed for key models of interest and their relative frequency within the full set (in which 224 models [MS4]are identified for the 211 papers in the database). Considerations for making this selection were as follows:

1. If coupled model packages (like CoupModel, housed in its own interface, or DigiBog/MPeat, where code is freely available in common languages like Fortran and MATLAB (though varying in cost barrier)) already exist that appear flexible enough to apply to a northern peatland context, these should be prioritised, especially considering the FAIR (Findable, Accessible, Interoperable, and Reusable) accessibility guidelines which can improve research communication and future application of models beyond academia (Mozafari et al., 2023).
2. As demonstrated in Table 2, just over one fifth of the total database consisted of unnamed, often numerical models, hand-made for specific research needs and rarely used more than once or twice. They are therefore less likely to contribute significantly to the sharing of modelling methods because their accessibility is limited to the creator. Additionally, the consolidation of approaches improves confidence in modelling, making the use of unnamed models less beneficial, along with less commonly used models serving similar purposes to more commonly used ones.
3. Focussing on the ecological side of ecohydrological modelling became pertinent because of the wealth of background already present for pure hydrological models and this review's emphasis upon moving beyond hydrology as the priority for restoration targets.

The full dataset, including each paper's DOI, first author, year published, model(s) used, and a brief description of the research scope, is summarised completely in Tables S1 and S3. Within the 211 papers recorded, 234 unique study site locations were identified, catalogued, and analysed against raster data for the Köppen-Geiger climate classification scheme (Tables S2 and S4): developed by Wladimir Köppen and Rudolf Geiger and published by Köppen in 1936, the system has since become an established multidisciplinary standard for describing the climate of a region (Rubel et al., 2017). This was done in order to evaluate the potential prevalence/preference for the use of different models depending on the climate conditions of sites on which they were tested. Additionally, data types and durations used in some papers were documented as the review progressed, to provide a fuller picture of the potential utilisation of key models.

Post-hoc analysis of shortlisted models occurred to explore what information will aid potential modellers in determining either the suitability of a single model for their purposes, or the potential compatibility of combining existing codes or running models in tandem. This centred around general model specifications and information about data inputs as discussed above. Observations and conclusions made based on data solely from the second literature search will be designated as such.

3. Results

The following observations were made for papers collated within the 7 model categories (Table 2):

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"Pure Hydrology": Seventy-seven total papers were catalogued for this category, making it the largest (approximately 36.5% of the full database). MODFLOW featured here prominently, with 15 papers using the model, around 19.5% of all models in this category. Only 6 papers across the entire category (7.8%) were published in 2022 or 2023, 3 of which came from the second literature search.

GHG Dynamics: Forty-one total papers were found for this category, approximately 19% of the full database. Additionally, it is possible that some models in this category are in fact "integrated" or "coupled" (i.e., they include hydrological or other processes, as well as the necessary biochemistry) but the only outputs are GHG-flux related. Ten papers across the category (25%) were published in 2022 or 2023, 9 of which came from the second literature search.

Peat Accumulation: Ten total papers were found for this category, making it the smallest (approximately 5% of the full database). The majority of models use historical climate reconstructions as the basis of the model. The papers in this section also had an average publication year of 2009, making this category "older" than the others, all with average ages between 2014 and 2016. No new peat accumulation topics were identified in the second literature search except for one paper classified as a Model Combination which incorporates peat accumulation.

Global Models: Sixteen total papers were found for this category, approximately 7.5% of the full database. While it was not expected for many of these papers to be relevant to the current study, because individual countries may appear as only 5–10 cells within a large grid and individual peatland sites may be indistinguishable, it may still be important to account for the models used here, especially those which represent "northern peatland" condition. Only 1 paper in this category was published since 2021; all others were published in 2020 or earlier.

Model Combinations: Nineteen total papers were found for this category, approximately 9% of the full database. "Model combinations" either present outputs not encapsulated by a single model or include the processes from two or more models to yield a more robust output. There may be more combinations among the other categories which are not presented outright, but these papers were considered to be unique because of the combinations they employ. Eight papers across the category (42%) were published in 2022 or 2023, 6 of which came from the second literature search.

Coupled/Integrated Models: The second-largest category (approx. 20.5% of the full database) consists of coupled models housed within the same interface or code, with 43 total items. Some "suites" of papers from the same authors occur here where model development can be tracked, or multiple outputs are analysed for the same sites and published separately over a number of years.

Remote sensing: Finally, an emerging trend regarding models that include a remote sensing aspect was found in the past year (2022-2023): almost one in three (9/29) papers from the second literature search[MS5] included remote sensing data or was based on a remote-sensing classification model. Five of these papers (Ball et al., 2023; Dabrowska-Zielinska et al., 2022; Dadap et al., 2022; Jussila et al., 2023; and Puertas Orozco et al., 2023) presented their approach and results as distinctly remote-sensing oriented and were placed in their own "Remote sensing" category for post-hoc discussion. These take up the remaining 2.5% of the total database.

Thirteen of the 31 Köppen-Geiger classifications were represented by the peatlands modelled in this review (Figure 1). Most sites were within the Dfc (subarctic climate), Dfb (warm-summer humid continental climate), and Cfb (temperate oceanic or subtropical highland climate) classifications. Note that Dfc, Cfb, and Cfc classifications describe most of NW Europe, whereas Dfb primarily describes Canada in this review. The Cfb and Dfb classifications are similar with the key distinction that Dfb locations are continental rather than coastal, and thus experience more snow. The greatest proportion of papers originated from western European countries, whilst the single country with the most attributed study sites was Canada; a GIS map layout plotting the coordinate locations of individual study sites is included in Figure 2.

Seventeen papers did not use physical study sites, many of which were global or regional studies scaling up data from a wealth of site-specific research. Three papers (Bechtold et al., 2020; Qiu et al., 2018; and Qiu et al., 2019) catalogued too many sites to document meaningfully (these were also housed within the “Global Models” category).

The following process-based models were identified to have the most potential applicability to northern peatland restoration scenarios (in no specific order): (1) DigiBog (including DigiBog_Hydro); (2) MPeat; (3) CoupModel; (4) *ecosys*; (5) McGill Wetland Model (MWM, including CLASS3W-MWM); (6) SWAT; and (7) LPJ (including LPJ-GUESS and LPJ-WHyMe). The top three most-used of these models, based on the frequency of their use on distinct site locations, were LPJ, *ecosys*, and DigiBog, in that order (Table 3). Note that no recent (2022-2023) papers used models highlighted as high-potential except for CoupModel; however, the prevalence of CoupModel is still smaller than *ecosys*, the other coupled model highlighted, and thus further analysis or modification of “top three” models was not deemed necessary.

The high-potential models included here fell into the Peat Accumulation category (DigiBog, MPeat), the GHG Dynamics category (MWM, SWAT, LPJ), and the Coupled Models category (CoupModel, *ecosys*). For each of the models, the focus of climate region differs. Papers using DigiBog concentrated their focus on theory (“no location listed”) and UK sites (Cfb), given that the model was developed by researchers from the UK. LPJ and *ecosys* both focus heavily on Df-regions, where 5 of 14 *ecosys* study locations (36%) are within the Dfb region, and 7 of 16 LPJ study locations (44%) are within the Dfc region.

The models incorporating the most natural processes were the coupled models: CoupModel and *ecosys*. While *ecosys* has a multi-dimensional capability, the highest dimension attempted by only one paper included in this review is 3-D (Putra et al., 2022).

