Methane Dynamics in Peat: Importance of Shallow Peats and a Novel Reduced-Complexity Approach for Modeling Ebulition


Northern peatlands are one of the largest natural sources of atmospheric methane (CH$_4$), and it is important to understand the mechanisms of CH$_4$ loss from these peatlands so that future rates of CH$_4$ emission can be predicted. CH$_4$ is lost to the atmosphere from peatlands by diffusion, by plant transport, and as bubbles (ebullition). We argue that ebullition has not been accounted for properly in many previous studies, both in terms of measurement and the conceptualization of the mechanisms involved. We present a new conceptual model of bubble buildup and release that emphasizes the importance of near-surface peat as a source of atmospheric CH$_4$. We review two possible approaches to modeling bubble buildup and loss within peat soils: the recently proposed bubble threshold approach and a fully computational-fluid-dynamics approach. We suggest that neither satisfies the needs of peatland CH$_4$ models, and we propose a new reduced-complexity approach that conceptualizes bubble buildup and release as broadly similar to an upside down sandpile. Unlike the threshold approach, our model allows bubbles to accumulate at different depths within the peat profile according to peat structure, yet it retains the simplicity of many cellular (including cellular automata) models. Comparison of the results from one prototype of our model with data from a laboratory experiment suggests that the model captures some of the key dynamics of ebullition in that it reproduces well observed frequency-magnitude relationships. We outline ways in which the model may be further developed to improve its predictive capabilities.

1. METHANE LOSS FROM PEATLANDS

1.1. Mechanisms of Loss

Methane (CH$_4$) is an important greenhouse gas, and future changes in atmospheric concentrations of CH$_4$ may have significant impacts on global climate [cf. Gedney et al., 2004; Frolking et al., 2006; Intergovernmental Panel on Climate Change, 2007; Walter et al., 2001a]. Northern peatlands are one of the largest natural sources per annum of CH$_4$ emissions to the atmosphere, yet there are considerable uncertainties about how CH$_4$ is stored in, and released from, these vast ecosystems. CH$_4$ is lost to the atmosphere from peatlands via three mechanisms: (1) diffusion through pore water to the water table and thence through the zone above the water table (if one exists) to the peatland surface, (2) diffusion or active transport through vascular plants, and (3) ebullition, bubbles moving to the peatland surface. Until quite recently, ebullition was considered to be only locally important, and most attention was focused on matrix diffusion of dissolved CH$_4$ and plant-mediated transport. However, recent research, as summarized in Table 1, suggests
### Table 1. Examples of Recent Studies of CH$_4$ Ebullition From Peat Soils

