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Review and Synthesis: Peatland and Wetland Models Simulating CH_4 Production, CH_4 Oxidation and CH_4 Transport Pathways

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Abstract. Peatlands play an important role in the global CH_4 cycle and models are key tools to assess global change effects on CH_4 processes. It remains unclear how well our existing wetland modelling frameworks are suited to peatland questions. Therefore, we reviewed 16 peatland or wetland models operating at different spatial (seconds-to-decadal) and temporal (soil core-to-global) scales, having different spin-up periods for carbon pool stabilization and various CH_4 production, oxidation and transport processes. Through a literature review, model specific advantages and limitations, common and specific driving inputs of all models and critical inputs of individual models impacting CH_4 plant-mediated transport, diffusion and ebullition were summarized. The 16 reviewed models were qualitatively ranked 0 to 4 (none-to-full process representations) with respect to CH_4 production, oxidation and transport. The most common temporal and spatial scale for 14 models was daily time-step and field scale respectively, while the spin-up stabilization periods of different carbon pools (peat, litter, roots, exudates, microbial, humus, slow, fast) of all models ranged 7 to 90102 years. With regards to CH_4 production and oxidation, 50% of reviewed models (Ecosys, CLM-Microbe, ELM-Spruce, Peatland-VU, Wetland-DNDC, TRIPLEX-GHG, TEM, CLM4Me) exhibited full to adequate process representation. Meanwhile 44, 44 and 25% models exhibited full to adequate process representation for plant mediated transport, diffusion and ebullition respectively. This meant there is ample scope to improve ebullition processes in the remaining 75% models. We conclude that existing models are adequate for site-level CH_4 flux assessments but may lack a predictive understanding of CH_4 production pathways.

1 Introduction

Northern peatlands contain partially decomposed plant derived organic matter that has accumulated over millennial time scales, due to the continuously water-logged conditions, acidic soils and low air temperatures (Nichols and Peteet, 2019; Hugelius et al., 2020; Loisel and Gallego-Sala, 2022). These waterlogged conditions drastically slow down the decomposition of organic matter, resulting in net accumulation of peat (Hugelius et al., 2020; Qiu et al., 2020; Qiu et al., 2021). Although peatlands cover 3% of the global land area they store twice as much carbon as the world's forest (Humpenöder et al., 2020; Loisel and Gallego-Sala, 2022). Globally, 600 ± 100 Pg C is stored in peatlands (Leifeld and Menichetti, 2018; Leifeld et al., 2019; Nichols and Peteet, 2019). However, during the last century, peatlands across the globe have been drained and degraded and converted into agricultural lands, grasslands and croplands, releasing stored carbon as CO_2 (Abdalla et al., 2016; Fluet-Chouinard et al., 2023). To mitigate CO_2 losses to the atmosphere, peatlands are being rewetted by raising the water levels closer to the soil surface to enable continuous anaerobic conditions for carbon sequestration (Leifeld et al., 2019). Even though peatland rewetting most commonly decreases net CO_2 emissions, it simultaneously increases CH_4 emissions (Abdalla et al., 2016; Günter et al., 2020). This tradeoff is important since CH_4 is the second most potent greenhouse gas (GHG), having 34 times stronger radiative forcing compared to CO_2, but a shorter lifetime (12 years) compared to CO_2 (300-1000 years) (Abdalla et al., 2016). Furthermore, CH_4 fluxes from rewetted peatlands are spatially and temporally variable and driven by peat depth, vegetation types, microbial compositions, peat and air temperatures, precipitation and resulting water table depths (Wilson et al., 2015; Abdalla et al., 2016; Vroom et al., 2022; Ge et al., 2024).

The two most common monitoring approaches that are utilized to measure CH_4 fluxes from peatlands and wetlands are the top-down and bottom-up approaches (Ma et al., 2021; Erland et al., 2022; Liu et al., 2023; McNicol et al., 2023; Forbich et al., 2024). Bottom-up measurement approaches typically quantify spatial and temporal trends in CH_4 fluxes via chamber measurements with known area and volume (Hutchinson and Livingston, 2002; Kutzbach et al., 2007; Hendriks et al., 2007; Schrier-Uijl et al., 2010) and continuous eddy covariance (EC) measurements (Baldocchi et al., 2001a; Denmead, 2008; Oertel et al., 2012). Although chamber measurements quantify CH_4 fluxes from specific source areas, they require multiple replications to capture spatial and temporal variations and often do not provide continuous flux data, while the EC method provides continuous temporal CH_4 flux data, but these measurements are not easily attributable to a specific microsite type (Erland et al., 2022). Automated chambers of different designs (Courtois et al., 2019; Mander et al., 2022) also measure CH_4 fluxes at a sub-daily temporal resolution and are utilized to capture hot moments from a known source area, typically not captured by manual chamber and EC methods (Zhao et al., 2024). The top-down approach utilizes atmospheric observations of CH_4 concentrations combined with models that account for atmospheric transport from an emitting to an observation location (NASEM, 2018; Erland et al., 2022). The different top-down approaches that are generally utilized are remote observations, towers, aircraft, and satellites (Tedeschi et al., 2022). However, for predicting future wetland/peatland CH_4 fluxes under a range of climatic and environmental conditions, computer models are parametrized against measured CH_4 fluxes and in-situ environmental data to minimize the error between simulated and measured fluxes (Grant, 1998; Grant, 1999; Xu et al., 2016; Morin et al., 2022). Models are also utilized to enhance the understanding of various processes occurring in different peatlands and wetlands such as the CH_4 production, CH_4 oxidation and CH_4 transport (plant-mediated, diffusion and ebullition) (Tang et al., 2010; Riley et al., 2011; Zhang et al., 2022). The other important goal of developing models is identifying the critical inputs that influence modelled outputs related to CH_4 production, CH_4 oxidation and CH_4 transport pathways to improve the process understanding (Xu et al., 2016; Mozafari et al., 2023).

The recent reviews of CH_4-revelant models by Xu et al. (2016) and Mozafari et al. (2023) highlighted and discussed the processes of methanogensis, methanotrophy and CH_4 transport pathways of different terrestrial models impacted by their associated environmental conditions and differentiated 45 peatland and wetland models that simulated CH_4 production, CH_4 oxidation and CH_4 transport into four categories: 1) terrestrial ecosystem models simulating biogeochemical and vegetation dynamics, 2) hydrological models, 3) land surface models, 4) ecohydrological models simulating bogs and fens in the Northern hemisphere respectively. Meanwhile Forbich et al. (2024) provided an historical overview on inclusion of wetland CH_4 components in Earth system models (ESMs), discussed how CH_4 modelling approaches evolved over time and highlighted the knowledge gaps and challenges faced in accurately estimating CH_4 fluxes. However, it remains unclear as to what extent these models could be used for peatland applications. Furthermore, it remains unclear whether these models represent peatland relevant processes and inputs for CH_4. Across peatland applications, future users of models require information on relevant spatial-temporal scales, key model inputs (to ensure that they have corresponding measurements) and on process representation. Therefore, the goals of this review are to synthesize the attributes, strengths and weaknesses of existing models that could be applied to peatland CH_4 questions. Specifically, we: a) summarize the spatial and temporal operating scales and spin-up stabilization periods of different carbon pools; b) identify the model driving inputs that are common and separate to all reviewed models; c) summarize models simulating one or two or three CH_4 transport pathways i.e., plant mediation, diffusion and ebullition; d) qualitatively rank the process representations in each model for CH_4 production, CH_4 oxidation and CH_4 transport; e) summarize the advantages and limitations of each reviewed model; e) synthesize the critical model inputs impacting individual plant-mediation, diffusion and ebullition. ~~We hope~~ this review ~~enables new model users to decide which model suits their needs best, but also~~ provide a synthesis of CH_4 process representation across reviewed models.

2 Materials and Methods

2.1 Identifying models simulating CH_4 processes

We identified models that simulated CH_4 production, CH_4 oxidation and CH_4 transport (plant-mediated, ebullition and diffusion) in peatland and wetland environments using “Google Scholar” and “Web of Science” having the following search key words: a) models simulating CH_4 fluxes peatlands and wetlands; b) models simulating CH_4 transport pathways peatlands and wetlands; c) process based CH_4 models peatlands and wetlands; d) mechanistic models simulating CH_4 fluxes peatlands and wetlands; d) microbial models simulating CH_4 fluxes peatlands and wetlands; e) biogeochemical models simulating CH_4 fluxes peatlands and wetlands and f) dynamic global vegetation models simulating CH_4 fluxes peatlands and wetlands. Each key word resulted in a plethora of published papers, technical reports, documentation, non-peer-reviewed papers, grey literature (reports, policy documents, technical notes) and inaccessible full text papers respectively. Non-peer reviewed papers, grey literature and inaccessible full-text papers were not considered in this review.

2.2 CH_4 model selection and review

From each key word or phrase, peer reviewed published papers associated with each model were identified i.e., model specific development papers, model application papers, model review papers and technical model documentation. Also, models were only chosen if they were written in English and published from 1997 to 2022. Model documents pertinent to the above-mentioned criteria were manually screened, identified and selected. Statistical or black box models simulating CH_4 fluxes in peatlands and wetlands were not considered in this review. This review specifically focused on identifying models that are process based, mechanistic and microbial, operating at the plot, field, regional, national and global scales that simulated all three CH_4 transport pathways (plant transport, ebullition, and diffusion), at least two CH_4 transport pathways or simulated total CH_4 flux. From these above-mentioned criteria, 16 models were selected (Table 1). Firstly, we distinguish the spatial and temporal operating scale of each model, quantify the spin-up period required to stabilize different carbon pools for each model, summarize models simulating one or two or three CH_4 transport pathways and qualitatively rank each model into five process representation categories from 0 to 4, with the rank 0 having no process representation, rank 1 minimal process representation, rank 2 intermediate process representation, rank 3 adequate process representation and rank 4 full process representation with respect to CH_4 production, CH_4 oxidation, CH_4 plant transport, CH_4 diffusion and CH_4 ebullition. The no process representation implies that the specific peatland or wetland model does not incorporate any processes or mechanisms simulating CH_4 production, oxidation and transport. In case of the minimal process representation, the specific peatland or wetland model exhibits simplified representation of CH_4 fluxes without quantifying in detail the different CH_4 production, and oxidation pathways, while the transport process are only described using rate coefficients. Models with intermediate process representation incorporate some degree of CH_4 production and oxidation, while CH_4 transport is described based on rate coefficients and CH_4 concentrations supporting bubbling, minimum and threshold CH_4 concentrations and vegetation specific CH_4 transport and oxidation factors. The adequate process representation quantifies different CH_4 production, oxidation and transport pathways (Zhuang et al., 2004; Zhu et al., 2014; Salmon et al., 2022), while full process representation quantifies detailed microbial CH_4 production and oxidation processes (Grant and Roulet, 2002; Xu et al., 2015; Wang et al., 2019; Ricciuto et al., 2021). A concise description of all the reviewed models is available in the Supplementary material.