Bog growth modelling applications for peat regeneration were identified chiefly in DigiBog, with MPeat demonstrating similar capabilities without real-world application in the literature (to date) and incorporating additional soil mechanical processes. HPM, while also developed to model long-term bog growth, was more often used in global/regional scales, lessening its value in a restoration context where decisions and targets will need to be made most often at a single-peatland scale.

MWM and SWAT feature less often than LPJ; this is primarily because the 6 papers employed LPJ models in multiple site-scale instances. One of the LPJ models, LPJ-WHyMe, is tailored to wetland ecosystems but limits its GHG output focus to methane only (Wania et al., 2010). MWM has multiple limitations: it is one-dimensional with fixed vegetation settings; hydrology processes are used to inform GHG dynamics, but this coupling is not reversed; and there is no consideration of nitrogen cycling, methane, or dissolved organic carbon (Wu & Roulet, 2014). While SWAT did not feature as often in

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frequency, one recent paper by Melaku et al. (2022) modified the model to estimate groundwater table, carbon dioxide emissions, and net ecosystem exchange on a watershed scale for the Athabasca basin in Canada, integrated uniquely into a GIS interface.

Additional information was obtained for the "top three" most-used models, DigiBog, *ecosys*, and LPJ, to assist in anticipating the usability of these programs regardless of geographical context (Table 4). Fortran is employed for a majority of these programs, as it is the expectation that modification of the model's included processes, etc. will require direct coding. Furthermore, most models include multi-dimensional modelling capabilities, with the exception of DigiBog. Finally, time spans for data collection and model simulations were recorded for a selection of key papers using the "top three" models in Table 5; the full description of time spans for all "top three" models is included in Table S4.

4. Discussion

4.1 Modelling restoration development from a bog growth perspective

Within past decades, numerical models have been refined to represent peatland-specific complexities, especially considering changes occurring in the acrotelm (the hydrologically active, living layer of bog peatlands) characteristics interacting with hydrological boundary conditions (such as bog shape).

DigiBog is significantly more concise than ecosystem-based models such as CoupModel or *ecosys* with respect to nutrient cycling, but is able to evaluate restoration over time because of its spatial flexibility and fewer parameters and outputs to focus on key metrics such as peat thickness and WTD. Planners, engineers, and policymakers may also be able to employ DigiBog without necessarily needing extensive knowledge in organic chemistry, hydraulics, or microbiological processes, which are required to properly interpret more detailed ecosystem-based models.

Morris et al. (2011) created four 1-D bog growth models (BGMs) to serve as the basis for DigiBog, but did not include any of the biogeochemical changes associated with fen-bog transition. Fen-bog transitions occur along geologic time scales when the water table becomes consistently high to cease meaningful interactions with groundwater (Wu & Roulet, 2014). In a restoration case, one may wish to model a degraded (often bare-peat) bog-fen transition, as revegetation brings more wetland shrubby habitats and vascular standing-water plants capable of withstanding rewetting by inundation and less acidic conditions. After modelling a "forced" shift from bog soil to fen habitat, in time the land would revert into a bog, making the inclusion of changes in vegetation and hydrology/soil characteristics valuable especially in process-based models.

According to Mahdiyasa (2021), comparisons between MPeat and DigiBog show that assuming a constant bulk density throughout the column, plane, or full bog volume will create a "stiffer" bog, potentially overestimating peat accumulation and WTD (i.e., reality may have lower values of each compared to modelled outputs in DigiBog) over the span of millennia, compared to estimates from MPeat and HPM. However, MPeat is only 1-D, so restoration efforts cannot easily be captured spatially.

The 2-D application of DigiBog for a blanket peatland, demonstrated by Young et al. (2017), shows the impact of ditches/blocking can be included, which is encouraging for future restoration modelling, which may include more intensive measures like bunding (Figure 3). However, a constant bulk density is used in the Young et al. (2017) adaptation. In some DigiBog simulations, water table can be fixed or forced before evaluating bog response, allowing for WTD predictions to vary based on human interventions (Young et al., 2017). Given that many restoration actions control the water table primarily, such as cell bunding managed by weirs or pipes, it may be a valuable application of the model to force the WTD prior to simulating it long-term.

In studies using peat accumulation models, changes in soil characteristics (especially where bare peat is concerned) were not investigated. In a recently inundated bare-peat bog beginning rehabilitation or restoration, there is the potential for peat mechanical behaviour to be "stiffer" than in natural cases, due to the drying of peat at the surface has dried, such that microporosity is fundamentally changed. It may be valuable to compare peat hydraulics for degraded and pristine material to more properly represent bare peat in restoration modelling.

While DigiBog's and MPeat's focus on peat accumulation and hydrology to better characterize bog growth/formation change omits some of the key outcomes of interest for restoration like GHG dynamics, they present a potentially valuable starting point to predict how a degraded system may recover (or not) in years to come. There is a considerable lack of recent focus upon peat accumulation modelling as demonstrated by this review, especially by the absence of this category in recent (2022-2023) papers. But, the application of the BGM may be pertinent for monitoring and modelling peatland rehabilitation, especially if a degraded bare-peat site is being managed to transition into either a bog or fen habitat over the long term without expecting immediate results. Like what has been developed in this review's "Model Combinations" category, a similar linkage could be made between a BGM like DigiBog and a terrestrial ecosystem model or something similar (especially if both are written in Fortran, such as *ecosys*), either in multiple 1D locations or in multiple dimensions, to incorporate long-term projections into restoration modelling.

4.2 General ecosystem models: emissions as key restoration "targets"

Often, the use of general ecosystem models on peatlands has an overarching goal of future incorporation into global climate models (e.g., Sulman et al., 2012), which deviates from the goals of field-based peatland restoration. However, organising a process-based ecosystem modelling system to analyse carbon fluxes in peatlands may be of interest for policymakers at a local or regional scale, rather than calculating metrics such as ecosystem respiration, gross primary productivity, and net ecosystem production manually based solely upon field measurements from specific sites. Here, ecosystem models are grouped based on the observed overlapping of processes which may be of interest to researchers, engineers, or policymakers.

4.2.1 *ecosys* and CoupModel: coupled, fully detailed models

The capabilities demonstrated by *ecosys* overlap with many other models of interest identified here. For example, several papers have produced numerical models specifically to capture dynamics in hummock-hollow patterning (e.g., Couwenberg, 2005; Nungesser, 2003; Eppinga et al., 2009; Heffernan et al., 2013; Kaplan et al., 2012); meanwhile, *ecosys* can spatially simulate this feature as well as including general ecosystem processes. Additionally, CoupModel can simultaneously simulate WTD and carbon dioxide fluxes in 1-D (e.g., Kasimir et al., 2018; He et al., 2023a/2023b); *ecosys* shares this capability in addition to lateral flow capabilities in multiple dimensions.

Both CoupModel and *ecosys* require a rigorous understanding of manifold environmental processes, but CoupModel is housed within a browser User Interface (UI) rather than requiring knowledge with Fortran. Additionally, *ecosys*'s complexity does not make the model "better" according to Sulman et al. (2012). In fact, the model over- and under-estimated some of the same GHG fluxes seasonally and across different landscape types similar to the less complex models in the review (perhaps calling into question the necessity of such detail if outputs are not significantly more accurate or precise). For the purposes of evaluating ecohydrology, however, *ecosys* matches performance from the ecological process side while also simulating WTD, unlike other models reported by Sulman et al. (2012) which do not have hydrological outputs.

