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Management and rehabilitation of peatlands: The role of water chemistry, hydrology, policy, and emerging monitoring methods to ensure informed decision making

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ABSTRACT

As the world's most abundant source of terrestrial carbon, peatlands provide numerous ecosystem services, including habitat biodiversity and freshwater quality. Land and water management practices in relation to peatlands, for either exploitation or rehabilitation, are complicated by several factors: spatial diversity in geochemistry; laborious survey methods that may be subject to confounding factors; regional and irregular climate variations; a lack of generalizability regarding appropriate strategies; and, in some countries, by non-implementation of water quality assessment policies for pollution control and land use. Such factors raise uncertainty in the effectiveness of restoration and rehabilitation strategies, while modern peatland management looks to develop land use schemes that offer minimal risk to the environment. The aims of this paper were to (1) investigate the disparate factors influencing peatland management which confound appropriate interventions for enhanced water quality (2) examine how non-implementation of national policies for water pollution control may result in adverse environmental impacts, and (3) propose an innovative peatland management methodology for a detailed and robust land analysis with water quality being the primary consideration. The paper suggests that optical, radar, and radiometric remote sensing methods may be used to identify management zones within a peatland, that may require variable management strategies during restoration. Satellite remote sensing and Earth observation methodologies are well documented; hence, the prospect and properties of a less documented airborne electromagnetic approach may present an opportunity for improved management of peatlands.

1. Introduction

Peatlands are considered to be environments sensitive to anthropogenic pressures since the initiated departure from their peak processing of resources for biofuel and agriculture. Although peat-covered landscapes extend across much of the globe, they account for only a small percentage of the Earth's land area (Xu et al., 2018). Prior treatment of peat soil, before the emergence of rehabilitation and restoration, and the conditions placed on it have since created the need for new knowledge on land and water management practices to help promote proper decision making for sustaining peatlands. Their protection is paramount, as they have been proven to act as a channel in the natural carbon cycle (Rixen et al., 2016) and serve as a vital asset towards carbon dioxide conveyance from air to earth material. Created by the buildup of partially decayed plant material and under wet conditions, development of these natural environments over the last 10,000 years has occurred at an average rate of 0.5 to 1 mm yr^{-1} (Renou-Wilson et al., 2011a). Such a slow growth rate offers a major concern when trying to assess the effectiveness of peatland management; to determine not only the success of a conservation strategy but also to develop measures that may induce peat formation.

The goal of peatland restoration is to demonstrate efficiencies using the environmental protection schemes that are expected to restore wetland environments to their appropriate functioning capacity in nature (Kareksela et al., 2015). Rehabilitation efforts usually consist of an artificial manipulation on a natural peatland process to cause a change in either water level or vegetation; the success of which is usually difficult to claim if a peatland has suffered catastrophic damage (Tan et al., 2021). A common practice in rehabilitation involves raising the peatland water table through the construction of dams and drainage

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blocks at surface outlets (Buschmann et al., 2020). Construction measures effectively create a high soil water content and decrease oxygen availability for microorganisms, limiting and altering the respiration process that occurs in peat-forming vegetation, enabling peat formation (Husen et al., 2014). When large-scale changes are made to peatlands (drainage, peatland afforestation, and turf harvesting), climate change and airborne and water pollution become a major consideration. The typical activities carried out on fens and raised bogs have invoked questions regarding the roles of peatlands and how they play into global equilibria. The often scrutinized areas of peatland health consider how peat removal, draining, and drain blocking, which is believed to have a positive impact, can potentially introduce pollution into fresh water resources and alter the global greenhouse gas (GHG) budget (Abdalla et al., 2016). For example, raising water levels can create the anoxic environments that promote anaerobic respiration in the absence of oxygen (Zhu et al., 2018). This condition in the risen water table then has the potential to introduce gaseous methane, which is a much more powerful GHG than atmospheric carbon on a 100-year timescale (IPCC, 2021). Likewise, the anoxia engineered within a once-drained peatland can introduce reactive phosphorus (P) in the soil (Van De Riet et al., 2013) and intensify the presence of ammonium (NH_4^+) in the uppermost layers of peat (Lundin et al., 2017). Ammonium behavior is often well synchronized with the nitrification process, and the ways in which P movement corresponds to changes in water quality parameters usually indicate some effect of soil structure on geochemical properties (Morison et al., 2018). Phosphorus movement and mobilization are also strongly associated with peatland microbial activity and vegetation type and abundances (Luo et al., 2021).

Peatland activities on exhausted lands, whether practices consider environmental sustainability or energy and economic yield, have raised concern on land use and the pressures on water quality that they may present. Traditional approaches to monitoring diffuse pollution have relied primarily on walkover survey methods (Reaney et al., 2019), and in recent years there has been a focus on laboratory and desk-based research methods. The challenge with standard monitoring methods to date has been creating a reliable method to account for temporal and spatial changes in catchment-scale hydrology (Saarimaa et al., 2019; Shore et al., 2014). Modern remote sensing techniques seek to investigate the relationship between diffuse nutrient concentrations and loads and a catchment's hydrological controls (Shore et al., 2014).

Long-term alterations in the water table significantly influence peatland function, and peatland hydrological properties, such as soil-water retention characteristics, are crucial for raised bog self-maintenance (Liu et al., 2022). The rehabilitation work performed on peatlands, based on hydrology, is ineffectually documented and there is an increasing focus on the restoration of hydrological processes of degraded raised bogs, which involves blocking vast drainage networks and outlets (Menberu et al., 2016). In order for a raised bog to reach an optimal growth rate it must be annually water logged (Renou-Wilson et al., 2019). It is accepted that by inundating a peatland to an appropriate level, degradation becomes minimized through recreating the hydrological conditions of the healthy peatland's preferred state (Menberu et al., 2016). In any case, excessive runoff is almost always imminent, given the changes in a peatland's ability to store water at a specific time step. Where runoff occurs in degraded peatlands, there can often be a threat of contaminant transport through the bog, especially if fertilizers containing nitrogen (N) and P have been applied within the relevant catchment (Koskinen et al., 2017). Industrial peat extraction also increases the likelihood of pollution influx into neighboring watersheds, ergo results in negative effects on downstream water resources. Constructed wetlands have been used as viable options to alleviate the negative impacts and have displayed good N and P retention capacity (Karjalainen et al., 2016). Frequent water table analysis has served as a good alternative when assessing water and contaminant retention ability of a restored site (Menberu et al., 2016); however, soil characterization of site-specific locations may provide a new proxy.