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Table 1. Selected peatland or wetland model and their references.

Model name	Model references
CLM-Microbe	Xu et al. (2015) ; Wang et al. (2019) ; He et al. (2021) ; Zuo et al. (2022); He et al. (2024)
HIMMELI	Raivonen et al. (2017)
Peatland-VU	van Huissteden et al. (2006); van Huissteden et al. (2009); Petrescu et al. (2010); Budishchev et al. (2014); Mi et al. (2014); Lippmann et al. (2023)
Wetland-DNDC	Li et al. (1992a), Li et al. (1992b) ; Li (2000) ; Zhang et al. (2002) ; Gilhespy et al. (2014) ; Deng et al. (2015); Webster et al. (2013) ; Taft et al. (2019)
TRIPLEX-GHG	Zhu et al. (2014) ; Zhu et al. (2016); Zhu et al. (2017)
WETMETH	Nzotungicimpaye et al. (2021)
ORCHIDEE model (various versions)	Largeron et al. (2018) : high-latitude-ORC-HL-PEAT; Qiu et al. (2018) : revision 4596 ; Giumberteau et al. (2018) : MICT (v.8.4.1) ; Qiu et al. (2019) : PEAT land surface model (SVN r5488) ; Salmon et al. (2022): revision 7020-PCH$_4$,
BASGRA-BGC	Huang et al. (2021)
TEM	Zhuang et al. (2004) ; Zhuang et al. (2010) ; Tang et al. (2010) ; Li et al. (2020)
Ecosys	Grant and Roulet (2002) ; Grant et al. (2015a) ; Grant (2015b) ; Grant et al. (2017a); Grant et al. (2017b) ; Chang et al. (2019)
LPJWhyMe	Wania et al. (2009a) ; Wania et al. (2009b); Wania et al. (2010)
MEM	Lai (2009)
CH4MOD	Li et al. (2010) ; Li et al. (2012) ; Li et al. (2016) ; Li et al. (2017), Li et al. (2019); Li et al. (2020); Zhang et al. (2020);
PEPRMT	Oikawa et al. (2017) ; Fertitta-Roberts et al. (2019); Mack et al. (2023)
ELM-SPRUCE	Xu et al. (2015) ; Shi et al. (2015) ; Hanson et al. (2020) ; Yuan et al. (2021); Wang et al. (2019); Ricciuto et al. (2021)
CLM4Me	Oleson et al. (2010) ; Lawrence et al. (2011); Riley et al. (2011)

3 Results

3.1 Model temporal and spatial scales

The reviewed peatland or wetland models operate at different temporal scales. For example, Ecosys (Grant and Roulet, 2002; Grant et al., 2012; Grant et al., 2017a, b) operates at seconds and hourly time scale, while HIMMELI (Raivonen et al., 2017) and ORCHIDEE-PCH4 (Salmon et al., 2022) operate at half-hourly time scale, PEPRMT (Oikawa et al., 2017) operate at daily time scale and CLM-Microbe (Xu et al., 2015 ; Wang et al., 2019), TEM (Zhuang et al., 2004), ELM-Spruce (Xu et al., 2015 ; He et al., 2020 ; Yuan et al., 2021 ; Wang et al., 2019) and Ecosys operate at hourly time scale (Table 2). However, the most widely utilized temporal scale for 14 out of 16 models was the daily-time step. With regards to spatial operating scale, CLM-Microbe operates at lab, plot and field scale, while the most widely utilized spatial scale for 14 out of 16 models was field scale (Table 2).

3.2 Model spin-up times for stabilizing different carbon pools

The spin-up time required for stabilization of different carbon pools for all models ranged from 7 to 90102 years (Fig. 1). For example, HIMMELI, which is not embedded into any peatland carbon model requires seven-spin-up years to stabilize peat CH_4 concentrations (Raivonen et al., 2017). Peatland-VU (van Huissteden et al., 2006) requires 20-60 years for stabilizing different carbon pools such as peat, litter, roots, exudates, microbial and humus (personal communications, Tanya Lippmann, 2022). However, Wetland-DNDC (Zhang et al., 2002) requires 20-200 years of spin-up to stabilize soil organic carbon (SOC), soil N pools and soil water filled pore spaces (WFPS) (Webster et al., 2013; Deng et al., 2015; Taft et al., 2019). The exact number of years for stabilizing different carbon pools in Peatland-VU and Wetland-DNDC depends upon

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the site-specific climate, soils, vegetation and local environmental conditions. Models such as Ecosys (Grant and Roulet, 2002), ORCHIDEE (peat land surface, MICT, Peat-4596, PCH_4) (Largeron et al., 2018; Qiu et al., 2018; Giumberteau et al., 2019), TEM (Zhuang et al., 2010; Li et al., 2020) and TRIPLEX-GHG (Zhu et al., 2014) require 41-300 years spin-up to stabilize hydrology, soil thermal regimes, soil moisture, C in dead plants and vegetation productivity (Fig. 1). However, the spin-up time of ORCHIDEE-PCH_4 varies depending on the site type i.e., bog vs. fen vs. marsh. For example, the spin-up period for carbon pool stabilization at Winous Point Marsh site, USA was 32 years, while it was 10060 years at a fen site in Germany (Salmon et al., 2022). Qiu et al. (2018) utilized ORCHIDEE-PEAT (revision 4596) at 30 peatland sites located in boreal, temperate, arctic and arctic permafrost and the spin-up time to stabilize carbon pools was 10100 years. Models like CLM4Me (Riley et al., 2011), LPJWhyMe (Wania et al., 2010) and ELM-SPRUCE (Ricciuto et al., 2021) have spin-up times of 1500, 1000 and 1250 years respectively. Spin-up times in CLM4Me (Riley et al., 2011) consists of: 1) 500 years spin-up using atmospheric data and 2) 1000 years spin-up subject to land use, N and aerosol deposition. In LPJWhyMe (Wania et al., 2010), 1000 years spin-up implemented using climate data such as air temperature, cloud cover, monthly total precipitation and monthly number of wet days, while in ELM-SPRUCE (Ricciuto et al., 2021), four soil carbon pools and three litter pools were stabilized for 1250 years. However, carbon pool stabilization in LPJWhyMe requires 90000 years spin-up +102 years of transient runs (Wania et al., 2009b). The carbon pool stabilization in CLM-Microbe varies for different biomes, e.g., tropical and temperate 1500 years spin-up, boreal and arctic 2000 years and wetlands 3000 years (Fig. 1; He et al., 2023). Meanwhile the stabilization in WETMETH consists of three phases: 1) 5000 years spin-up for climate state equilibrium; 2) 169 years transient runs of CO_2 concentrations and 3) site-specific runs based on measured data (Nzotungicimpaye et al., 2021). However, no information on carbon pool stabilization is provided for MEM (Lai, 2009), CH4MOD (Li et al., 2010) and PEPRMT (Oikawa et al., 2017) as of October 22, 2024.

Table 2. Temporal and spatial operating scales of 16 peatland or wetland models.

Spatial scales	**Peatland or Wetland Models**	**Temporal scales**	**Peatland or Wetland Models**
Seconds	Ecosys	**Lab**	CLM-Microbe
Half hourly	HIMMELI, ORCHIDEE-PCH4	**Plot**	CLM-Microbe, HIMMELI, Peatland-VU, Ecosys, ELM-SPRUCE
Hourly	CLM-Microbe, TEM, Ecosys, ELM-SPRUCE	**Field**	CLM-Microbe, Peatland-VU, TRIPLEX-GHG, TEM, LPJWhyMe, MEM, ELM-SPRUCE, HIMMELI, Wetland-DNDC, BASGRA-BGC, Ecosys, CH4MOD, PEPRMT, CLM4Me
Daily	CLM-Microbe, Peatland-VU, TRIPLEX-GHG, BASGRA-BGC, LPJWhyMe, PEPRMT, CLM4Me, HIMMELI, Wetland-DNDC, ORCHIDEE-PCH4, TEM, MEM, CH4MOD, ELM-SPRUCE	**Regional**	TRIPLEX-GHG, WETMETH, ORCHIDEE-PCH4, TEM, CLM4Me
Monthly	TRIPLEX-GHG, LPJWhyMe, CLM4Me	**National**	TRIPLEX-GHG, WETMETH, ORCHIDEE-PCH4, TEM, CLM4Me
Seasonal	WETMETH	**Global**	TRIPLEX-GHG, WETMETH, ORCHIDEE-PCH4, TEM, CLM4Me
Yearly	WETMETH, LPJWhyMe		
Decadal	WETMETH		