Ecosys models produced by Dimitrov et al. (2010) for a bog and later a peatland transition zone (Dimitrov et al., 2014) focussed solely on hydrology, and further produced coupled versions in other contexts. Models did not display very high accuracy (R2 between 0.40 and 0.56) for monitoring WTD and water content in the intact bog. Macropore flow was included in the models; results were even less accurate without the inclusion of this process (R2 between 0.27 and 0.41). In bare peat conditions, where the surface no longer maintains macroporosity prior to revegetation, there is the risk that the model will provide less reliable results compared to the "ideal" bog with Sphagnum-covered peat. Mezbahuddin et al. (2017) used *ecosys* for coupled ecohydrological purposes in a Canadian boreal fen. They controlled lateral flow between a chosen number of cells, while including microbial activity and carbon dioxide fluxes (which can be reduced to GPP or NEP), as well as simulating WTDs within the plane, with decent accuracy (R2 between 0.68 and 0.84 for CO2 fluxes). Figure 4 demonstrates an example of an *ecosys* output (Mezbahuddin et al., 2017).

The primary challenges with *ecosys* and many general ecosystem process-based models remain that simulating changes in peat near-surface characteristics (i.e., key features such as bulk density, macroporosity, and vegetation) over time due to restoration is not integrated and may need to be forced, and these programs do not account for peat volume change in the long term. Additionally, Sulman et al. (2012) point out that the models are "better" at modelling fens than bogs, in that there is more significance in trends linking WTD with GHG fluxes.

CoupModel and *ecosys* are able to provide truly robust ecohydrological and biogeochemical outputs as a result of the numerous "switch" specifications (i.e., choosing if certain processes should be considered and in what manner – e.g., accounting for snowmelt or soil freezing and thawing, or neither) required, and parameters defined. However, this inevitably generates a steep learning curve which may deter researchers or consultants from implementing these models. But, given the precedence in applications to peatland ecosystems specifically, pre-existing model interfaces/codes are valuable for the foundation they provide for collaboration and further refinement.

In the case for modelling degraded, bare peat landscapes, for which there is little precedent, further modifications will be needed to model the dynamics of vegetation arising from these conditions. One recent paper by He et al. (2023a) did model

GHG emissions coupled with hydrological and chemical impacts of an actively extracted peatland using CoupModel, establishing a precedent for this interface. Additionally, the impacts of restoration altering degraded peat hydraulics (especially depending on the severity of peat extraction) can potentially transform degraded bogs into either fens or bogs. It may be worth exploring if models with a higher level of complexity can possibly predict bare-peat transitions, or if too many assumptions must be made during calibration. Additionally, pairing a peat accumulation model with *ecosys*/CoupModel side-by-side or in conjunction may be valuable to test if WTD can be simulated at similar levels in the long term, and to test to what extent the incorporation of peat growth processes impacts the hydrology such that GHGs simulated in fully coupled general ecosystem models might be over- or under-estimated.

4.2.2 LPJ, MWM and SWAT: wetland specificity

Wu and Roulet (2014) used CLASS3-MWM, a coupled version of the McGill Wetland Model (MWM), to simulate GHG dynamics across multiple climate scenario projections. This 1-D model represents C fluxes as Net Ecosystem Production (NEP) for representative single-year batches throughout a century. The model was able to support fen-bog transitions from the circa 2000 to 2100. With imposed climate change scenarios, the model predicted resiliency in bog ecosystems and that fen-bog transitions could make peatland ecosystems more resilient in the changing climate. The key divergence in applicability of MWM is the representation of whole peatland ecosystems with 1-D points to compare bog and fen ecosystems broadly. Additionally, the threshold between a modelled C sink/source was shown in the balance between gross primary production and decomposition, concluding that the soil C response of bogs to climate change is determined chiefly by vegetation production and decomposition in the acrotelm (Wu and Roulet, 2014). In the vulnerable years at the start of degraded bog rehabilitation, models may need to represent vegetation growth and associated ecohydrological changes with greater detail than what is demonstrated with MWM here.

Tang et al. (2018) modelled dissolved organic carbon (DOC) transport through a watershed (excluding gaseous C fluxes) using LPJ-GUESS, demonstrating higher DOC quantities in peatlands (bog and fen) than in mineral soils. The model code (C++) is modifiable; DOC and "water routing" modules were added in by the researchers. There is no indication of the consideration of peat growth or microtopography. Despite originating from the same model, LPJ-GUESS is fundamentally different from LPJ-WHyMe (with wetland methane-specific GHG outputs) where each exists as a discrete package with specific output objectives. From a policy perspective, if concerned with specificity, such as simulating short-term methane emissions resulting from rewetting or long-term vegetation community extents to incorporate in land-use change projections, it may be advantageous to maintain a "base" model with a hydrological site/region focus and subsequently vary a connected ecological model element relative to a desired output (i.e., "Model Combinations" like in Bernard-Jannin et al., 2018; Booth et al., 2022; Wilson et al., 2022). Compared to using a fully coupled model like *ecosys* or CoupModel, this approach may not require as much data, parameter calibration, time, and power to compute results.

Finally, the ecosystem-based model SWAT was employed in ArcGIS by Melaku et al. in 2022 (Figure 5); the model has been adapted for uses ranging from farmland nutrient tracing to cold wetland watershed organic cycling (Kalcic, Chaubey, and

Frankenberger, 2015). It is formed on the basis of Hydrologic Response Units (HRUs), which are user-defined areas of similar land use, soil type, and topographical characteristics, which can be tailored to peatland landscapes and intra-peatland landscape variations. They present newly developed subroutines for nitrous oxide release into the atmosphere and carbon dioxide emissions using microbially mediate soil organic matter (SOM) decomposition for the Athabasca River Basin in Canada (Melaku et al., 2022). Many areas in the basin have been exploited for oil sands development, so the model is able to handle some form of degradation though perhaps only as a fixed state.

Setting up land-use boundaries for HRUs (with a limit of a few hundred unique types allowed) may be a useful way to delineate restoration techniques within a bog plot on a micro-scale, with the potential for scaling up and perhaps examining interactions with nearby agricultural lands. The paper acknowledges, however, that HRUs limit the resolution available for classifying different kinds of wetlands, which may pose a challenge for demonstrating heterogeneity in site-scale modelling (Melaku et al., 2022). Additionally, having a subroutine for wetlands specifically is a new development for SWAT, making the field of research employing this model for wetlands quite small.

4.3 Connectivity with spatial analysis

4.3.1 Process-based modelling with a spatial element

A 1-D column cannot realistically represent an entire peatland, especially those with mosaics of different stages of degradation and revegetation. Models with direct links to spatial imagery software can more easily incorporate already-existing satellite data or mapping data to hopefully improve accuracy or precision in results. Additionally, GIS (especially ESRI) products are often employed by engineers and scientists in planning, design, and dissemination of knowledge for peatland restoration.

As described previously, SWAT can be housed within a GIS software, potentially making it more accessible for those already familiar with GIS. But, producing full maps outlining carbon dioxide fluxes per pixel per unit of time may be more rigorous than necessary, especially for a site-scale, bog-per-bog restoration analysis. If comparing spatial differences in restoration design, one could perform comparisons via 1-D points (e.g., Kasimir et al., 2018) or a 2-D transect between two zones (e.g., Young et al., 2017). Once the distinct dynamics of degraded, intact, and restored zones are more fully understood, this information could be incorporated into a larger scale 2D plane or 3D model.