This review seeks to explore the unknown factors that may conceivably influence peatland management practices; particularly those that refer to the rain-fed bogs of the northern hemisphere. Most of the current successes of restoration on raised bog sites have lacked generalizability (Renou-Wilson et al., 2019); therefore, certain questions that pertain to raised bog activities have remained loosely answered. Questions such as: How does peatland drainage and use affect hydrology and water quality at field and catchment scale? Which peatland areas should be protected from drainage and intensive land use, and which areas can be used with limited environmental impacts? And finally, how can land and water management be combined in a sustainable way to limit the impacts of threats to water for human consumption and other environmental impacts?

Therefore, the aim of this review is to address the current policies that are active in the realm of wetland conservation and to assess novel techniques for developing peatland management methods. The techniques for identifying critical areas requiring improved management, in theory, can offer further understanding of the mechanisms that control nutrient pathways and retention across a watershed, allowing for knowledge to be gained in the role of nutrients for sustaining environmental structure and function.

2. Methodology

The manuscript is divided into three parts: the interaction between peatland chemistry and water quality parameters with water table changes, policies relating to the restoration of peatlands, and remote sensing methods for analyzing and mapping the characteristics of peatlands that are important for hydrology. In a systematic review, information from published literature in the last 30 years was collated to answer the research questions: how does peatland management practices affect water quality and hydrology, and which are most effective? How has international policy affected management? How can emerging technologies be used to identify, characterize and assist in the management of peatlands?

To answer these questions, a comprehensive systematic literature review on the following databases was performed: Scopus, ScienceDirect, Google Scholar, Web of Science, and the Multidisciplinary Digital Publishing Institute (MDPI). Keywords in the literature search included: ammonium, phosphorus, leachate, land management, nutrient pollution, remote sensing, and restoration and rehabilitation. Regional limitations were not applied in this paper, although only papers and policy documents published in the English language are included. A methodology flowchart is illustrated in Fig. 1.

After the initial search results were compiled, the reference list was further reduced to include only original research papers or policy documents focusing on one of the three aspects of this paper. The reasons for exclusion of papers were if they lacked scientific rigor or if they were unrelated to the search criteria. In the case of research articles, and particularly in relation to the reporting of the impacts of management practices on water quality, only papers that reported long-term, robust scientific data before and after interventions, were included in this review. As a result of these criteria, 145 papers were selected of which over 50% were published in the last five years. A schematic of the content of the following sections, which focus on the three areas identified above, is shown in Fig. 2.

3. Interactions between peatland chemistry, water quality and water table

Peat formation is a perennial occurrence involving an incomplete decomposition of perished vegetation that is perpetuated while being subjected to waterlogged conditions. Essentially, poor drainage characteristics in the long term result in peatland formation (Treat et al., 2019). When masses of peat-forming vegetation are fully saturated, an absence of oxygen inhibits the full decay of plant matter through an

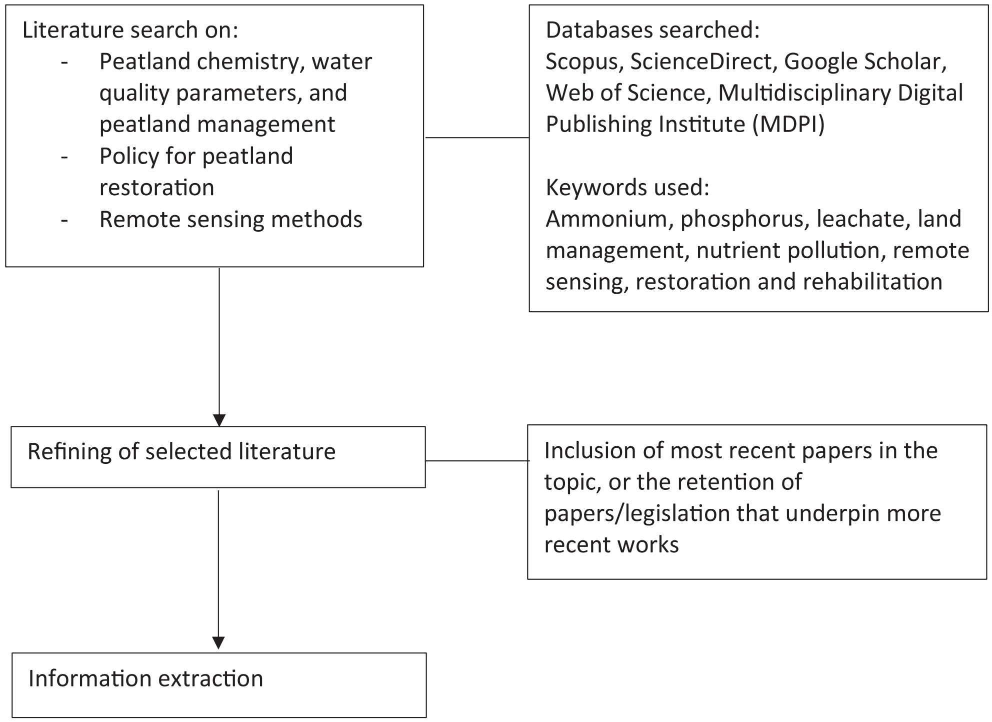

Fig. 1. Methodology flowchart.

increase in vegetation productivity. When the peat is drained of its freshwater reserves, oxygen is reintroduced and the decay process restarts towards a complete reduction of plant remains (Overbeek et al., 2020).