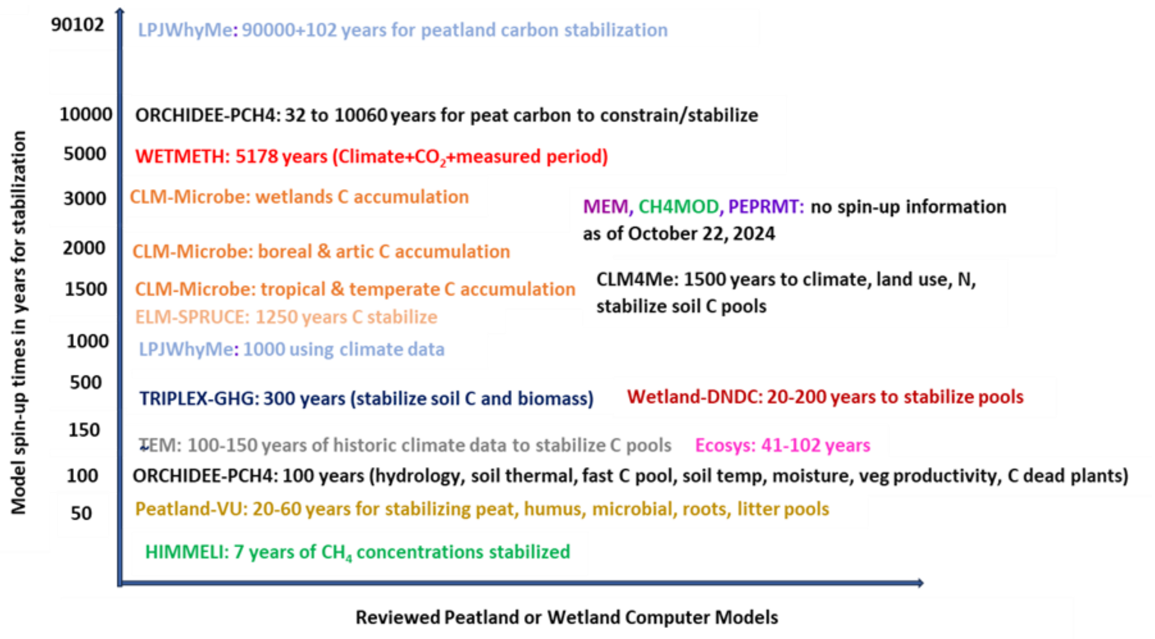

Figure 1. Spin-up times in terms of stabilizing different carbon pools for all reviewed wetland or peatland models. Each model has its own unique color for easy identification. Also, a single model can possess different time scales, e.g., CLM-Microbe having different C stabilization periods for tropical, temperate, and arctic ecosystems.

3.3 Common model driving inputs

Each of the selected peatland or wetland models (Table 1) was manually screened to identify driving inputs common to all models with respect to climate, hydrology, peat physical and chemical and different vegetation species (Table 3). Generally, climate inputs are easily available from on-site measurements or global databases (NCAR climate data, Copernicus, Europe, NASA Climate data services, NOAA Climate data and local databases (Irish Metrological Service and United States Environmental Protection Agency). The hydrological and peat physical and chemical data (Table 3) can be obtained from literature, laboratory and site-specific field measurements.

3.4 Model specific driving inputs

The number of model inputs (Table 4) are generally proportional to how comprehensively each model simulates the intricacies of processes like hydrology, soil physical, soil chemical, soil microbial processes and vegetation dynamics. For example, CLM-Microbe (Xu et al., 2015; Wang et al., 2019) and Ecosys (Grant and Roulet, 2002; Grant, 2015; Grant et al., 2015) and ELM-SPRUCE (Ricciuto et al., 2021; Yuan et al., 2021) require extensive microbial inputs (growth, death rates and temperature sensitivity of acetoclastic methanogens, aerobic methanotroph and growth rate H_2-CO_2-dependent methanogens) compared to MEM (Lai, 2009) which only requires acrotelm and catotelm depth, decomposition rates and carbon to peat ratio. Models like Peatland-VU, Wetland-DNDC, TRIPLEX-GHG, BASGRA-BGC, ORCHIDEE-PCH4, LPJWhyMe and CH4MOD utilize different decomposition rates for different carbon pools (humus, peat, roots and litter, exudates, slow and fast carbon pools) which are rarely available from site-specific measured data, instead, they are fine-tuned during model parametrization (van Huissteden et al., 2006; Webester et al., 2013 ; Li et al., 2004a ; Zhang et al., 2002; Zhu et al., 2014 ; Zhu et al., 2016 ; Zhu et al., 2017; Salmon et al., 2022; Huang et al., 2021; Wania et al., 2010; Li et al., 2010 ; 2016 ; 2020 ; Zhang et al., 2020). Also, inputs related to CH_4 transport such as plant-mediated transport, CH_4 oxidized during plant transport, ebullition and diffusion rate coefficients are not measured at all peatland and wetland sites but fine-tuned to minimize the error between simulated and measured CH_4 fluxes. The model specific driving inputs that are generally available from site-specific studies are specific leaf area, harvested above-ground biomass, maximum and minimum vegetation growth rates, rooting depth, peat thickness, initial peat carbon levels, growing degree days, standing water above peat surface, WTDs, leaf and litter C and N, lignin concentration in litter and C:N ratio.

Table 3. Driving inputs common across peatland or wetland CH_4 models (for individual model references see Table 1).

Climate inputs	**Hydrological inputs**	**Physical & Chemical inputs**	**Vegetation inputs**
Precipitation	Water table depths	No of peat layers & individual depths	Leaf area index,
Evapotranspiration	Peat moisture in different depths	Initial soil organic C all peat depths	Specific leaf area,
Air temperature	Surface flow inputs (runoff)	pH all peat depths	Max root depth, length, & tortuosity
Solar radiation	Hydraulic conductivity all peat layers	Bulk density all peat depths	Plant functional types (PFTs),
Short & long wave radiation	Porosity all peat layers	Peat temperature all peat depths	Above & below ground biomass, its C: N concentrations
Wind speed	Field capacity all peat layers	C:N ratios all peat depths	Litter C & N concentrations
Humidity	Wilting point all peat layers	Soil CH_4 concentrations each peat layer	Initial senescence rates/scalars and above & below ground biomass
Cloud cover	Volumetric water content	Threshold CH_4 concentration for ebullition	
Vapor pressure			

Table 4. Model specific driving inputs for reviewed peatland or wetland models.

Model specific driving inputs				
CLM-Microbe (Xu et al., 2015 ; Wang et al., 2019)	**HIMMELI** (Raivonen et al., 2017)	**Peatland VU** (van Huissteden et al., 2006 ; 2009)	**Wetland DNDC** (Webester et al., 2013 ; Li et al., 2004a ; Zhang et al., 2002)	**TRIPLEX GHG** (Zhu et al., 2014 ; Zhu et al., 2016 ; Zhu et al., 2017)
1) half-saturation coefficient of available carbon mineralization, 2) max rate of acetate production available carbon, 3) decomposition rate constant dissolved organic matter, 4) decomposition rate constant biomass of bacteria and fungi, 5) leaf N fraction Rubisco enzyme, 6) growth respiration parameter 7) methanogen growth & death rates 8) plant mediated, diffusion & ebullition rate constants	1) aerobic & anaerobic respiration rate 2) CH_4 oxidation inputs (Michaelis-Menten) 3) methanogenesis sensitivity to O_2 inhibition, 4) root decay constant, 5) root tortuosity 6) ebullition & diffusion constants & specific leaf area	1) SOM decomposition constants (peat, humus), 2) min & max primary production 3) carbon fraction each layer organic matter reservoir, 4) root and litter senescence 5) exudate factor 6) harvested biomass fraction 7) CH_4 oxidation & production 8) CH_4 transport (rate constants)	1) Atmospheric CO_2, NO_3-N, NH_4-N in precipitation, 2) biomass & leaf C & C:N ratio in wood 3) growing degree days 4) vegetation growth respiration and dark respiration fraction, 5) humus fraction, 6) vegetation harvesting dates, 7) fertilization rates. 8) CH_4 production, oxidation & transport parameters	1) diurnal temperature range 2) wet day frequency, 3) soil texture, 4) plant functional types, 5) topography (soils & veg) 6) decomposable, structural, and resistant carbon pool decomposition rates, protected slow pool, passive pool, and non-protected slow pool rates), 7) CH_4 production, oxidation, and transport parameters.

Table 4. continued.

Model specific driving inputs				
WETMETH (Nzotungicimpaye et al., 2021)	**ORCHIDEE-PCH$_4$** (Salmon et al., 2022)	**BASGRA-BGC** (Huang et al., 2021)	**Terrestrial Ecosystem Model (TEM)** (Zhuang et al., 2004 ; 2010 ; Tang et al., 2010)	**Ecosys** (Chang et al., 2019 ; Grant and Roulet, 2002 ; Grant, 2015 ; Grant et al., 2015 ; Bouskill et al., 2020)
1) thickness of oxic-anoxic zone 2) carbon content 3) topographic maps (spatial wetland distribution) 4) plant functional types 5) CH$_4$ production (temperature coefficient) 6) CH$_4$ oxidation scaling parameter.	1) plant functional types, 2) CH$_4$ production & oxidation, 3) CH$_4$ transport (oxic: anoxic decomposition ratio, methanotrophy rate, root CH$_4$ oxidation, root depth, efficiency plant mediated CH$_4$ transport, moisture connectivity and CH$_4$ mixing ratio bubbles).	1) C & N, root, leaf & stem 2) dissolved organic carbon, 3) harvest date, fertilizer 4) distance between two drainpipes, radius & depth 5) labile, very labile, and passive SOM constants, 6) grass maintenance and growth respiration rates, 7) oxidation & production rates 8) CH$_4$ rate constants plant transport, diffusion, ebullition.	1) soil thermal conductivity 2) soil heat capacity, 3) soil C, N & soil texture, 4) vegetation (canopy water conductance, its max value & leaf water potential) 5) scalars: redox, pH, moisture, and soil temperature on CH$_4$ production and CH$_4$ oxidation 6) CH$_4$ pathways (rate constants ebullition, plant transport, diffusion, root area, plant aerenchyma factor)	1) soil organic carbon, sand, silt content, field capacity, wilting point, hydraulic conductivity, grid cell slopes 2) Atmospheric concentrations (O_2, CO_2, CH_4, N_2O) 3) tillage, fertilization, irrigation & harvesting inputs, 4) plant & microbial functional type (PFTs & MFTs) inputs 5) nutrient cycling (C, N, P)