However, some multidimensional modelling in a restoration context has been carried out. A “pure hydrology” paper from Jaenicke et al. (2010) created a 3-D dome model for restoring an Indonesian peatland by inputting remote sensing data to the SIMGRO model used with GIS (Figure 6). They relate their simulated hydrology to carbon storage by providing an index (developed by Couwenberg et al. in 2009) for carbon stored in a peatland of a given area per centimetre of groundwater rise. The focus of the paper was on developing a restoration scheme rather than evaluating its effectiveness, though it is likely that future monitoring and modelling will occur now that it is set up. Jaenicke et al. (2010) are able to generate a finely resolved map of WTD rise across an entire peatland area, though with no connection to carbon cycling or peat accumulation processes.

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While this model does not feature prominently in this review or within northern peatland applications, there remains potential for SIMGRO's usefulness.

DigiBog_Hydro has connectivity with GIS for determining peatland-specific hydrology in a 2-D plane, with applications in a restoration context (Putra et al., 2022; see Figure 7). Required inputs for DigiBog_Hydro are simply entered into a GUI, so no coding knowledge is required unless further modifications are attempted. Additionally, the user manual is well put together and freely available. DigiBog_Hydro does neglect some of the peat accumulation elements of DigiBog proper, though if they were developed in sequence there may be a higher possibility of incorporating the peat accumulation element in the future if desired. The model may provide a jumping-off point to obtain a hydrology "snapshot" for a site area before (or concurrently with) connecting it to ecosystem dynamics over time.

4.3.2 Spatial analysis via remote sensing and machine learning (ML)

The five papers which stood apart from the pre-existing analysis' model categories included outputs centred around predictions of soil moisture, vegetation communities/extents, and resulting gross primary productivity estimates; while these outputs have hydrological and ecological themes, they do not directly incorporate hydrological or ecological processes, and rather favour using the existing body of research along with ML predictions to form conclusions about the nature of peatland ecosystems with little to no physical intervention. Four other recent (2022-2023) papers gathered in the Model Combinations and GHG dynamics categories also featured satellite data with ML classification, though these were treated as data inputs to other models rather than being the end goal of the research.

The challenge posed in bringing together similar types of ML code for this type of review is a lack of official title for these programs apart from well-known algorithms like Random Forest (e.g., in Kou et al., 2022; Rissanen et al., 2023; Ross et al., 2023). Until now, there is not much consolidation of data or codes used for remote sensing projects. As the field of ecohydrological modelling progresses, the connection with spatial imagery may become more prominent and favoured not only as a way to incorporate more data into models when site-level instrumentation proves too difficult to orchestrate, but as a standalone technique for predicting hydrological and ecological changes and especially for enacting regional or nationwide policy decisions.

5. Conclusions

The potential application of ecohydrological process-based models is a promising current and future field of exploration for determining strategies for peatland restoration and evaluating post-intervention development over time. Modelling can contribute to the combined responsibilities of restoring peatland sites and tracking subsequent environmental impacts. While this review has stressed the GHG-emissions sphere of modelling peatland environments ecohydrologically, vegetation community and water/soil nutrient outputs from ecohydrological models may be of additional value: it is probable that models such as *ecosys* or CoupModel have the flexibility to produce outputs with implications for biodiversity or water quality as well, given that foundational biochemical processes are present. Predicting long-term peat accumulation (such as with DigiBog) may be less compatible with models producing other desired outputs. It may still be valuable to be develop peat depth projections as a result of current restoration efforts, though this may need to remain a separate and supplementary focus to the more prominent ecohydrological component. Additionally, the introduction of vegetation on a previously bare landscape is (understandably) not included in most models reviewed and may need to be forced to mimic a restoration "event" over a period of time. Finally, while the majority of this review has discussed process-based models, statistical (especially regression) models and ML provide additional ways to conceptualise and predict peatland processes; as requirements for spatial connectivity prove useful for policymaking or engineering design, newer research appears to diverge from site-by-site focus while still remaining distinct from scale-up global models.

Where current restoration efforts focus primarily on raising the WTD as a proxy for "successful" rewetting, here it may be argued that evaluating the "success" of peatland restoration, especially for former industrial sites, must include the monitoring and projections for emissions, nutrient loading, and other ecosystem changes without falling into the trap of assuming the scientific consensus that improved hydrology tends to improve environmental impact. As such, there may be additional management options required for peatland restoration in the future which could alter the demands of ecohydrological modelling and go beyond the considerations from this review.

Code/Data Availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Author Contribution

MPS conducted the literature searches and all subsequent analysis. LG provided advice throughout the review process. MGH proofread manuscript drafts to prepare for submission.

Competing interests:

The authors declare that they have no conflict of interest.

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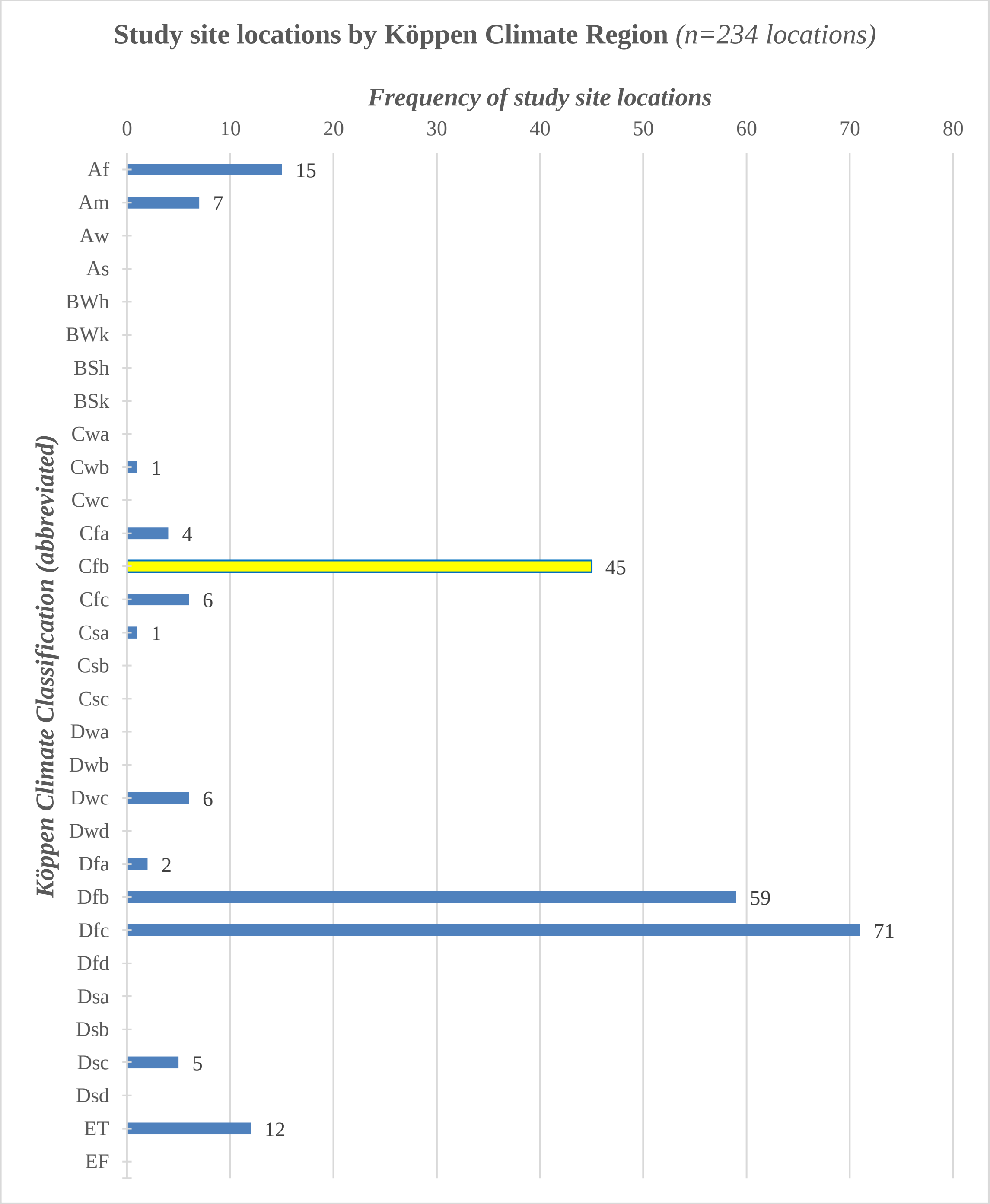
Figures