Acidity and mineralized water variation are two of many parameters that differ across peatland types (Yang et al., 2021). The chemical content of a peatland's groundwater and its discharge express local geochemistry and hydrological developments, with raised bogs tending to be more acidic and fens more alkaline (Griffiths et al., 2019). However, peat accumulation rates are dependent on the supply and cycle of limiting nutrients, N and P (Morison et al., 2018). Microbial behavior and anaerobic respiration cause a release of N and P from organic matter (OM) during decomposition (Andersen et al., 2013). Soil N forms a feedback mechanism with microbial biomasses in the peat as microbes utilize N and limiting P from soil and decomposition products, yet P cycling is more challenging to document as it is known to vary much less than N which can be associated by weight with peat depth and degree of composition (Morison et al., 2018; Tfaily et al., 2014). Barring any correlations with water table elevation and temperature, soil P is much more elusive as the primary limiting nutrient in freshwater resources (Griffiths et al., 2019). Measures of total phosphorus (TP), in nature, characterize a consequence of underlying fragmentation leaching from reduced parent material to cycle through soil bodies and pore water, and recent studies support the standing claim that a strong correlation exists between TP, water table elevation, and temperature (Griffiths et al., 2019; Munir et al., 2017; Živković et al., 2017).

Increased concentrations of orthophosphate (PO_4^{3-}) are usually anticipated at hollow and lawn locations (Macrae et al., 2013) due to an inherent nearness to surface pools and a variable water table height (Moore et al., 2013). With respect to peatland microform, Wood et al. (2016) quantified extractable PO_4^{3-} and N cycling from five different peatlands and described them based on abundances in the topography. Using multiple linear regression, an upper limit of 18 $\mu g\,g^{-1}$ PO_4^{3-} in hummocks and 48 $\mu g\,g^{-1}$ PO_4^{3-} in hollows showed a distinct influence of water on concentrations; quantified spatial N cycling yielded fewer significant results. Sapek et al. (2009) assessed the response of inorganic nutrients to groundwater level fluctuations and found that natural drainage was accompanied by significant increases in both PO_4^{3-} and NH_4^+ concentrations within high groundwater samples. Heightened subsurface temperatures during the dry season are significant simply because warmer soil suggests drier soil (Griffiths et al., 2019; Munir et al., 2017). Water table drawdown is often related to such soil temperature increases and the expectation is that the imposed circumstance should achieve greater productivity in the decomposition of OM, due to the enhanced aeration (Tuukkanen et al., 2017). Although ambiguous with respect to the exact forms N and P, Griffiths et al. (2019) further identified total nitrogen (TN) and TP behavior increasing with peat depth across several studied sites. Depending on peatland type (minerotrophic versus ombrotrophic) N-containing species may enter a fen peatland via ground water interaction and upwelling (Hill et al., 2016), and depending on the head level near the surface, oscillating oxic/anoxic environments at a groundwater interface can determine the speciation of N (Charlet et al., 2013; Tfaily et al., 2018).

Total P and its proportion of bioavailable PO_4^{3-}, along with soil total inorganic N (TIN), constrain peat forming vegetation together with soil temperature and water table positioning (Munir et al., 2017). Active drainage and peat extraction alter pore water chemistry and reduce nutrient immobilization. With an already complex nature of water quality evolution, anthropogenic activity resulting in erosion and subsidence has impacted the fate of transients and the deposition of nutrients within peatlands (Tuukkanen et al., 2017).

4. Policies relating to the restoration of peatlands

4.1. *The Ramsar convention*

The United Nations (UN) 2030 Agenda for Sustainable Development serves as the overarching motivation in peatland management for member states. Under Sustainable Development Goal six (SDG-6) for clean water and sanitation, protection of water-related ecosystems and addressing water pollution are most relevant in terms of peatland degradation (Lele, 2017). To promote engagement between partners on