Table 4. continued

Model specific driving inputs					
LPJWhyMe (Wania et al., 2010)	**Methane Emission Model (MEM)** (Lai, 2009)	**CH4MOD** (Li et al., 2010 ; 2016 ; 2020 ; Zhang et al., 2020)	**PEPRMT** (Oikawa et al., 2017 ; Fertitta-Roberts et al., 2019)	**ELM-SPRUCE** (Xu et al., 2015 ; He et al., 2020 ; Yuan et al., 2021 ; Wang et al., 2019)	**CLM4Me** (Lawrence et al., 2011 ; Oleson et al., 2010 ; Riley et al., 2011)
1) inundation stress non-flood tolerant PFTs 2) decomposition rates: fast & slow carbon pools 3) production & oxidation inputs 4) transport pathways inputs	1) acrotelm and catotelm (depth, decomposition, mineralization rates) 2) carbon to peat ratio	1) standing water depth; 2) sand fraction, 3) max above ground biomass 4) growing degree days 5) senescence degree day 6) non-structural component of plant litter, 7) SOM first order decay rate 8) initial N & lignin in litter 9) plant carbohydrates amount	1) absorbed photosynthetically active radiation (APAR), 2) initial soil organic carbon 3) labile soil organic carbon.	1) observed GPP, NPP, plant biomass, 2) DOC, acetate concentrations, 3) initial N concentrations, 4) bacterial and fungal turnover rates, 5) growth & death rates methanotrophs, methanogen, 6) minimum CH_4 solubility, 7) dissolved organic matter turnover rate. 8) maximum acetate production rate 9) half-saturation coefficient available carbon mineralization 10) dissolved organic matter turnover rate	1) CH_4 production (Q10 & pH impact) 2) CH_4 oxidation (max oxidation rate) 3) O_2 & CH_4 half-saturation oxidation coefficients 4) CH_4 transport parameters (aerenchyma radius, porosity, CH_4 concentration threshold)

3.5 Models simulating CH_4 transport pathways

Out of 16 reviewed models, 12 models simulate all three CH_4 transport pathways of plant-mediated, ebullition and diffusion (Fig. 2). MEM only simulates diffusion and ebullition but not plant-mediated transport (Lai, 2009) while CH4MOD only simulates plant-mediated transport and ebullition, but not diffusion (Li et al., 2010; 2016; 2017). The PEPRMT (Oikawa et al., 2017) simulates plant-mediated transport and diffusion but not ebullition, while WETMETH does not simulate any CH_4 transport pathways, but rather simulates total CH_4 flux (Nzotungicimpaye et al., 2021).

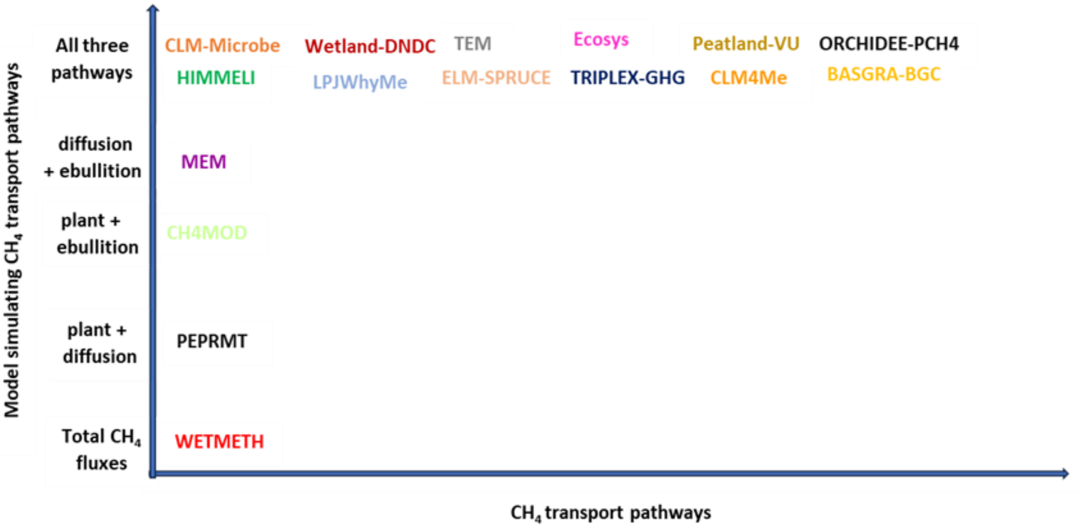

Figure 2. Reviewed peatland or wetlands models simulating CH_4 transport pathways. Each model has its own unique colour for easy identification. The + sign means model simulates both mentioned CH_4 transport pathways.

3.6 Model process-representations: Full (rank 4) and adequate (rank 3)

The 16 reviewed models were distinguished into five categories to qualitatively rank: CH_4 production, CH_4 oxidation and CH_4 transport processes. The ranking was done using qualitative categories 0 to 4 (as explained in section 2.2). The following sections provides information on models categorized under rank 4 (full) and rank 3 (adequate) based on their model process-representations for production, oxidation and transport processes, whereas categorization of all 16 reviewed models into the five categories is presented in Figures 3 and 4.

3.6.1 Production and oxidation models

Models like CLM-Microbe, Ecosys and ELM-Spruce (Fig. 3) exhibited full CH_4 production and oxidation processes, since they comprehensively simulate microbial mediated processes of production (hydrogenotrophic methanogenesis, acetoclastic methanogenesis and H_2 production) and oxidation (aerobic methanotrophy and anaerobic methanotrophy) (Grant and Roulet, 2002; Xu et al., 2015; Riccuito et al., 2021). Meanwhile models like Peatland-VU, Wetland-DNDC, TRIPLEX-GHG, TEM, CLM4Me exhibited adequate production and oxidation processes (Fig. 3). For example, in Peatland-VU, CH_4 production depends on C concentration in fresh soil organic matter reservoirs (root exudates, litter, manure, dead roots, microbes and humus), reference temperature, peat temperature and rate constant R_o (site-tuning parameter depending upon organic matter quality and environmental factors), while the CH_4 oxidation is temperature sensitive and simulated using Michaelis-Menten constants i.e., K_m (half saturation) and V_{max} (max reaction rate) (van Huissteden et al., 2006; 2009). In Wetland-DNDC, CH_4 production is simulated as a function of C substrates (electron donors: H_2 and DOC and electron acceptors: NO_3, Mn^{4+}, Fe^{3+}, SO_4^{2-} and CO_2) resulting from soil organic matter decomposition and root exudates, available CH_4 concentrations in each layer and pH, soil temperature and redox scalars (Zhang et al., 2002; Deng et al., 2015; Gilhespy et al., 2014), while the CH_4 production and oxidation can simultaneously occur within a given peat volume having anaerobic and aerobic portions based on soil redox (Zhang et al., 2002; Deng et al., 2015). Overall, 50% of the models exhibited full and adequate CH_4 production and CH_4 oxidation process representation, while the remaining 50% exhibited intermediate to no process representation (Fig. 3).

3.6.2 Plant mediated transport models

Models like Ecosys, HIMMELI, ORCHIDEE-PCH4, TEM, LPJWhyMe, CLM4Me, Peatland-VU exhibited full to adequate process representation (Fig. 4). For example, in Ecosys, plant-mediated CH_4 transport is simulated using air-water interfacial area in root, 1/2 distance between adjacent roots, root length, total cross-sectional area of root axes, detailed mathematical equations in Grant and Roulet (2002). Meanwhile the plant-mediated transport in HIMMELI is simulated using specific leaf area (SLA), leaf area index (LAI), root tortuosity and porosity (Raivonen et al., 2017) while the plant-mediated transport in Peatland-VU is simulated using root factor, vegetation specific CH_4 factor, vegetation growth rate proportional to primary production and fraction of CH_4 oxidized during plant transport (van Huissteden et al., 2006; 2009). Finally, in ORCHIDEE-PCH4, plant-mediated transport is simulated using vegetation rate constant, efficiency of plants in transporting CH_4, root fraction, vertical root distribution, LAI, CH_4 concentrations in soil and atmosphere and CH_4 oxidized during plant transport, detailed equations in Salmon et al. (2022). Overall, 44% of the models exhibited full and adequate CH_4 plant-mediated process representation, while the remaining 56% of models exhibited intermediate to no process representation (Fig. 4).

3.6.3 Diffusion models

Models like Ecosys, TRIPLEX-GHG, CLM4Me, HIMMELI, ORCHIDEE-PCH4, TEM, LPJWHYMe, exhibited full to adequate process representation (Fig. 4). For example, in Ecosys, diffusion is simulated using atmospheric CH_4 concentrations, constants for CH_4 oxidation, air filled porosity and diffusivity, extensive equation details, refer Grant and Roulet (2002). Meanwhile, in TRIPLEX-GHG, diffusion is simulated using CH_4 molecular diffusion coefficients in air and water, peat porosity, water filled pore spaces, peat tortuosity coefficient and relative volume of coarse pores based on soil texture (Zhu et al., 2014), while diffusion in CLM4Me is simulated using air-filled and water-filled porosities, aqueous and gaseous diffusion coefficients of CH_4 and O_2, peat temperature and water retention curve (Riley et al., 2011). Like plant-mediated transport, 44% of models exhibited full and adequate CH_4 diffusion process representation, while the remaining 56% models exhibited intermediate to no process representation (Fig. 4).

3.6.4 Ebullition models

Ecosys, HIMMELI, ORCHIDEE-PCH4 and TEM (Fig. 4) exhibited full to adequate process representation. For example, Ecosys simulates ebullition using temperature growth function related to fermentation & methanogenesis processes, Ostwald gas solubility coefficient 30°C, atmospheric pressure, soil temperature and gas constant, details refer Grant and Roulet (2002). Meanwhile in HIMMELI, (Raivonen et al., 2017) and TEM (Tang et al., 2010), concentrations of CH_4, CO_2, O_2 and N_2 and sum of their partial pressures are utilized to simulate the occurrence of ebullition. However, it is assumed that N_2 is always in equilibrium with its atmospheric concentration of 78% and solubilities of CH_4, CO_2, O_2 in water are computed using Henry's law coefficient, so essentially, if sum of the partial pressures of the dissolved CH_4, CO_2, O_2 and N_2 exceed the sum of atmospheric and hydrostatic pressure, ebullition occurs in HIMMELI (Raivonen et al., 2017). Tang et al. (2010) modified the TEM into a multi-substance model (CH_4, O_2, CO_2 and N_2) to simulate CH_4 production, oxidation, and transport using pressure-based ebullition algorithm, details, refer, Tang et al. (2010). Overall, only 25% of the models exhibited full and adequate process representation, providing an ample scope to improve diffusion processes in 75% models exhibiting intermediate to no process representation (Fig. 4).