<table>
<thead>
<tr>
<th>Study</th>
<th>Rates of Ebullition (mg CH$_4$ m$^{-2}$ d$^{-1}$)</th>
<th>Method</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baird et al. [2004]</strong></td>
<td>0–83</td>
<td>laboratory cores of near-surface Sphagnum peat ($n = 8$)</td>
<td>Rates are for threshold bubble content [cf. Kellner et al., 2006] and are based on 2- to 4-day averages of gas collected in gas traps. No detail is available on barometric pressure in the laboratory.</td>
</tr>
<tr>
<td><strong>Christensen et al. [2003]</strong></td>
<td>36–170</td>
<td>laboratory cores of near-surface northern temperate/subarctic peats of various compositions ($n = 4$)</td>
<td>Rates appear to be for threshold bubble content and are based on continuous measurements from throughflow chambers fixed to the cores. No detail is available on barometric pressure in the laboratory.</td>
</tr>
<tr>
<td><strong>Comas and Slater [2007]</strong></td>
<td>~400–&gt;1,200</td>
<td>laboratory monolith of near-surface Sphagnum peat</td>
<td>Rates are based on periodic measurements from chamber above monolith and include all transport mechanisms. However, bubbles were measured in the peat, and higher rates of CH$_4$ efflux seem to be associated with changes in peat bubble content.</td>
</tr>
<tr>
<td><strong>Glaser et al. [2004]</strong></td>
<td>35,000</td>
<td>field measurement of (1) changes in the elevation of the surface of a Sphagnum-dominated peatland using GPS and (2) pressure head using piezometers installed at depths of 1, 2, and 3 m</td>
<td>Rates are for short-lived (~4 h) ebullition events and assume (1) bubbles are lost from medium-depth peat (~2 m) and (2) a CH$_4$ content in the bubbles being released of 54%.</td>
</tr>
<tr>
<td><strong>Kellner et al. [2006]</strong></td>
<td>270</td>
<td>laboratory core of near-surface Sphagnum peat</td>
<td>Rates are for threshold bubble content and are based on 2- to 4-day averages of gas collected in gas traps.</td>
</tr>
<tr>
<td><strong>Rosenberry et al. [2003]</strong></td>
<td>4,300–10,700</td>
<td>field measurement of pressure head using piezometers installed at depths of 1, 2, and 3 m in Sphagnum peat</td>
<td>Rates are for short-lived (hours to days) ebullition events and assume (1) bubbles are lost from medium-depth peat (1–2 m) and (2) a CH$_4$ content in the bubbles being released of 50%.</td>
</tr>
<tr>
<td><strong>Strack et al. [2005]</strong></td>
<td>65</td>
<td>field measurement of gas trapped in collection funnels sunk into near-surface (upper meter) peat at a Sphagnum-dominated site</td>
<td>Rates are averaged over summer season. Individual events may give figures more than an order of magnitude greater.</td>
</tr>
<tr>
<td><strong>Tokida et al. [2005]</strong></td>
<td>76–1,233</td>
<td>laboratory core of near-surface Sphagnum peat</td>
<td>Rates are for threshold bubble content during periods of low barometric pressure and are based on high-frequency (once every 1.5–10 h) measurements using a chamber fitted to the core.</td>
</tr>
<tr>
<td><strong>Tokida et al. [2007]</strong></td>
<td>48–1,440</td>
<td>field measurement from two chambers installed on a Sphagnum-dominated site</td>
<td>Rates apply to periods of low barometric pressure and are based on high-frequency (once every 1.5–2 h) measurements using the chambers.</td>
</tr>
<tr>
<td>J. M. Waddington et al.</td>
<td>49–1,090</td>
<td>field measurement from seven funnels installed at the surface of a flooded cutover peatland</td>
<td>Rates are summer averages.</td>
</tr>
</tbody>
</table>
that ebullition may be the dominant pathway for CH₄ losses to the atmosphere and that previous measurements and calculations of peatland CH₄ losses may be underestimate. For example, from a study of ebullition from deep (>1 m) peats, Glaser et al. [2004] used indirect measurements to suggest that ebullition is temporally and spatially very variable and that it can exceed diffusive fluxes by 2 orders of magnitude. Work on shallow peats (upper 1 m), both in the laboratory [Baird et al., 2004] and the field [Strack et al., 2005; Tokida et al., 2007], also suggests that ebullition losses represent an important proportion of total CH₄ losses. Nevertheless, that ebullition is the dominant pathway for transport of CH₄ to the atmosphere in northern peatlands currently has the status of hypothesis, and more work is urgently needed on characterizing and modeling bubble buildup and losses from a range of different types of peat and plant communities.

How have (some) peatland researchers underestimated the role of ebullition in previous studies? Gas exchanges at the peatland surface are often measured using the chamber method. Permanent collars are inserted into the peat to a depth of 10–20 cm. When measurements of gas exchange are required, a chamber is fitted via a gastight seal to the collar. Typically, the following protocol is used, which we call the “normal chamber method” or NCM: (1) the chamber is fitted to its collar once/twice per week, (2) five or six sets of samples (i.e., including replicates at each time of sampling) of chamber gas are taken at regular intervals over an approximately 20- to 30-min period, (3) the samples are analyzed for CH₄ concentration, and (4) a linear regression line is fitted to the data to estimate the rate of CH₄ loss. A key assumption of the NCM is that CH₄ fluxes from peatlands are steady, at least over time frames of 1–2 weeks. Thus, if ebullition occurs continuously as a stream of small bubbles, the NCM will give accurate results. However, if ebullition is nonsteady (cyclic or episodic), the NCM could give very large errors; that is, we could be substantially underestimating the amount of CH₄ being lost from peatlands (see below). A 20-min sampling frame represents <0.2% of a week. If ebullition events are random in time and occur, on average, once a day or once every 3 days, the probability of recording a release with a chamber is 0.013 and 0.005, respectively. Recent evidence suggests that many ebullition losses are, indeed, nonsteady but that they can occur nonrandomly, with factors such as atmospheric pressure and water table decline acting as triggers for bubble release [e.g., Comas and Slater 2007; Strack et al., 2005; Tokida et al., 2005, 2007]. Many users of the NCM apparently have not used such knowledge to improve estimates of ebullition losses; that is, they have not sampled from chambers when ebullition is more likely. In this respect, the study of Tokida et al. [2007] is particularly notable. Tokida et al. [2007] measured CH₄ efflux using two chambers placed on a temperate bog dominated by Sphagnum spp. but also containing vascular plants such as Eriophorum vaginatum L. and Rhynchospora alba (L.) Vahl. High-frequency measurements of CH₄ efflux were taken using the chambers every 1.5–2 h over 4 days when atmospheric pressure varied but showed a general fall from 1017 to 1000 hPa. Over this period, ebullition contributed 50–64% of the total CH₄ efflux. However, during individual events, ebullition losses exceeded the other losses combined by 1 to 2 orders of magnitude.