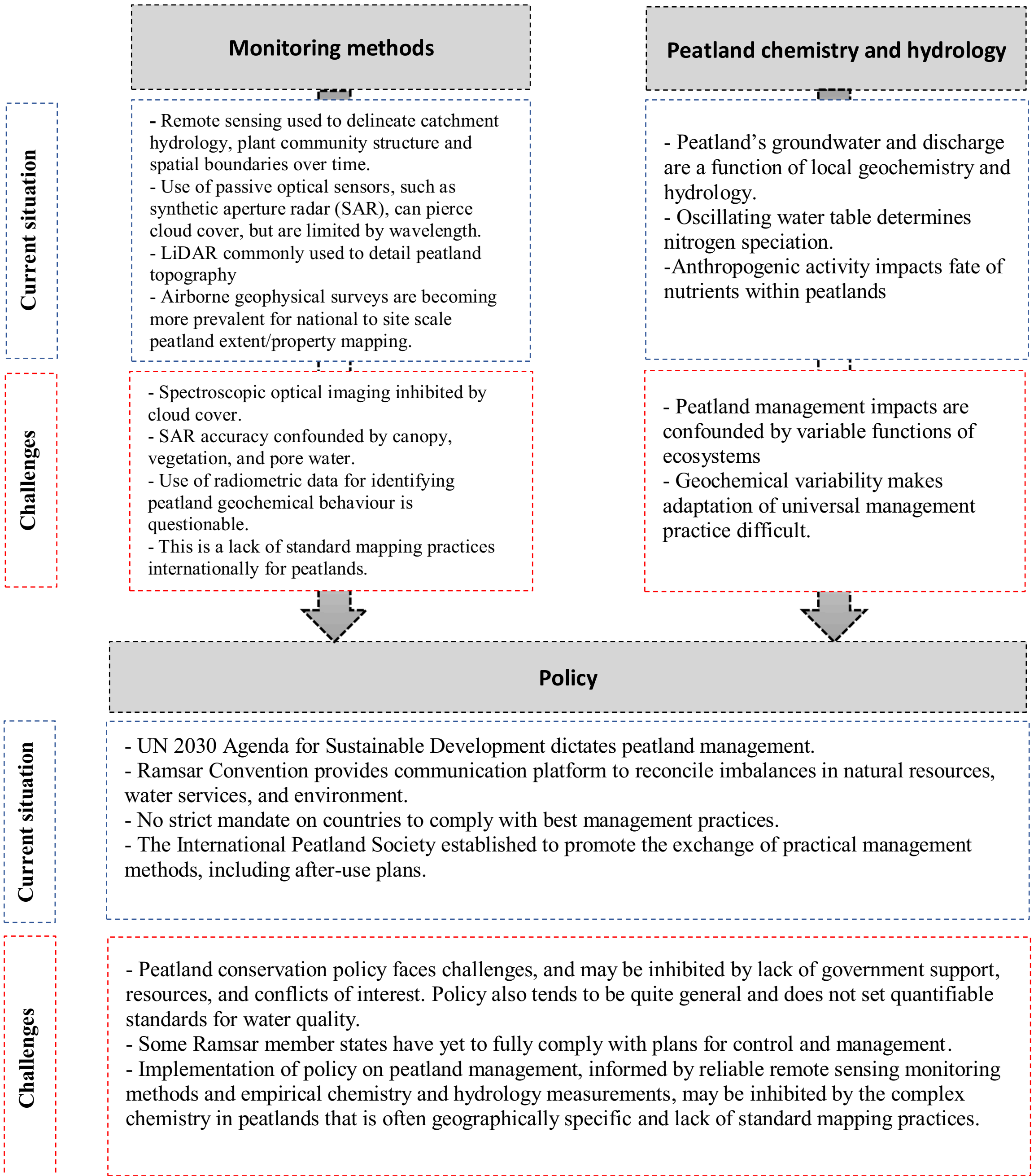

Fig. 2. Current situation and future challenges of the three focus areas of this paper: monitoring methods, peatland chemistry and hydrology, and policy.

a national level, the Ramsar Convention, established nearly fifty years ago, now provides a platform of communication that is necessary for reconciling the imbalances between natural resources, water services, and the environment (Everard and Mcinnes, 2018). Over the last several decades, the attention brought on wetland ecosystem services, which includes peatlands and mires, has promoted measures that seek to benefit wildlife habitats for threatened species, as well as reduce net emissions in a global GHG budget (Huth et al., 2022). All relevant countries are encouraged to adopt conservation policies; however, there is no strict requirement or enforceable mandate placed on governments to ensure that they comply (Moomaw et al., 2018). As it currently stands, there is concern that intergovernmental efforts will not meet SDG-6 by 2030 (Ortigara et al., 2018). Policies attempt to meet the needs of all reliant communities, yet their full application can be inhibited by a lack of stakeholder support, resources, and conflicts of interest (Barchiesi et al., 2018).

The Ramsar convention defines environmental flow as a water adequacy in wetland discharge, stemming from properly functioning catchments that are capable of satisfying ecosystem services and benefits, while sustaining themselves in the environment (Barchiesi et al., 2018). A wetland's effects will propagate on to receiving water bodies and many of the endorsed treatments for ecosystems intend to limit degradation and biodiversity loss, while assisting water quality demands through the same preventions. A system for decision making within the Ramsar Convention assesses values based on ecosystem effects, such as water resource provision, maintenance of options, regulation of hazards and extreme events, and ecosystem processes (Kumar et al., 2017). Effective management would align the values of these services with the best options for policy instrumentation and help bridge the knowledge gaps in land use and environmental flow balance. It is a goal to inform management and reveal to stakeholders how ecosystems can be prioritized while maintaining a concern for socio-economic return.

The 2002 Guidelines for management planning of Ramsar sites and other wetlands (Ramsar, 2002) called for the implementation of a uniform approach to peatland restoration management. It had been viewed as impossible to measure the total extent of these land features in all of their complex chemical aspects; the focuses on wetland health considered point measurement data of key parameters such as nutrient concentrations (Ramsar, 2002). The agreement still stressed the importance of implementing guidelines and urged governments to evaluate policies and to advance strategies (Ramsar, 2002). Consistent recall of the notion on the *wise use of wetlands*, which emphasizes active management of these lands, has been upheld in the addendums of resolutions to date (Ramsar, 2015b), i.e., in resolutions XIII.17, XII.12, and VIII.17 (Everard and Mcinnes, 2018; Ramsar, 2006; Ramsar, 2015a).

Beyond the influence of Ramsar, regional mechanisms such as the European Union (EU) also act to motivate states into compliance with environmental flow policy (EC, 2000). A 2006 EU directive (EC, 2006) mandated that member states establish threshold values for groundwater substances, e.g., ammonium. Since transposition of EU law is the responsibility of its members, threshold values vary from state to state (EC, 2006). In 2012, Ramsar member states adopted Resolution XI.8 Annex 2 (Rev. COP13) through which they agreed on the importance of incorporating aspects of nutrient quantification in peatland assessments (Ramsar, 2012).

4.2. Challenges facing implementation of policy

As of 2021, some Ramsar member states still had not fully adopted national plans for pollution control and management, or policies on wastewater management and water quality as they relate to environmental flow. Implementation of policy on peatland quality and environmental flows, at the international and national level, face challenges and it is evidenced that the existing strategies do not always address the quantitative issues of water quality, restoration, and management in detail (Reed et al., 2014). Regional bodies and international treaties communicate the intentions of the party with only general guidelines to approaches and therefore, it is difficult to determine acceptable standards for water quality; for instance, standards regarding nutrient load and leachate. Policy makers must decide to enact either accurate data measuring protocols or opt for cheaper and faster alternatives with less accurate results (Reed et al., 2014). Through analysis of the financial aspects to peatland management, Reed et al. (2014) emphasized that there are a number of ways by which peatland changes influence ecosystems service allocation. They suggested the use of a method whereby values are supplemented from other similar ecosystems when water quality data are lacking.

Another intergovernmental organization with the intent of advancing scientific knowledge on peat, the International Peatland Society (IPS), was established to promote an exchange of practical management methods (Joosten and Clarke, 2002). In 2008, this particular IOP sought to facilitate responsible peatland management with steps to foster the creation of a global peatland strategy in the "wise use of peatlands" (Clarke and Rieley, 2010). The IPS stresses the importance of after-use plans, identifying the entities that will be accountable for the operation of specified after-use, implementation of the most current technical knowledge of peatland functions and services to inform the after-use management practice, and consistent survey analysis of programs in a timely manner to improve procedures if the objectives are not realized (Clarke and Rieley, 2010; Gaudig and Tanneberger, 2019; Graf and Rochefort, 2016). Salomaa et al. (2018) describe criticisms and road-blocks to policy instruments at national levels due to disagreements regarding landowner rights and the requirements of conservation. Precise arrangement of after-use is likely to be settled by landowners or relevant stakeholders in consultation with a specific authority; arrangements typically incorporate an artificial rise in the peatland's water table (Clarke and Rieley, 2010). Mandatory policy is perceived as an effective instrument for attaining sustainability results, but the policies often lack acceptance.