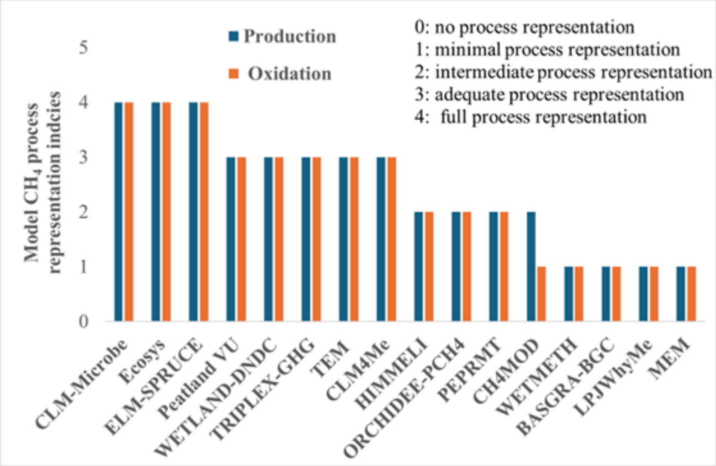

Figure 3. CH$_4$ process representation indices of production and oxidation. Note: the definition of the process representation indices is described in detail in section 2.2.

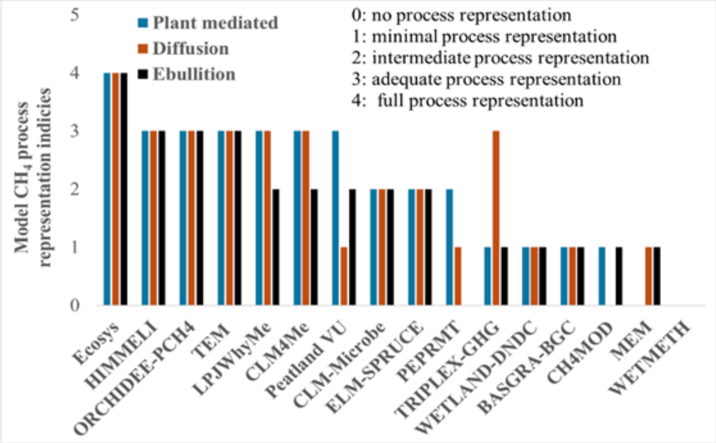

Figure 4. CH$_4$ process representation indices of plant-mediated transport, diffusion and ebullition. Note: the definition of the process representation indices is described in detail in section 2.2.

3.7 Advantages of reviewed models

All models were manually screened to identify the advantages of each model with respect to simulated CH$_4$ processes, robustness (tested in varied environments), global field testing, minimal inputs and simulation of specialized CH$_4$ transport processes (Table 5). For example, CLM-Microbe (Xu et al., 2015; Wang et al., 2019) comprehensively simulates CH$_4$ microbial processes, while BASGRA-BGC specifically simulates dual porosity nature of peat soils (Huang et al., 2021). The Ecosys (Grant and Roulet, 2002; Grant et al., 2015; 2017) comprehensively simulates WTDs, CH$_4$ production, CH$_4$ oxidation and three CH$_4$ transport pathways, while ELM-Spruce (Xu et al., 2015; He et al., 2020; Yuan et al., 2021; Wang et al., 2019) comprehensive simulates all CH$_4$ processes occurring in the forested peatlands. The PEPRMT (Oikawa et al., 2017) incorporates the lag effect of lowering water table on CH$_4$ production and quantifies CH$_4$ fluxes from restored wetlands and rice fields. With regards to robustness and global field testing, HIMMELI (Raivonen et al., 2017) has the ability to simulate varied peat environments, while Peatland-VU (van Huissteden et al., 2006; 2009; Budishchev et al., 2014; Mi et al., 2014), Wetland-DNDC (Li et al., 1992a, b; Li, 2000 ; Zhang et al., 2002; Gilhespy et al., 2014; Deng et al., 2015) and TRIPLEX-GHG (Zhu et al., 2014; Zhu et al., 2016; Zhu et al., 2017) were tested against field data from arctic, temperate, tundra and boreal peatlands and wetlands. BASGRA-BGC has been tested using field data from Finland, Sweden and Norway, but there is ample scope for further model testing from temperate and tropical sites (Huang et al., 2021).

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LPJWhyMe (Wania et al., 2010) simulates CH_4 fluxes across regional, national, and global scales, while CH4MOD (Li et al., 2010; 2016; 2017) can be utilized to simulate CH_4 fluxes from wetlands, marshlands, peatlands and fens. ELM-Spruce (Xu et al., 2015; He et al., 2020; Yuan et al., 2021; Wang et al., 2019) is widely tested against field measured data from forested Minnesota peatlands, tropical and Amazonian peatlands, while Ecosys (Grant and Roulet, 2002; Grant et al., 2015; 2017) is widely tested across the globe (100 or more publications). With regards to model inputs, WETMETH (Nzotungicimpaye et al., 2021), MEM (Lai, 2009) and PEPRMT (Oikawa et al., 2017) are less input intensive, but the modelled CH_4 fluxes simulated the measured CH_4 fluxes from different peatland and wetland sites located in pan-arctic, tropical, temperate and boreal regions (Lai, 2009; Oikawa et al., 2017; Fertitta-Roberts et al., 2019; Nzotungicimpaye et al., 2021). Finally, with respect to simulating specialized CH_4 transport processes, TEM incorporates a 4-substance (CO_2, CH_4, O_2 and N_2) pressure-based algorithm, which resulted in modelled CH_4 fluxes accurately simulating measured CH_4 fluxes (two Michigan peatlands) via ebullition (Tang et al., 2010).

3.8 Limitations of reviewed models

Similar to model advantages, the limitations of each model were differentiated with respect to processes not simulated, highly input intensive, larger computational resources, not simulating different peatland types and CH_4 transport pathways (Table 6). For example, HIMMELI (Raivonen et al., 2017) and BASGRA-BGC (Huang et al., 2021) do not simulate snow dynamics, while the HIMMELI does not simulate any electron acceptors, except O_2. Peatland-VU (van Huissteden et al., 2006; 2009; Budishchev et al., 2014; Mi et al., 2014) does not simulate particulate and dissolved organic carbon and peat subsidence, while Peatland-VU and ELM-Spruce (Xu et al., 2015; He et al., 2020; Yuan et al., 2021; Wang et al., 2019) do not simulate peat growth and changes in peatland microtopography. TRIPLEX-GHG (Zhu et al., 2014; Zhu et al., 2016; Zhu et al., 2017) does not incorporate different plant functional types (PFTs) and does not simulate dynamic O_2 concentration changes. WETMETH (Nzotungicimpaye et al., 2021) lacks detailed process representation of CH_4 production and oxidation and does not simulate CH_4 storage underneath frozen soil and its release upon snow melt. ORCHIDEE versions (Peatland surface, MICT, Peat-4596, PCH4) (Largeron et al., 2018; Qiu et al., 2018; Giumberteau et al., 2019) simulate vertical peat growth, but lateral peat development is lacking in grid-based simulations. For ORCHIDEE to simulate tropical peatlands, improvements in representation of tropical vegetation are required, for example, oxidation of deeper peat due to tropical tree pneumatophores (breather roots) (Qiu et al., 2019). ORCHIDEE versions also require improved representation of Holocene climate, distinguishing bogs vs. fens to parameterize water inflows and incorporating dissolved organic carbon (DOC) leaching to improve C budget and CH_4 emissions (Salmon et al., 2022). PEPRMT (Oikawa et al., 2017) ignores CH_4 production and CH_4 oxidation in multiple peat layers, while no carbon pools can be simulated at millennial to centennial time scales. TEM (Zhuang et al., 2004) does not simulate CH_4 release during the non-growing season in frozen climates and does not simulate CH_4 fluxes from coastal wetlands. MEM (Lai, 2009) does not simulate any vegetation types, while improvements are required in processes related to peat mineralization and water table simulations. CLM4Me (Lawrence et al., 2011; Oleson et al., 2010; Riley et al., 2011) requires improvements in simulating surface and subsurface hydrology, pH and redox, while daily WTDs are not simulated in CH4MOD (Li et al., 2010; 2016; 2017).

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Table 5. Advantages of reviewed peatland or wetland models.

processes	**Good model robustness and global field testing**	**Minimal inputs**	**Specialized CH_4 transport process**
CLM-Microbe, BASGRA-BGC, Ecosys, ELM-SPRUCE and PEPRMT: simulate key CH_4 processes.	**HIMMELLI, Peatland-VU, Wetland-DNDC, TRIPLEX-GHG, BASGRA-BGC, LPJWhyMe, CH4MOD, Ecosys and ELM-SPRUCE:** field tested in varied environments in different biomes (arctic, tundra, boreal, temperate and tropical)	**WETMETH, Methane Emission Model (MEM) and PEPRMT:** minimal inputs yet simulated fluxes followed the trends of measured fluxes adequately .	**TEM:** accurately mimicking measured CH_4 fluxes via ebullition

Table 6. Limitations of reviewed peatland or wetland models.