665 **Figure 1: Study site locations by Köppen-Geiger climate region. Much of NW Europe, a region of interest for this review's authors, is classified entirely as Cfb, highlighted in yellow. For a full breakdown of climate region classifications and their abbreviations, see Kottek et al. (2006).**

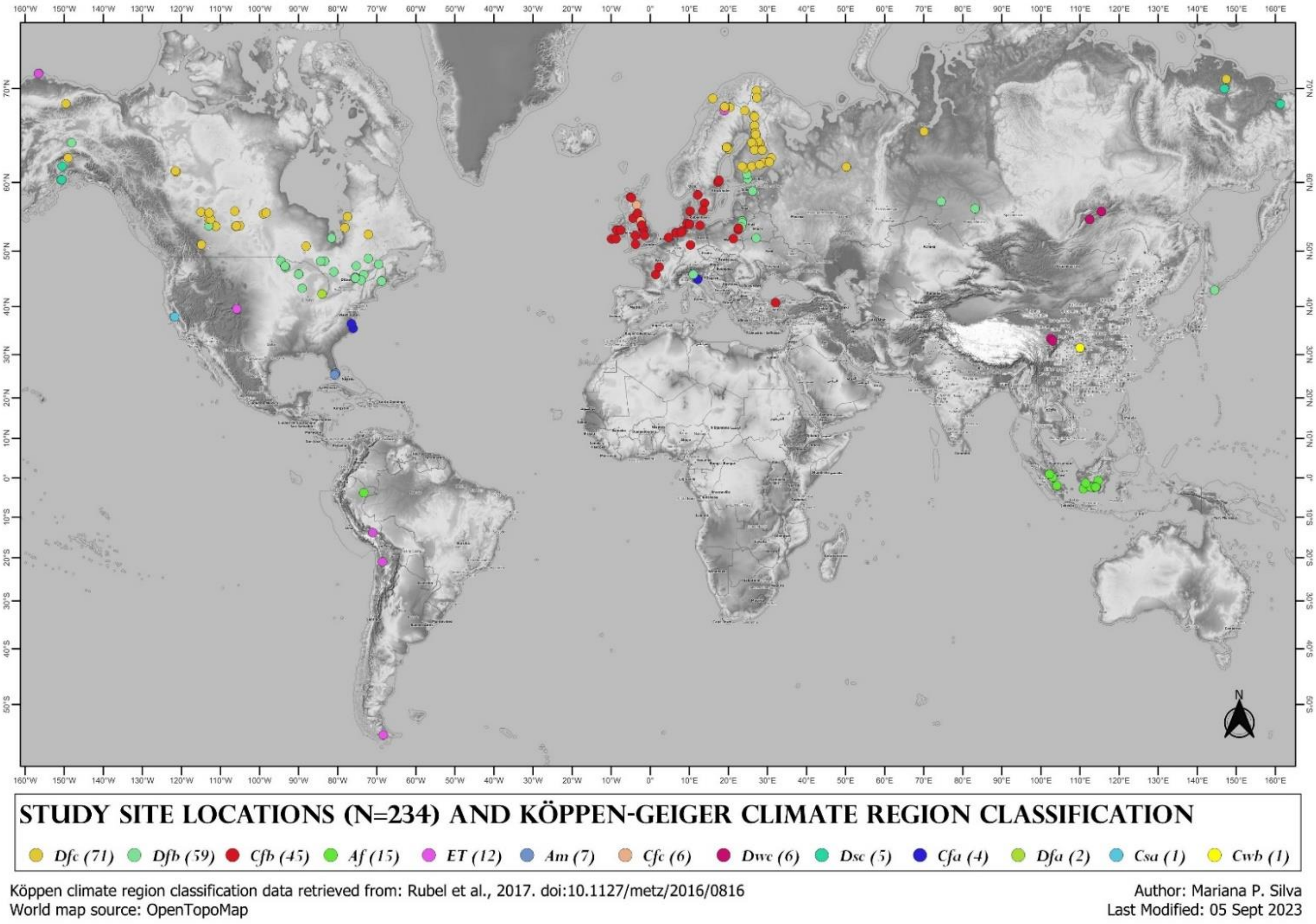


Figure 2: Individual site locations for the 234 sites identified in papers from this review, with their corresponding Köppen-Geiger climate region classifications. Map generated using QGIS.

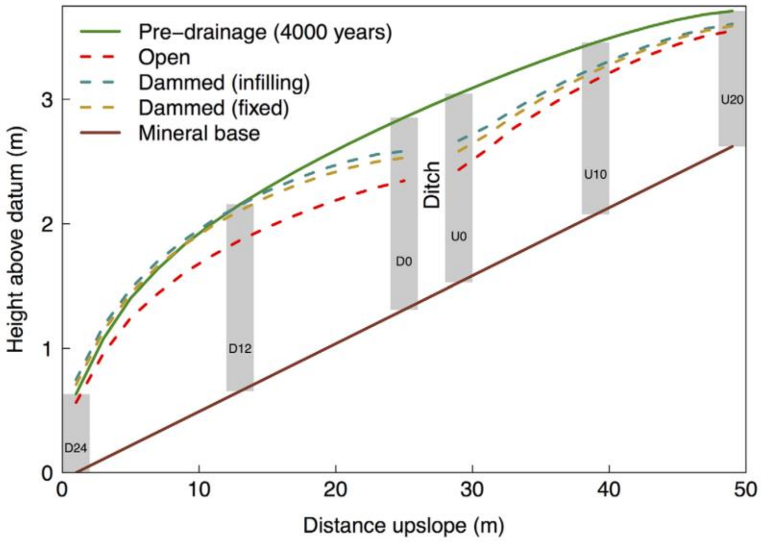


Figure 3: Predicted peatland surface height before and after (300 years) ditch drainage and damming imposed upon a blanket bog transect, modelled using DigiBog by Young et al. (2017). Peat accumulation is modelled here alongside hydrology for the annotated peat columns (e.g., D24, D12); columns are identified using their position upslope (U) or downslope (D) of the ditch and the distance (m) of their edges that are nearest the ditch (e.g., column U10 occurs 10 m upslope of the ditch).