4.3. Links between peatland management, policy and water quality

Limited research fails to convey how peatland conservation measures are chosen at the national level and how they are effectively integrated during policy operation (Salomaa et al., 2018). However, regardless of national policies and their acceptance, independent studies of peatland management and the effects of restoration are ongoing. Table 1 shows water quality changes of key nutrient species produced in peatland after-use strategies.

Considering the three management methods described, the frequency of sample collection in the rewetted/flooded scenarios ranged from one week after treatment, in Beltman et al. (2014), to more seldom and annual sample collection regimes (Lundin et al., 2017; Menberu et al., 2017). Menberu et al. (2017) reported that water level fluctuation impacted pore water quality, especially in the time period immediately after management implementation. Lundin et al. (2017) investigated the effect of long-term inundation and contrarily demonstrated the success of rewetting; notably in decreasing ratios of PO_4^{3-}-P to TP and inorganic N to organic N, that began to stabilize with time. The temporal scale of each study accounted for hydroclimate variability by considering nutrient dynamics and biogeochemical behavior over the years monitored (Gu et al., 2017). Discrepancy between the reported conclusions is a result of inherent variability. Drought duration prior to rewetting, intermittent water level fluxes, topography, and the magnitude of hydrologic instabilities can trigger or inhibit nutrient release (Blackwell et al., 2013; Brödlin et al., 2019; Gu et al., 2017); prolonged drought followed by heavy rainfall activated N loss and release in Wang et al. (2016). Even P mineralization can vary based on the spatial occurrence of microenvironment varieties within catchments, and depending on the chemistry of soils, increases of dissolved iron hydroxides through constant waterlogging (Gu et al., 2017; Jeanneau et al., 2014; Pant, 2020). Biogeochemical N turnover, however, differs from P transformations (Macek et al., 2020) through processes of: (1) plant and organic N mineralization to NH_4^+ (Hinckley et al., 2019) (2) anaerobic NH_4^+ oxidation under redox conditions; optimized growth of a functional group by soil exposure to the atmosphere (Kim et al., 2017) (3) nitrification, the conversion of intermediate NH_4^+ to NO_3^-, governed by oxidation-reduction (Jiang et al., 2015) (4) NO_3^- conversion to NH_4^+ occurring under anoxia and in environments with NO_3^- limited bed material (Zhao et al., 2019), and (5) denitrification (Taghizadeh-Toosi et al., 2020).

In riparian wetlands, the mineralization of N follows the processes of its respective cycle (Reverey et al., 2016). Anoxia and the repressed redox environment in peatland rewetting can prevent nitrification, which in turn leads to a depletion of available NO_3^- via the pending denitrification process (Hinckley et al., 2019). By this mechanism, nitrification cessation is a direct consequence of rewetting management and promotes the risk of introducing NH_4^+ in surface waters (Nieminen et al., 2020). The peatland observed in Beltman et al. (2014) displayed a threefold increase in NH_4^+ following rewetting (Table 1). Although increases were detected, the data were derived from samples collected approximately one week after flooding and were likely the result of a rapid nutrient surge (Dinh et al., 2018; Sola et al., 2018). The high frequency of N evolution has implications for the management of N flux and is a crucial factor of consideration in peatland restoration (Kasak et al., 2021).

Peatlands can potentially act as critical source areas (CSAs), locations within a watershed where areas generating pollution overlap hydrologically sensitive areas (Ghebremichael et al., 2013), as they possess the capacity to chemically restructure accumulated nutrients (Gu et al., 2017). The attribution of land management practices and their critique are often masked by the details of catchments and the variable functions

Table 1
Changes in mean concentrations (mg/L) of total nitrogen (TN), total phosphorus (TP), ortho-phosphorus (PO_4^{3-}), ammonium (NH_4^+) and dissolved organic carbon (DOC) from several European catchments after various management interventions to restore them; measured annually in porewater studies (except for NH_4^+ concentrations in Beltman et al., 2014), and biweekly in Stimson et al. (2017).

Management	Peatland type	Location	Mean annual rainfall (mm)	Concentration (mg/L)										Reference
				Before intervention					After intervention					
				TN	TP	PO_4^{3-}	NH_4^+	DOC	TN	TP	PO_4^{3-}	NH_4^+	DOC	
Rewetted / flooded[1]	Raised bog/fen	Sweden	800	2.58	0.034	0.095	0.82		2.38	0.104	0.101	0.59		Lundin et al. (2017)
	Raised bog	Sweden	800	1.58	0.016	0.009	0.82		1.51	0.021	0.012	0.97		Menberu et al. (2017)
	Minerotrophic fens, pine and spruce mires	Finland	513–656	2.29	0.150				2.38	0.206				Beltman et al. (2014)
	Fen meadow	Ireland				<0.05	0.17[3]				<0.15	0.19[3]		
	Fen meadow	Ireland				<0.05	0.13[3]				<0.10	0.44[3]		
	Fen meadow	Netherlands[4]				<0.05					<0.25			
	Raised bog[5]	Wales						~90					320	Fenner et al. (2011)
	Forested peatland	Finland	620	~2.6	~0.25	~0	~0	~50	~12	~1	~0.7	~2.5	~250	Koskinen et al. (2017)
Fertiliser application[2]	Blanket bog[6]	England				~1					233			Stimson et al. (2017)
	Cutaway peatland[7]	Ireland	875			0.014					3.01			Renou-Wilson and Farrell (2007)

1 Porewater and groundwater nutrient measurements.
2 Nutrient measurements in runoff via peatland catchment drainage.
3 Ammonium ion concentrations measured approximately one week after restoration/flooding.
4 Utrecht catchment had a history of fertilization treatment (95 kg P ha^{-1} y^{-1} and 250 kg N ha^{-1} y^{-1}).
5 Values reported are maxima for a control ("before intervention" in the categorization rubric of this table) and rewetted bog ("after fertilization").
6 Data taken from the largest catchment in the Stimson et al. (2017) study.
7 P applied at 25 kg ha^{-1} in 1999 and again in 2002. Sampling period from 1999 to 2004. "After intervention" value is the maximum recorded in 2000.