Model limitations due to unrepresented processes	Highly input intensive, larger computational cost & associated modelled uncertainties	Limited representation of wetland types
HIMMELI, Peatland-VU, TRIPLEX-GHG, WETMETH, ORCHIDEE-PCH4 revision 7020, BASGRA-BGC, Terrestrial Ecosystem Model (TEM), Methane Emission Model (MEM), CH4MOD, PEPRMT, ELM-SPRUCE and CLM4Me: model processes related to snowpack, electron acceptors, dissolved organic carbon, peat subsidence, peat growth, changes in peatland microtopography, incorporating more multiple plant functional types (PFTs), improving ebullition algorithm, improving process representation of CH_4 production and CH_4 oxidation, incorporating tropical peat vegetation, distinguishing peatlands vs. fens to better parameterize water inflows, improvements in simulating surface and subsurface hydrology, pH and redox, simulation of daily water table depths etc.	**CLM-Microbe**: highly microbial input intensive, site-specific microbial inputs not always available impacting modelled CO_2 and CH_4 fluxes. **TRIPLEX-GHG**: high computational resources. **ELM-SPRUCE**: extensive microbial inputs & high computational resources. **Peatland-VU**: field measured soil carbon reservoir (peat, roots, litter) data not available at all sites leading to higher uncertainties in model outputs. **BASGRA-BGC**: lack of drainage data, carbon (C), nitrogen (N) contents impact model results. **Ecosys:** lack of continuous spatial and temporal field data constrains calibration and validation. **Terrestrial Ecosystem Model (TEM)**: not every peatland site has measured ebullition data.	**WETMETH**: does not distinguish and simulate different wetland types. **ORCHIDEE-PCH4**: does not distinguish ombrotrophic vs. minerotrophic peatlands. **CLM4Me**: grid cell approach does not capture differences in wetland types.

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3.9 Model inputs most impactful on simulating CH_4 fluxes

Published literature pertinent to individual models were manually screened, and it was identified that 5 out of 16 models tested their model-sensitivities on inputs for predicting total CH_4 fluxes, rather than individual CH_4 transport pathways (Fig. 5). Of the remaining 11 models, three models did not publish their sensitivity analysis, while eight models tested their sensitivities to model inputs for simulating individual CH_4 transport pathways (Fig. 7). Based on the reviewed published model-sensitivities, the model-inputs were categorized for each model into those that have a critical impact on the total CH_4 fluxes (Fig. 6) and individual CH_4 transport pathway predictions (Fig. 7).

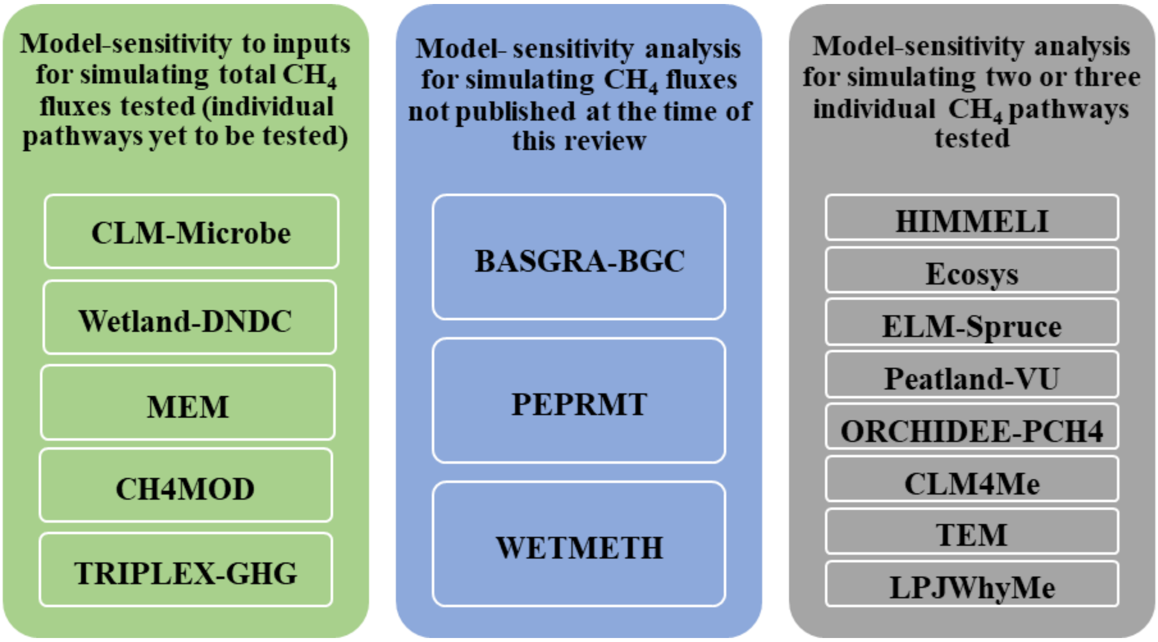

Figure 5. Reviewed peatland or wetland models distinguished into three categories shown above. Note: this figure reflects the information relevant to this review only and at the time when this review was conducted.

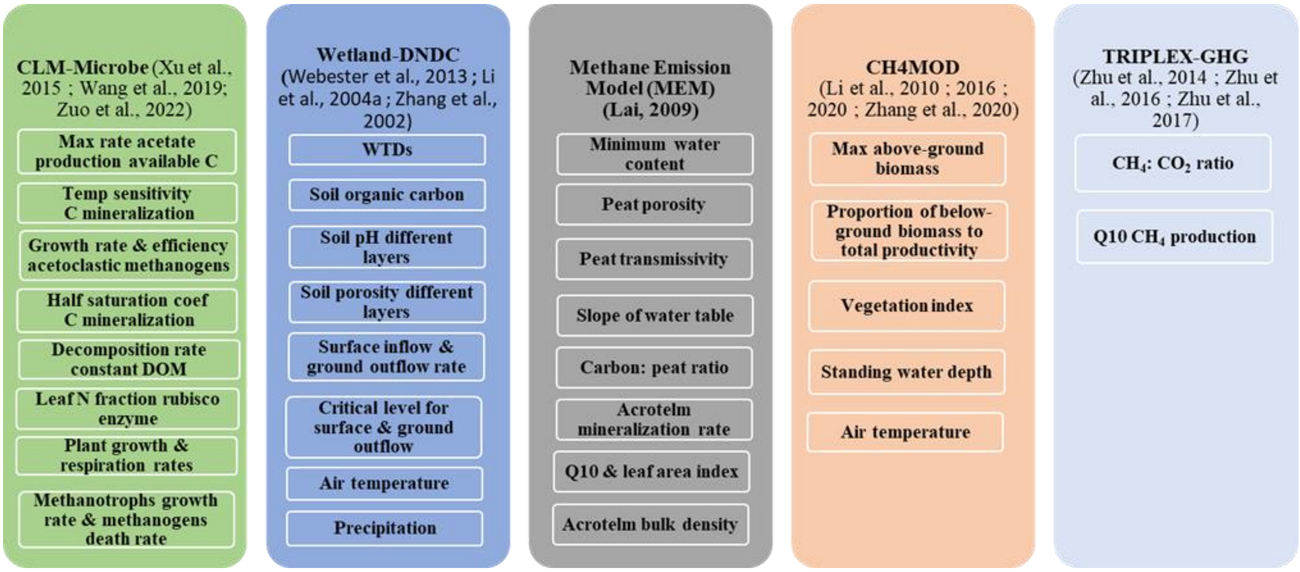

Figure 6. Critical inputs in each model impacting total CH_4 flux predictions.

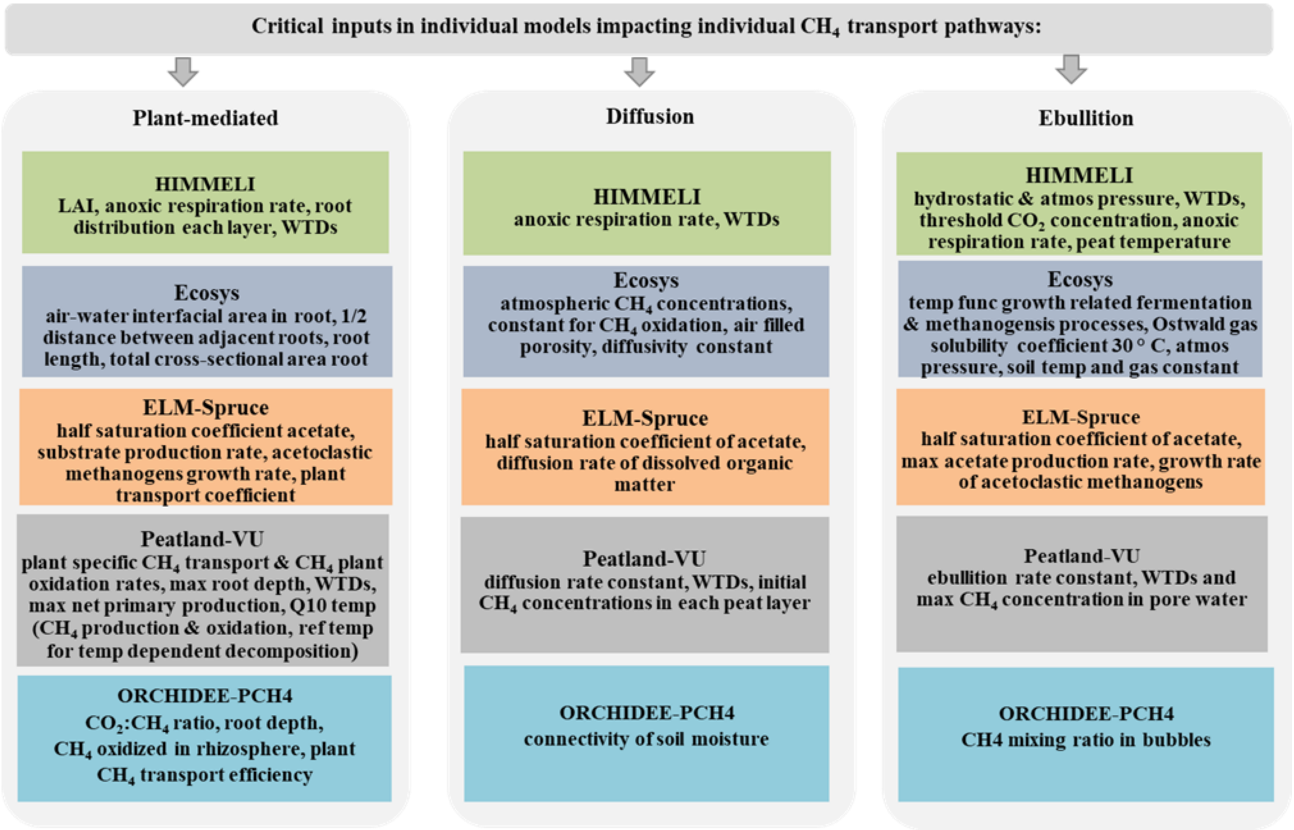

Figure 7. Critical inputs in each model impacting individual CH_4 transport pathway of plant-mediated transport, diffusion and ebullition.