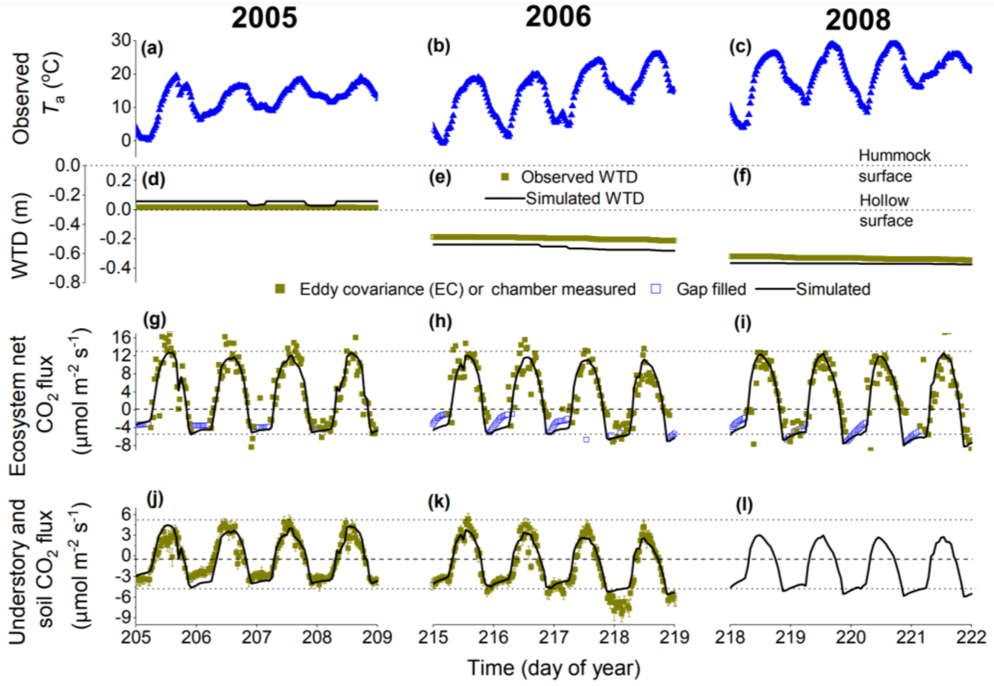
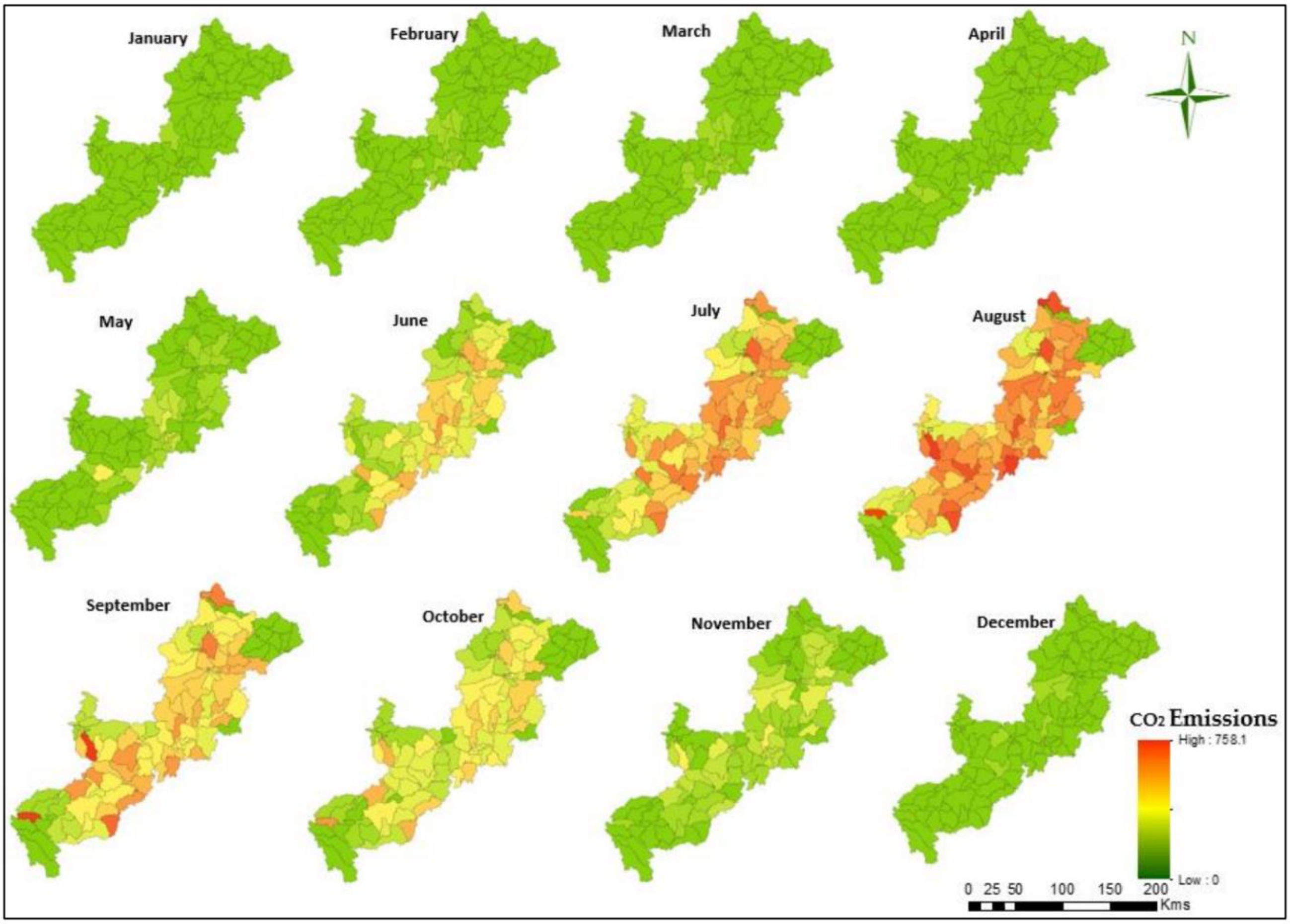


Figure 4: Simulated hourly WTD and CO2 fluxes for July-August 2005, 2006, and 2008 by Mezbahuddin et al. (2017) using ecosys. Compared against half-hourly observations (a-c) air temperatures (Ta), (d-f) WTD, (g-i) EC-measured and gap-filled net CO2 fluxes, and (j-l) automated chamber-measured soil CO2. No chamber CO2 flux measurement was available for 2008; bars for 2005-2006 chamber measurements represent standard errors (j-k). A positive flux indicates a flux entering the system, and a positive WTD represents a depth above the surface.