of ecosystems (Nieminen et al., 2020; Purre and Ilomets, 2018; Schulte et al., 2019). Prior to their most recent work on P speciation within peatlands, Negassa et al. (2019) addressed a deficiency in modern experimental data that links spatial variability of biogeochemical properties to peatland phenomena, under pristine and degraded conditions; specifically, regarding the influence of rewetting impacts on P evolution. In an added effort to rectify the notion, Negassa et al. (2020) conveyed the importance of considering soil P species and abundance with peatland class, temporal conditions associated with drainage and rewetting, and land use within catchments in order to better isolate biodiversity and anthropogenic nutrient impacts, caused via management. Most of a catchment's diffuse pollution originates from a small portion of the total area. CSAs are the locations from where major amounts of the total pollution disperse into the landscape (Hepp et al., 2022). Regarding agricultural practices, CSA concerns encompass N, P, and sediment (Giri et al., 2016). Primary CSA concerns involving wetlands have always included sediment and P, but there is very little information in the literature reporting influences of anthropogenic pressure on N cycling and N runoff (Giri et al., 2016). The spatial diversity of geochemical processes presents complication (Gu et al., 2017) and for survey analysis, it is important to establish efforts from informed peatland ecosystem and hydrologic relationships (Schulte et al., 2019).

5. Current and emerging survey methods of peatlands

In 2019, the UN Environment Assembly implemented policy (Resolution 16) calling on the UN Environmental Program (UNEP), in collaboration with the Ramsar Convention and member states, to establish a global inventory of peatlands; ergo, to record the wide use of specific interventions, mitigation, and planning for peatland maintenance and land use (UNEP, 2019). The UN Environment Assembly of the UNEP cites Ramsar Resolution XIII.13 as a main framework for interpretation and technical guidance (UNEP, 2019) on the value of satellite remote sensing and how techniques, along with geophysical survey methods, can inform restoration planning. Through remote sensing, it is recommended that practitioners determine peatland dimensions and site locations that could benefit from restoration works. The recommendations further state that if it is possible, the parameters of peat quality and the potential influences that it may have on the environment after restoration should be considered (Ramsar, 2018).

5.1. Current survey methods

Application of remote sensing technology to peatland profiling is not a recent concept (Worsfold et al., 1986). For roughly half a century, governmental agencies have been attempting to gain knowledge on the extent of peatland dimensions and Ramsar has consistently emphasized its SMART (specific, measurable, achievable, relevant and time-bound) objectives (Barchiesi et al., 2018), putting forth significant effort towards developing baseline inventories (Rebelo et al., 2008). When implemented, remote sensing can assist in the delineation of a catchment's hydrology, identify plant community structure, and highlight spatial boundaries (Harris and Bryant, 2009). Many remote sensing methodologies currently look to reduce the need for specific ground-based observations via a one-time calibration, while seeking increased accuracy in detecting land use and land cover changes. There is also the offered capability of monitoring sites under high temporal resolution, with some satellites being able to provide data on regular time intervals of one to sixteen days (Lees et al., 2018). This consistent reoccurrence allows for the monitoring of short term events, such as the seasonal oscillation of a peatland's surface height, flooding, drying, and peatland restoration over time (Tampuu et al., 2020).

5.2. Emerging survey methods

5.2.1. Satellite remote sensing

Active remote sensing techniques emit their own energy source and passive systems detect radiation that is either reflected or emitted in response to a natural source, i.e., the sun. As methodologies continue to improve, active and passive techniques are often combined to reduce the influence of limitations characterized in a single set of inputs (Bourgeau-Chavez et al., 2018). Passive optical sensors, notably IKONOS, shortwave infrared, and UV–Vis near infrared, are capable of providing up-to-date information for the purpose of soil mapping and providing good resolution at multiple spatial scales (Escribano et al., 2017). However, the use of spectroscopic optical imaging for peatlands as a single metric presents limitations that are caused by cloud cover and an inability to detect small scale height variation across a landscape's surface, i.e., in the hummock and hollow microtopography (Anderson et al., 2010; Niculescu et al., 2016). Longer wavelength, active remote sensing methodologies such as synthetic aperture radar (SAR) can pierce cloud cover and capture three-dimensional topographic variation. The created microwave radiation and the backscatter detected by SAR sensors usually enable a capable methodology aimed at under-canopy observation, detecting inundation, and the classification of wet soils hidden by vegetation (Bourgeau-Chavez et al., 2018). However, a majority of these benefits are heavily dictated by the appropriate wavelengths (Millard and Richardson, 2018). For agricultural monitoring of land cover change, SAR can be ideal due to the scatter of longer wavelengths which are caused by easily discernible crop and large vegetation structures (Mandal et al., 2019). In ecosystems where plant cover is generally tall, SAR detection and volume scattering, as described in Bechtold et al. (2018) whereby electromagnetic radiation transmits between media, would be dependent on canopy structure and vegetation wetness (Millard and Richardson, 2018). When monitoring a peatland, water level variation is significant over very short distances and this is evidenced in the peatland microtopography (Millard and Richardson, 2018). In addition, volume scattering can occur as EM radiation infiltrates into surficial peat and this further extends to the properties of peat surfaces, texture, and roughness; therefore, not only is a backscatter rebound related to the canopy and vegetation, it is also affected by pore water content and the characteristics of the peat (Millard and Richardson, 2018). Since the reproductive response observed in bog vegetation occurs over a multi-decadal time frame (Ratcliffe et al., 2018), an undisturbed peatland surface displays very limited temporal variation in contrast to an agricultural crop land (Millard and Richardson, 2018).

5.2.2. Synthetic aperture radar (C-band)

For the purpose of monitoring water table depth, Bechtold et al. (2018) explored the use of C-band backscatter data (information derived from a specific microwave range of frequencies) available through the European Space Agency's ENVISAT satellite. Concurrently, Millard and Richardson (2018) had made brief reference to a capacity for quality spatial resolution (eight meters aggregated to one-hundred meters for improved classifications) that could be obtained by C-band backscatter, especially in relation to peatlands. Bechtold et al. (2018) applied an advanced SAR technique and linked field observations of water table depth to the backscatter that may only be detected in the top one to two centimeters of peat soils, using vertical-vertical polarization. The results were considered useful for predicting some behavior of water fluctuation beneath a peatland's groundwater interface, but due to limitations there was little consistency in the relationship between the study's measured water table heights and the backscatter response associated with threshold depths (Bechtold et al., 2018). Across the observed sites, it was suggested that a depth range of half a meter to one and a half meters below the surface presented a threshold where correlation between water level and backscatter was lost, and possibly explained by reduced capillary action (Bechtold et al., 2018). In spite of inconsistencies and ENVISAT SAR coarse spatial resolution of one kilometer, the predictions motivated by C-band SAR served as adequate indicators of water level dynamics above thresholds and the method was viewed as having high potential for future investigations (Bechtold et al., 2018).