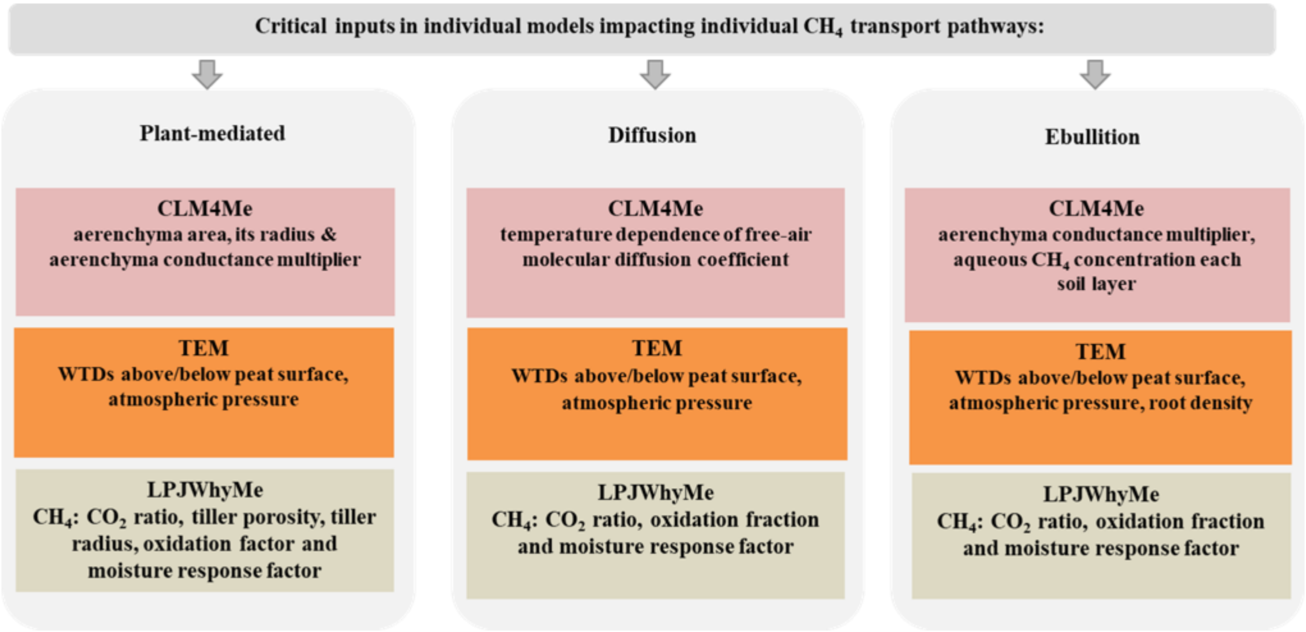

Figure 7. continued.

4 Discussion

4.1 Model parameterization for fine-tuning measured and simulated CH_4 fluxes

The common driving variables required to parametrize any peatland or wetland models are climate, hydrology, physical and chemical properties, vegetation (Table 3) and measured CO_2 and CH_4 fluxes (Schrier-Uijl et al., 2010; Oertel et al., 2012). These variables vary spatially and temporally within a single and different sites, thus strongly impacting CH_4 production, oxidation and transport (Zuo et al., 2022; He et al., 2024). Therefore, models are parametrization against measured fluxes and driving variables available for limited spatial and temporal periods. But different models operate at different spatial and temporal scales (Table 2), exhibit different time frames for stabilization of different carbon pools (Fig. 1) and exhibit varying degrees of process representations (Figs. 3 and 4). Model parameterization in this review does not refer to the parameterization performed in the source-code, but it refers to the fine tuning of the model inputs (Table 4) to minimize the error between the simulated and measured CH_4 flux data. So, parametrization will depend upon how adequately each model simulates CH_4 production, CH_4 oxidation and CH_4 transport processes. For example, CLM-Microbe, Ecosys and ELM-Spruce exhibit full CH_4 production and oxidation process representation (Fig. 3) since they have larger microbial inputs such as growth and death rates of methanogens and methanotrophs etc., where such site-specific microbial data is rarely available, but is fine-tuned to have good agreement between simulated and measured fluxes (Xu et al., 2015; Wang et al., 2019; Ricciuto et al., 2021). However, Zuo et al. (2024) parameterized CLM-Microbe using site-specific genomic data which improved the model's ability to accurately reproduce measured CH_4 fluxes. But such site-specific genomic data is not available at all sites, so simulated changes in methanogen biomass cannot be verified against measured data (Zuo et al., 2022). Models like Peatland-VU, Wetland-DNDC, BASGRA-BGC, HIMMELI, MEM, PEPRMT, CH4MOD have lesser microbial inputs compared to CLM-Microbe, Ecosys and ELM-Spruce. However, the key parametrization inputs in less microbially intensive models are aerobic and anaerobic decomposition rates of different pools (peat, humus, roots, litter, exudates, fast, slow), vegetation (leaf area index, primary production), and CH_4 parameters (Michaelis-Menton oxidation, diffusion, ebullition and plant transport rate constants) (Table 4). However, the decomposition rates of different pools are rarely available from site-specific studies, but they are rather fine-tuned to reduce the error between simulated and measured fluxes, as in Peatland-VU (Mi et al., 2014) and Wetland-DNDC (Deng et al., 2015; Taft et al., 2019). Models like TRIPLEX-GHG, CLM4Me, ORCHIDEE-PCH4, LPJWhyMe, TEM and WETMETH simulate fluxes at regional, national and global scale consisting of grid scale resolutions varying from 0.25-0.5° respectively. These key inputs are spatial distributions of soil texture, pH, carbon contents, topographical features, wetland distributions and satellite derived inundation and non-inundation data (Table 4). But these models are linked to earth system models, for example, ORCHIDEE-PCH4 is embedded in ORCHIDEE-PEAT revision 4596 (Qiu et al., 2018) and ORCHDEE land surface model (Krinner et al., 2005) having their own inputs. However, generally regional, national and global scale models require larger time frames for carbon pool stabilizations (Fig. 1), exhibit larger flux uncertainties due to lack of detailed CH_4 production and oxidation processes (Nzotungicimpaye et al., 2021), do not distinguish bogs, fens, or marshes and lack incorporation of dissolved organic carbon (DOC) leaching to improve C budget and CH_4 fluxes (Salmon et al., 2022).

4.2 Model performance of goodness of fit between measured and simulated CH_4 fluxes

All reviewed models evaluated the goodness of fit between simulated and measured data using R-squared (R^2, Coefficient of Determination (CD). However, a few models: BASGRA-BGC, and PEPRMT utilized normalized root mean square error and Nash Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) to compare simulated vs measured. Field testing of CLM-Microbe (Arctic tundra, freshwater marsh, mountain peatland and undisturbed Alaska fen), Ecosys (upland tundra, lowland fen, poorly drained fen) and ELM-Spruce (ombrotrophic peatland) found simulated fluxes in agreement with measured CH_4 fluxes having an R^2 0.41-0.91 (Grant and Roulet, 2002; Grant et al., 2015; Ricciuto et al., 2021; Yuan et al., 2021; Wang et al., 2019; Zuo et al., 2022). But discrepancies between simulated and measured CH_4 fluxes were observed, for example in CLM-Microbe, simulated CH_4 fluxes peaked earlier than measured CH_4 fluxes (Xu et al., 2015), while simulated CH_4 fluxes were under-estimated at daily and hourly scale by 20 and 25% compared to measured CH_4 fluxes (Wang et al., 2019). Meanwhile, Peatland-VU was field tested at eutrophic and oligotrophic Dutch sites, Stordalen mire (discontinuous permafrost) and Northeast Siberia (continuous permafrost) (van Huissteden et al., 2009; Petrescu et al., 2008; Mi et al., 2014) and Wetland-DNDC at North American wetlands, boreal fens Ontario, Canada, Alaska, fen and intensively cultivated horticultural UK peat soils (Zhang et al., 2002; Webster et al., 2013; Deng et al., 2015; Taft et al., 2019). Peatland-VU simulated CH_4 fluxes agreed with measured CH_4 fluxes at seasonal and annual scale, but exhibited low R^2, since measured peaks were not captured by simulated peaks, this under-estimation was some-what improved by incorporating net primary production (vegetation) and CH_4 oxidation parameters (van Huissteden et al., 2009). The R^2 in case of Wetland-DNDC varied from 0.37-0.66 (North American Wetlands), 0.37-0.85 (Alaska fen) and exhibited low R^2 in UK horticultural peat soils due to simulated moisture not in agreement with measured moisture. Field testing of BASGRA-BGC (Huang et al., 2021) in Finland, Denmark and Norway, MEM in Mer Bleue Bog, Canada (Lai, 2009), CH4MOD in marsh and mountain peatlands, China (Li et al., 2010), PEPRMT in restored wetlands and rice paddies in Sacramento-San Joaquin River Delta, California (Oikawa et al., 2017) and HIMMELI in two Finland peat sites (Raivonen et al., 2017) revealed good agreement between simulated and measured CH_4 fluxes having R^2: 0.25-0.80 (BASGRA-BGC), 0.31-0.82 (CH4MOD), 0.46-0.81 (PEPRMT), 0.63-0.70 (HIMMELI). While the field testing of TRIPLEX-GHG (Zhu et al., 2014), WETMETH (Nzotungicimpaye et al., 2021), LPJWhyMe (Wania et al., 2010), ORCHIDEE-PCH4 (Salmon et al., 2022), CLM4Me (Riley et al., 2011) and TEM (Zhuang et al., 2004) across wetlands, fens, marshes and peatlands located in Temperate, Tropical, Boreal, Pan-arctic, Arctic, Sub-arctic, Tundra and Boreal forest generally revealed good agreement between measured and simulated CH_4 fluxes having R^2 0.1-0.7 (TRIPLEX-GHG), simulated CH_4 fluxes (4.1 Tg yr^{-1}) in agreement with measured CH_4 fluxes (3.9 ± 1.3 Tg yr^{-1}) for West Siberian lowlands (WETMETH), normalized root mean square error (NRMSE 0.40-1.15) for LPJWhyMe at all peatland and wetland sites respectively.