685 **Figure 5: Spatiotemporal CO2 emissions (µmol CO2-C m-2 day-1) for the Athabasca River Basin as developed by Melaku et al. (2022) using SWAT. The model also produced 3-year continuous predictions for CO2 emissions, NEE, WTD, Reco, and soil temperature, each representing an aggregate value for the whole basin.**

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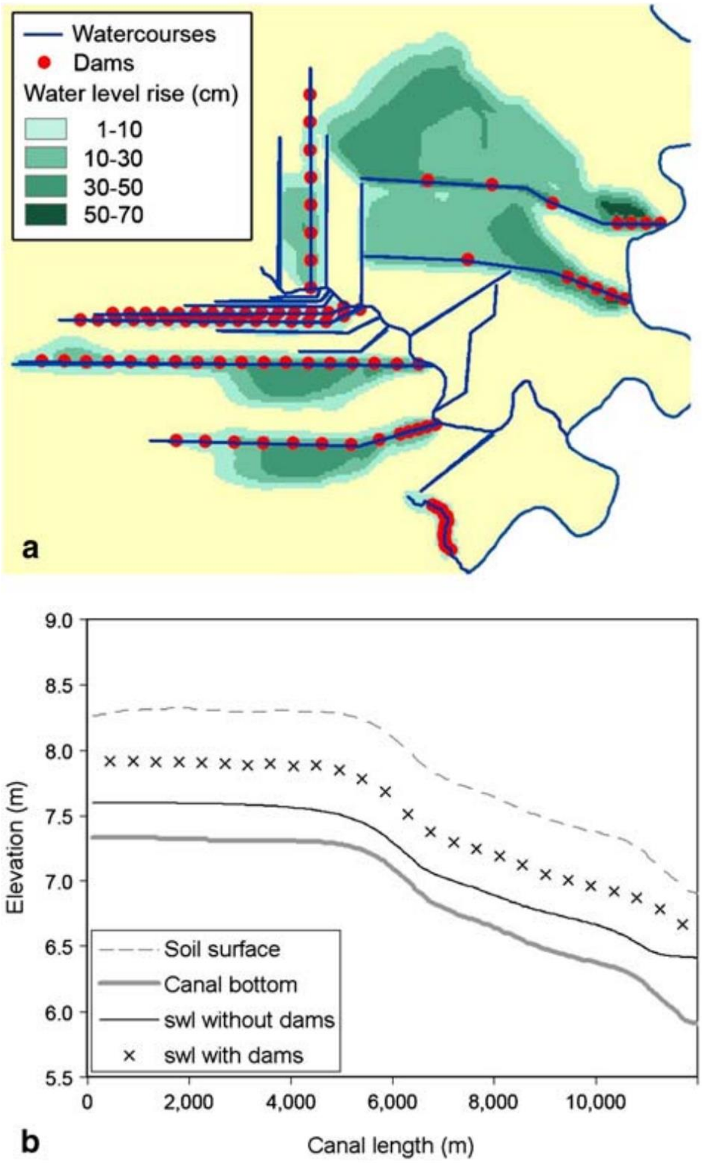
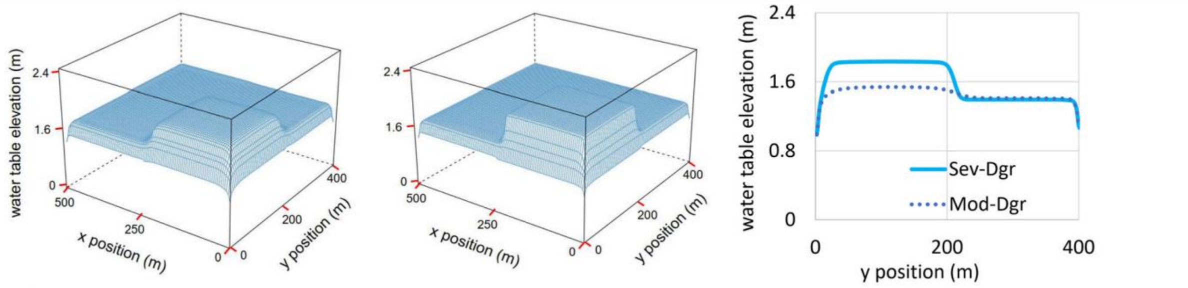
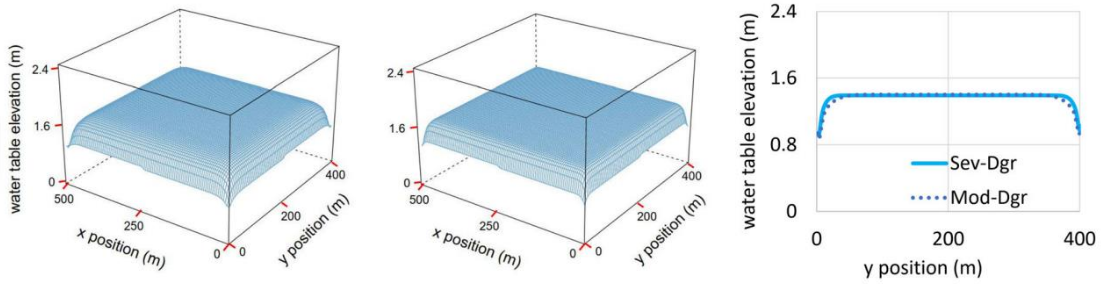


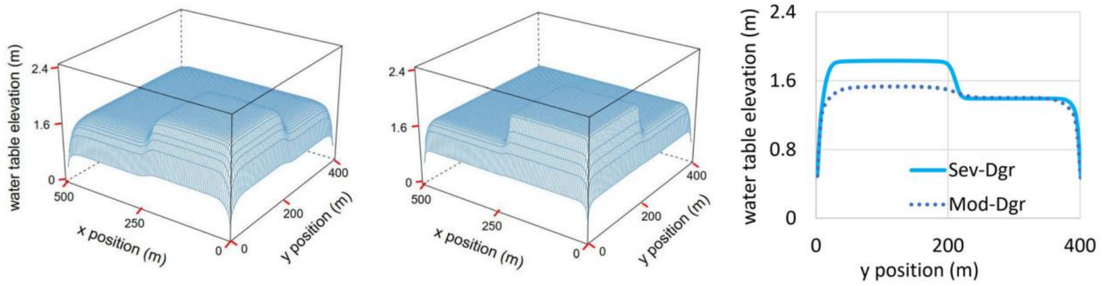
Figure 6: GIS-based predictions of water level rise for a tropical peatland using SIMGRO (Jaenicke et al., 2010). (a) Plan view of groundwater level rise after dam construction; (b) Surface water level rise (relative to soil surface elevation) in a single canal after dam construction.



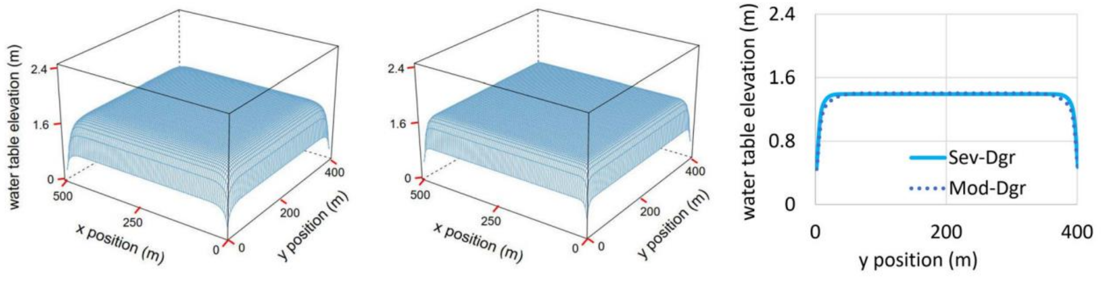
(a) Combined (Mod-Dgr) Combined (Sev-Dgr) Combined



(b) Dammed (Mod-Dgr) Dammed (Sev-Dgr) Dammed



(c) Bunded (Mod-Dgr) Bunded (Sev-Dgr) Bunded



(d) Control (Mod-Dgr) Control (Sev-Dgr) Control

Figure 7: Three and two-dimensional spatial WT profiles modelled for different peatland conditions using DigiBog_Hydro by Putra et al. (2022). Shown is only one day of the full 364-day simulation. The 2D profiles are taken along the line of x = 50 m.