5.2.3. Combination of SAR and LiDAR data

In a 2016 report on wetland vegetation mapping, passive and active data from optical sensors and SAR were linked with airborne laser scanning via light detection and ranging (LiDAR) in the Danube Delta (Niculescu et al., 2016). Modern LiDAR is a tool that has been developing over the last decade and is capable of returning three-dimensional digital representations of surfaces based on laser cycling and wavelength (Giarola, 2018). In cases of remote sensing where surface heights are generalized from field measurements and interpolation, the application of LiDAR offers a direct measure of vertical surface components and allows for vertical diversity with ten centimeter accuracy along a Z axis (Niculescu et al., 2016). Although the results of this study did not confirm the greatest accuracy when integrating all three sensor types together, Niculescu et al. (2016) revealed efficient abilities to discern ecological complexes through combinations of optical and airborne LiDAR data, and optical data paired with Satellite C-band RADARSAT SAR, for vegetation classes that exist within the area observed. To ascertain the health of a raised bog and the scope of a restoration procedure on its hydrological system, surveys have often relied on an ecotope typology, which is described by the smallest distinct living component within the scale of the landscape (Schouten et al., 2002). In a study similar to Niculescu et al. (2016), that involved vegetation distinctions on an ombrotrophic bog, airborne LiDAR data and IKONOS optical image bands (Anderson et al., 2010) were combined in a multispectral and spatial approach. Anderson et al. (2010) were able to demonstrate that airborne LiDAR data can detail peatland topography and allude to eco-hydrological distinctions. The study effectively enhanced the spatial characterization of a peatland's surface conditions and vegetation via the joining of airborne LiDAR data, with one-meter spatial resolution and a twenty-five-centimeter vertical accuracy to multispectral classifications of four-meter spatial resolution via IKONOS.

5.2.4. Combination of modelling tools and LiDAR-based DEMs

Like degraded peatlands, contemporary agriculture tends to alter natural nutrient behavior and introduces further complexity to the source-pathway-receptor scheme associated with nonpoint source pollution and hydrologically sensitive areas (Mockler et al., 2016). Novelties regarding freely available, remotely sensed information have advanced environmental modelling approaches and led to more exact descriptions of CSAs at the landscape and catchment scale (Djodjic et al., 2018). To capture and highlight agricultural nonpoint source pollution flows, studies often depend on the use of the Soil and Water Assessment Tool (SWAT) (Chen, 2019; Hua et al., 2019). This modelling tool is frequently paired with Airborne LiDAR based Digital Elevation Models (DEMs) in keeping with the current trend of using the highest resolution data available (Foulon et al., 2019). LiDAR-based DEMs are capable of achieving consistent spatial accuracy of between one and two meters (Lee et al., 2019), whereas other sources, e.g., Advanced Spaceborne Thermal Emission and Reflection Radiometer, CartoDEM, and Shuttle Radar Topography, are less effective at providing high resolution imagery for small spatial applications (Goyal et al., 2018). This is especially important in peatland mapping where small vegetated structures, hummocks, and hollows dominate the topography (Kalacska et al., 2018). LiDAR continues to remain an effective component when incorporating land elevation criteria, even though the technique only captures a static representation of the ground surface and its vegetation (Millard and Richardson, 2018). However, peatland biomass responds at a slow enough rate (average rate of 0.5 to 1 mm yr^{-1}), even under optimal growing conditions (Renou-Wilson et al., 2011b), which allows remote sensing survey regimes on the scale of years to be suitable when accounting for natural landcover change.

5.2.5. Electromagnetic survey methods

Remote sensing and Earth Observation are terms usually associated with satellite borne methods; however, they can also refer to geophysical methods which are becoming more common for large-scale subsurface environmental investigations (Binley et al., 2015). Geophysical surveys enable vertical and lateral investigation into the subsurface to tens of meters and have been used for mapping peatlands in terms of spatial extent and intra-peat variability (Minasny et al., 2019), whereas satellite remote sensing typically returns information from the top few centimeters of a surface. Broadly speaking, geophysical surveys can be broken into airborne and ground surveys, where the former benefits from larger survey areas and the latter from an increased resolution. The Electromagnetic (EM) method uses low frequency EM waves to map variation in the electrical conductivity of subsurface structures and relates to physical properties such as saturation, porosity, permeability, and mineral content (Carcione et al., 2003). To peatland hydrogeological investigations, EM data offer the means to characterize a subsurface where passive and satellite methods may only provide surficial information (Boaga, 2017). Airborne EM methods consisting of both frequency-domain and time-domain approaches, measure the apparent electrical conductivity of the ground to depths ranging from a few to a few hundred meters, depending on the instrument selected and the ground conductivity (Paine and Minty, 2005). Apparent conductivity serves as a descriptor for integrated soil properties such as bulk density, salinity, and moisture content (Paine, 2003). Boaga (2017) highlighted the development of the ground-based frequency domain electromagnetic (FDEM) method and its use in hydrogeophysics. FDEM has been shown to be a powerful tool for characterizing soil properties through the use of a multifrequency system that collects information from the soil at many simultaneous depths (Boaga, 2017). The approach offers high spatial resolution and a depth of investigation from centimeters to several decameters, depending on the instrumentation and the properties of the ground. Silvestri et al. (Silvestri et al., 2019a; Silvestri et al., 2019b) employed the time domain EM (TDEM) survey method and the study served as the premier undertaking in the use of airborne electromagnetics (AEM) for regional scale peat depth analysis. The TDEM survey results were combined with artificial neural network (ANN) methodology to estimate peat thickness from 14 field samples where peat thickness was known. This network was then employed to estimate peat thickness and volume over a larger survey area. TDEM can be appropriate for peatland characterization due to its heightened sensitivity to shallow variations in subsurface properties (Silvestri et al., 2019b). The amount of field observations performed was regarded as a primary limiter to the studies, as peat characterization could not be performed extensively (Silvestri et al., 2019a). In Silvestri et al. (2019b), the AEM methodology was used to construct an accurate three-dimensional representation of a peatland, accounting for peat thickness across the entire ecosystem. Aside from the logistical adversities, e.g., flight line spacing and cost, both studies highlighted limitations of the TDEM method. Limitations included difficulty with imaging the base of peat due to low electrical conductivity contrasts between organic matter and bedrock, an inability to detect thin layers of both peat and clay, and a low number of field samples for ground truthing (Silvestri et al., 2019a; Silvestri et al., 2019b). However, it was noted that in the presence of high electrical contrasts, this method would have an increased ability to detect peat thickness and may be more applicable in other situations.