4.3 Model sensitivity analysis

Models like BASGRA-BGC, PEPRMT and WETMETH have ample scope for conducting sensitivity analysis to identify critical inputs impacting CH_4 production, oxidation and transport. Meanwhile, CLM-Microbe, Wetland-DNDC, MEM, CH4MOD and TRIPLEX-GHG have not yet identified critical inputs sensitive to individual CH_4 pathways (Fig. 6). However, HIMMELI, Ecosys, ELM-Spruce, Peatland-VU, ORCHIDEE-PCH4, CLM4Me, TEM and LPJWhyMe identified critical inputs for individual CH_4 transport pathways (Fig. 7). However, all these models conducted local sensitivity analysis to identify the critical inputs, except Peatland-VU which conducted global sensitivity analysis (GLUE methodology) (van Huissteden et al., 2009). More effort should be directed to conduct global sensitivity analysis rather than local sensitivity analysis. For future model users, critical plant mediated inputs, common to all models, are root distribution in each layer, WTDs, LAI, max root depth, plant transport coefficient, CH_4 oxidized in rhizosphere, plant-specific CH_4 transport factor, plant growth and respiration and Q10 production and Q10 oxidation. Common critical diffusion inputs are WTDs, air-filled porosity, soil porosity, CH_4 diffusion rate constant, CH_4 atmospheric concentration, CH_4 concentration in each soil layer, soil moisture connectivity and CH_4:CO_2, while common critical ebullition inputs are CH_4 concentrations in each soil layer, pore-water and threshold CH_4 concentrations, WTDs, CH_4:CO_2, CH_4 ebullition rate constant, soil temperature and CH_4 atmospheric concentration.

4.4 Modelling challenges

All reviewed models revealed common difficulties affecting their parametrizations due to non-availability of continuous flux and in-situ environmental data (Ueyama et al., 2022). So, models are often parametrized using discontinuous flux and in-situ environmental data. For example, Peatland-VU, Wetland-DNDC, BASGRA-BGC and CLM4Me were generally parametrized using discontinuous CH_4 flux and spatially and temporally limited environmental in-situ data, resulting in simulated CH_4 peaks not adequately capturing the measured CH_4 peaks, while in case of CLM-Microbe, there were time-lag differences between simulated and measured CH_4 fluxes (Xu et al., 2015; Wang et al., 2019). Another challenge is the process complexity of CH_4 dynamics, since production and oxidation are characterized by complex interactions between microbial communities, hydrology, soil physical and chemical properties and vegetation (Zuo et al., 2024). However, many models simplify these interactions, by utilizing generic parameter values such as scaling parameters of CH_4 production and CH_4 oxidation as in WETMETH (Nzotungicimpaye et al., 2021) and exclusion of critical processes in PEPRMT such as no CH_4 production and CH_4 oxidation in multiple peat layers and no carbon pool simulations at millennial to centennial time scales (Oikawa et al., 2017). However, CLM-Microbe, Ecosys, and ELM-Spruce, incorporate detail CH_4 production and CH_4 oxidation processes governed by growth and death rates of methanogens and methanotrophs, typically derived from lab incubation studies (Xu et al., 2015; Wang et al., 2019). Similar incubation studies are not widely available across different peatland or wetland sites and across different ecoregions (tundra, arctic, tropical, boreal and temperate) limiting the applicability of these microbially-based models. Moreover, models struggle to capture the CH_4 fluxes during extreme weather events which is crucial for accurately predicting future CH_4 dynamics, where shifts in precipitation patterns and temperature could significantly alter CH_4 fluxes (Abdalla et al., 2016). Therefore, to adequately capture extreme weather

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events, continuous weather, CH_4 fluxes and in-situ environmental data should be available for at-least 5 years, for models to have independent calibration and validation datasets, so that the future CH_4 fluxes can be accurately predicted under future climatic conditions (Xu et al., 2016).

4.5 Suggestions and recommendations on future research directions

a) **Need for continuous long-term field data**: For more accurate model-input parameterizations, it is recommended to have available continuous site-specific data on precipitation, evaporation, radiation, air temperatures and in-situ environmental data (e.g. WTDs, peat temperature, peat moisture and leaf area index). A combination of manual chamber, EC tower, and automated chamber data be at-least available for 5 years, so that high quality spatial and temporal CH_4 fluxes are available for model parametrization, to accurately predict CH_4 fluxes under future climatic conditions including extreme events. To improve CH_4 predictions from different earth system models (ESMs) continuous flux and environmental in-situ data are required from data scarce regions namely Congo, Amazon and Southeast Asia rainforests, rice crop areas in India and Bangladesh, Savanah, Africa, Central and South America (McNicol et al., 2023; Zhao et al., 2024).

b) **Online data repository**: There is a need to create an on-line repository containing genomic data related to methanotrophs, methanogens, bacteria and fungi from peatlands, marshes and fens of different nutrient gradients (rich, intermediate and poor) from different ecosystems such as arctic, subarctic, tundra, tropical, boreal and temperate to better parameterize microbial models like CLM-Microbe, Ecosys and ELM-Spruce.

c) **Development of new models**: Future modelling efforts should prioritize the mechanistic understanding of the microbial processes, possibly through the development of multi-species models that simultaneously simulate the interactions between different microbial communities and their influence on CH_4 fluxes. There is also a pressing need for an integrated model that considers the interplay between CH_4 dynamics and C and N cycling.

d) **Artificial intelligence (AI), Hybrid modelling and Machine learning**: Utilize continuous in-situ flux and environmental data into different AI models which are computationally less intensive and faster than traditional models (US DOE, 2024). More studies across the globe need to utilize the multi-model ensemble (MME) approach combining different machine learning models (decision tree (DT), random forest (RF), extreme gradient boosting (XGB), artificial neural network (ANN), Gated Recurrent Units (GRU) and Long Short-Term Memory (LSTM) using CH_4 chamber, EC tower, in-situ environmental data and current and future climate data to estimate current and future global peatland and wetland CH_4 emissions (Chen et al., 2024; Chinta and Zu, 2024; Xiao et al., 2024).

e) **Sensitivity analysis**: Models like BASGRA-BGC, PEPRMT and WETMETH have ample scope for conducting local or global sensitivity analysis to identify critical inputs impacting CH_4 production, oxidation and transport, while CLM-Microbe, Wetland-DNDC, MEM, CH4MOD and TRIPLEX-GHG have ample scope to identify critical inputs impacting individual CH_4 transport pathways. All the reviewed models need to conduct global sensitivity analysis rather than local sensitivity analysis.

f) **Remote sensing**: Utilize high-resolution remote sensing data alongside continuous data on CH_4 flux, peat moisture, peat temperature and WTDs, so that the earth system models can better capture wetland and peatland heterogeneous environments to accurately estimate CH_4 fluxes under different climatic and environmental conditions.

g) **Improvements in model process representation**: Models like HIMMELI and BASGRA-BGC may need to incorporate snow processes, while Peatland-VU may need to incorporate particulate and dissolved organic carbon processes and peat subsidence. TRIPLEX-GHG may benefit from incorporating different plant functional types, while WETMETH from detailed CH_4 production and CH_4 oxidation processes. Following improvements are suggested for ORCHIDEE-PCH4: incorporation of lateral peat growth, tropical vegetation growth processes, distinguishing between bogs and fens to parameterize water inflows and incorporate dissolved organic carbon (DOC) leaching to improve C budget and CH_4 fluxes. Suggested improvements for CLM4Me include improving surface and subsurface hydrology, while suggestions for CH4MOD include incorporating groundwater processes to simulate daily WTDs.

5 Conclusions

This study reviewed 16 peatland and wetland models that simulated different temporal and spatial scales, exhibited different spin-times for stabilization of different carbon pools, simulated two or three CH_4 transport pathways or total CH_4 fluxes and exhibited variable process representations of CH_4 production, CH_4 oxidation and CH_4 transport. To further improve the parameterization of microbial mediated models (Ecosys, ELM-Spruce and CLM-Microbe), we propose the development of online-data repository i.e., international databases incorporating genomic data related to methanogens and methanotrophs from different peatland and wetland types (bogs, fens, marshes, forested peatlands) located in arctic, subarctic, tundra, tropical, boreal and temperate. In case of the ebullition, only 25% of the models exhibited full to adequate process representation. This essentially means that 75% of the models have scope to incorporate detailed processes or mechanisms related to ebullition. But direct measurements of ebullition from peat-water matrix are challenging and rarely measured in the field. More field studies need to measure ebullition using AI enabled platforms of edge computing and autonomous laboratories to capture ebullition hotspots and hot moments during extreme storm events, where CH_4 fluxes rapidly occur within a shorter time frame. Also, along with incorporating high frequency field data, models also could improve their ebullition algorithms by incorporating different approaches (CH_4 pore water concentration (ECT), pressure (EPT) or free-phase gas volume (EBG) threshold), so that simulated CH_4 fluxes can capture the peaks of the measured CH_4 fluxes resulting in a better statistical agreement. In conclusion, we find that the existing CH_4 models could be adequate for site, plot and field scale CH_4 flux predictions, but that a mechanistic predictive understanding, particularly of CH_4 transport pathways, is still lacking.

Code and Data availability. The authors confirm that the data supporting the findings of this study are available within the article and its Supplement.

Author's contributions. Amey S. Tilak: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing original draft, funding acquisition, review and editing. Ruchita Ingle: conceptualization, review and editing. Alina Premrov: Conceptualization, Formal analysis, review and editing. Nigel Roulet: Conceptualization, review and editing. Benjamin Runkle: Visualization, review and editing. Matthew Saunders: funding acquisition, review and editing. Avni Malhotra: Conceptualization, Formal analysis, Visualization, review and editing, Kenneth A. Byrne: Visualization, funding acquisition and review and editing.

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