Tables

Table 1: Details summarising common topics in papers removed from the dataset prior to analysis.

	Justification for removal	
	Diverged from an ability to link with hydrology	**Too specific**
1st Pass	Ecological surveys of testate amoebae as proxies [MH6] of palaeoenvironmental reconstructions	Permafrost dynamics
	Papers solely focussed on palaeoenvironmental reconstructions	Wildfire dynamics in forested peatlands
2nd Pass	Vegetation dynamics with no link to water table depth	Digital elevation models used solely for mapping
	Peat hydraulics modelling carried out with lab samples rather than a full ecosystem	Tropical peat models with a distinct northern-latitude software counterpart
3rd Pass		Single-crop agricultural models (e.g., CERES for rice and DNDC for oil palm)

Table 2: Relative frequencies of named and unnamed models in this review.

Model category	*# Named*	*# Unnamed*	*% Unnamed*
Pure hydrology	64	13	16.9%
GHG dynamics	30	11	26.8%
Peat accumulation	8	2	20.0%
Global models	14	2	12.5%
*Model combos**	22	15	40.5%
Coupled models	42	2	4.5%
*Remote sensing***	1	4	80.0%
Total	181	49	21.3%

** 11 of 13 papers in this category list 2 models per paper. A total of 23 distinct models are counted here based on the information available from the papers.*

*** Remote sensing papers featured prominently from a second post-hoc literature search; most are categorised in other categories if possible. However, 5 papers remained distinct in their objectives and were given their own category.*

Table 3: Instances of use for models of interest, organised by Köppen-Geiger climate region classification. "Instances" may occur more than once within the same paper for different sites; here they are recorded as separate counts.

	Model of Interest							
Köppen Classification	**Digibog**	**MPeat**	**CoupModel**	***ecosys***	**MWM**	**SWAT**	**LPJ**	**Total per climate region**
No location listed	4	1					1	5
Af	1			2				3
Am								0
Cfa								0
Cfb	4		2			1		7
Cfc								0
Dwc				2			1	3
Dfa							1	1
Dfb			2	5	2		4	**13**
Dfc			1	2	4	1	6	**14**
Dsc								0
ET				3			2	5
Total per model	**9**	1	5	**14**	6	2	**15**	

Table 4: Breakdown of model specifications for "top three" models identified.

Relevant information	***DigiBog***	***LPJ***	***ecosys***
Data file requirements	1. Surface DEM (*.asc); 2. Basal DEM (*.asc); 2. Layer classification (*.asc); 4. layer properties (*.csv); and 5. time series of net rainfall (*.txt). DEM files can be obtained from GIS.	*Input driver data:* Monthly mean air temperature, total precipitation and c percentage of full sunshine, annual atmospheric CO2 concentration and soil texture class. *Output:* NetCDF file outputs.	**.h* files containing all parameters. These are pre-defined in GitHub files *readi.f* (soil and topographic inputs), *readq.f* (soil and plant management inputs), and *reads.f* (plant species and management inputs). These files also set "switches" to build a site-specific scenario (e.g., WTD, presence of drains, climate zone).
Processes included	Oxic and anoxic decay; soil/atmosphere water relations. Significantly limited compared to LPJ/*ecosys* and would require pairing with other models to provide a complete picture of the effects of restoration.	LPX-Bern: "updated soil and plant hydrology using leaf interception, surface evaporation, snow parameterization and melting, soil heat diffusion in eight soil layers regulating thawing and freezing in soil and related changes in the carbon pools, as well as dynamic interaction with the nitrogen cycle" (Saurer et al., 2014). LPJ-WHyMe: Plant physiology (as plant functional types (PFTs), carbon allocation, decomposition, and hydrological fluxes. LPJ-GUESS: plant physiology, nitrogen/methane cycling, and permafrost/managed land functionalities.	(1) Microbial C, N, and P transformations; (2) Soil/plant/atmosphere water relations; (3) GPP, autotrophic respiration, growth and litterfall; (4) Soil water/heat/gas/solute fluxes; (5) Soil solute transformations; (6) Soil/canopy N2-fixation; (7) CH4 production/consumption; (8) Soil inorganic N transformations; and (9) Soil erosion.
Interface/code for use	Fortran 90. DigiBog_Hydro has been modified to add a GUI element so direct coding is not needed.	Fortran 77, C/C++.	Fortran. Complete package is managed in a GitHub repository: https://github.com/jinyun1tang/ECOSYS/tree/master.vfire
Manual for use*	DigiBog proper: https://github.com/youngdm/Digibog_PDM_WRR2017 DigiBog hydro: https://water.leeds.ac.uk/wp-content/uploads/sites/36/2020/12/DigiBog_Hydro_user_manual_v1_FINAL.pdf	LPX-Bern: https://www.climate.unibe.ch/research/research_groups/earth_system_modelling_biogeochemical_cycles/lpx/index_eng.html LPJ-GUESS (general ecosystem model): https://web.nateko.lu.se/lpj-guess/index.html LPJ-WHyMe: https://daac.ornl.gov/MODELS/guides/LPJ-WHyMe_v1-3-1.html	Not publicly available. Retrieved after contacting JinyunTang@lbl.gov.
Minimum time step	yearly	daily	Sub-hourly
Spatial element (at least 2D?)	DigiBog proper: no[LG7][MS8]; DigiBog_hydro: yes, 3D 1x1 m (site scale)	Yes, 3D, 0.5-1.0 degrees (regional/global scale), or 1D for single coordinate location	Yes, mm to km scale in 1, 2 or 3D

**URLs accessed on 16 August 2023.*

Table 5: Relative time spans involved per site for selected papers utilising “top three” models.

	Paper	*Time span of site data[MS9][MH10]*	*Time span of simulation*
DigiBog	Young et al., 2017	Climate data: 2010-2013; no field measurements	4000-year spin-up, 300 years simulated
	Putra, Baird, Holden, 2022	Climate data: 2011-2015; no field measurements	2011-2012, 2013-2014, and 2015-2016
ecosys	Mezbahuddin, Grant, & Flanagan, 2017	Climate data and field measurements (for both calibration and validation): 2003-2009	Spin-up: 1961-2002; analysis: 2004-2009
	Chang et al., 2019b	Climate data and field measurements (for both calibration and validation): 2011-2013	Spin-up: 1901-2001; analysis: 2002-2013
	Grant et al., 2017	Field measurements: 2013; climate data: 1981-2013 and 2013-2015	Spin-up: 1980-2013; analysis: 1985-2015
***ecosys* and LPJ**	Sulman et al., 2012 (Mer Bleue site)	Field measurements: 1999-2006; climate data measured/gap-filled for the same period	Spin-up: not specified--at least 5 years; analysis: not specified (possibly same as field measurement spans)
LPJ	Chaudhary, Miller, & Smith, 2017 (Sweden site)	Climate data: 1901-2000; no field measurements	5000 calibrated BP -2000; 1900-2100
	Spahni et al., 2013	Climate data: Last Glacial Maximum (LGM)-2000AD and RCP climate forcing scenarios 2000-2100	Spin-up: 1500 years; analysis: LGM-2100
	Tang et al., 2018	Climate data: 1913-2000 and 2001-2012; field measurements: 2007-2009	Spin-up: not specified; analysis: 2007-2009