5.2.6. Ground penetrating radar

Ground-based geophysical methods, such as ground penetrating radar (GPR) again, use low frequency EM waves with slightly higher energies than those detected by EM methods to identify peatland stratigraphy and thickness (Zajícová and Chuman, 2019). GPR is capable of detecting changes in the EC of water occupying void space; however, it cannot detect hydrological connections without some form of supplemental inputs, e.g., a tracer solution (Holden, 2004). Characterization by EC, via electrical resistivity surveys, has also been explored in peatland assessments (Clément et al., 2020). The concept fueling this particular avenue of research lies in the chargeability of peat. Peatland conductance, or resistivity, in the partially decomposed organic matter could allow for mapping by electrical properties (Márquez Molina et al., 2014). By this measure, nutrient species and independent ions cannot be directly quantified but relationships with chargeability can be drawn as this has been performed in agricultural assessments of TN and mineral N (Fahmi et al., 2019). However, similar to the application of GPR, when considering airborne EM and the physical diagnostic of EC, if peat substrate materials are highly conductive or if conductance is highly variable over short distances (Parsekian, 2018) the signal interference potential in the substrate could mask the desired detection. The methods mentioned thus far, and similar methods of induced polarization and EM induction, are all variations of an EC metric (Mclachlan et al., 2017).

5.2.7. Radiometric surveys

Lastly, gamma ray spectrometry, or radiometric survey, relies on the decay of potassium (^{40}K), uranium (^{238}U), and thorium (^{232}Th) radionuclides which are characteristic elements of bedrock materials; and, unlike the previous methodologies, signal detection takes the form of a passive reading due to the radioactive decay of the associated elements that make up the top sixty centimeters of the subsurface, approximately (Beamish, 2013). The incoherent scattering produced during radioactive decay (Beamish, 2013) can undergo attenuation or, put another way, a loss of flux occurs as a portion of gamma scatter interacts with an absorber medium, i.e., water. Soil can be described as a three-phase system with solid, liquid and gas being referred to as the parent material. Porewater and air are the phases and aspects of the parent material that affect the radiometric attenuation in the soil. Depending on the level of saturation, soil water content lends to a functioning increase in the attenuation of the gamma signal. Beamish (2013) highlighted the theoretical depth of investigation in the majority of near-surface earth materials to be approximately sixty centimeters, depending on saturation. As peat is made up of organic material it acts solely as an attenuator as opposed to a source of the radioactive signal. The relatively low dry bulk density combined with high porosity and typically high saturation give peat its unique significance within the realm of radiometric surveys. Beamish (2013) demonstrated that intra-peat variability could be noted within an airborne radiometric survey from Northern Ireland. This variability was linked to either varying peat depth or peat saturation with ground truthing required to verify any results. The effect of saturation is clearly demonstrated when focused on peat.

The ability to precisely distinguish boundaries has led to radiometric associations in the general mapping of peatlands. In Northwest Germany, Siemon et al. (2020) most recently used radiometric detection with helicopter-borne FDEM for mapping peat volume within a bog. The German study sought to quantify thickness and extent, but it was noted that the radiometric data could not be used solely. Due to the nature of the radioactive decay and the parent material, and the attenuators, e.g., degree of water saturation in the peat, the precise nature of the radioactive decay cannot be known through simple qualitative analysis (Siemon et al., 2020). It is considered a must to combine radiometric input with some other method for developing novel methodologies. As Siemon et al. (2020) have paired radiometric data with AEM, Gatis et al. (2019) have combined the data with airborne LiDAR. In the latter example, a digital surface model produced from the LiDAR, with one-meter resolution, was aggregated to contain cell sizes of ten meters in order to better accommodate radiometric counts. The soil attenuation information and the detected microrelief produced a spatial interpretation that accounted for peat depth and offered a modelled scale that is considered to be effective enough for land management decisions (Gatis et al., 2019). Airborne geophysical survey by radiometric detection and its integration have also been previously used in conjunction with peat depth and soil organic carbon (SOC) data to spatially interpolate SOC throughout a peatland (Keaney et al., 2012).

6. Conclusion

Discrepancies between state-level attitudes and international initiatives have historically dampened the efforts of an accepted global policy; one that is aimed at safeguarding environmental flow derived from peatland ecosystems. Regardless of destructive activities, national intricacies, and the posteriority of sustainable development goals placing peatlands in states of distress, there is uncertainty regarding the effectiveness of rehabilitation and restoration. To assess the benefits of management activities and to weigh those benefits against their potentially hazardous impacts, there must be an informed methodology that can provide suitable hydrological and geochemical characterization at a site scale. Such a methodology should serve a twofold purpose: offering data that may infer the health of a peatland ecosystem and data that can act as input for water quality and NPS pollution models. General applications of remote sensing give true results covering many soil processes; however, their use for identifying peatland geochemical behavior is questionable. High variation in subsurface water levels that occurs over short distances within a peatland has long been a challenge for groundwater predictions, and this water level flux is suspected to have a dramatic influence on the composition and chemical activity of stored water. Exploration into the synergistic use of optical, radar, and radiometric resolution will expand as a metric for assessing the relevant phenomena, whether they be natural or anthropogenic. These combined techniques can provide detail from within the shallow subsurface and may counteract the current limitations associated with existing EM methods.

Declaration of Competing Interest

None.

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