1.2. Conceptual Models of CH₄ Loss From Peatlands (Deep Versus Shallow Sources of Bubbles)

Interesting work has recently been undertaken suggesting that CH₄-containing bubbles may form deep (>3 m) within peat deposits and build up at middle depths (2 m) [Glaser et al., 2004] below confining layers of woody peat. The mid-depth accumulations may become so large that, episodically, they break through the confining layer to the surface causing very large rates of CH₄ loss to the atmosphere (e.g., 35 g CH₄ m⁻² per event). The evidence for the buildup and release of such large pockets or reservoirs of free-phase gas comes from changes in pore water pressures as measured using closed and open piezometers [Rosenberry et al., 2003], from changes in the surface elevation of the peatland [Glaser et al., 2004], and from ground-penetrating radar surveys [e.g., Comas et al., 2005, 2007].

From their work on the glacial Lake Agassiz peatlands (GLAP) in Minnesota, Glaser et al. [2004] proposed a conceptual model of ebullition in peatlands that is shown as Figure 1. Although developed specifically for the GLAP, the model has been widely discussed and is sometimes thought of as canonical in terms of how ebullition takes place in peatlands. For example, in a study of heat transfer in peat, McKenzie et al. [2007, p. 369] note “Peatlands release methane, formed by anaerobic bacteria [sic] at depth, to the atmosphere. The transfer of methane from depth within the peat profile occurs either by episodic releases of large volumes of methane gas associated with the lowering of peatland water tables . . . or by continuous diffusion through the peat soil.” A probably unintended consequence of the model is that it has caused the role of shallow peats as sources of bubbles escaping to the atmosphere to be somewhat overlooked. We suggest that bubbles may form more readily in shallow peats than in deep peats for at least three reasons:

1. There is a more abundant local supply of labile carbon (including exudates from the roots of vascular plants) to act as substrate for methanogens.

2. There is a greater range of temperatures near the peatland surface, with both higher and lower temperatures being
Because CH$_4$ production shows a strongly non-linear increase with temperature [e.g., Dunfield et al., 1993], it will be higher near the surface than at the peatland base even if there is no difference in average temperatures (or substrate supply) between the two.

3. During water table rise after rainfall, air becomes encapsulated within peat; in other words, bubbles are immediately formed during water table rise. Once stripped of their oxygen, these bubbles may grow, as biogenic gases are produced within the peat. Thus, they may act as nuclei for free-phase CH$_4$ accumulation. Encapsulation during water table rise has been observed by, among others, Beckwith and Baird [2001] and Baird and Waldron [2003].

Noting reasons 1 and 2, it is not surprising that workers such as Daulat and Clymo [1998] and Laing et al. [2008] have measured intense CH$_4$ production within 20 cm of the water table. In addition to the points above, it has also been shown that the accumulation of bubbles within the peat profile does not require the presence of a woody confining layer (see Figure 1). Indeed, in samples of near-surface and poorly decomposed Sphagnum peat without confining layers, volumetric gas contents (gas volume per unit volume of peat) as high as 0.16 (16%) have been recorded [e.g., Baird and Waldron, 2003; Kellner et al., 2006]. Gas accumulations in the absence of confining layers have also been found in the field [e.g., Strack et al., 2005].

The studies cited above deal with bog or poor-fen peats. We have also found bubbles at shallow depths in rich-fen peats. For example, we installed triplicate gas trap funnels (20-cm diameter) at depths of 20, 40, and 60 cm below the surface (all below the water table) of a 1.2-m-thick rich-fen peat in southern Ontario in Canada (Fletcher Fen) at a marl flat site devoid of vascular vegetation. Upward acting bubble fluxes of CH$_4$ as recorded by the traps over a 2-month period during the summer of 2006 (14 June to 21 August) were significantly greater ($p < 0.05$) in the 20-cm shallow traps (1630 ± 746 mg CH$_4$m$^{-2}$d$^{-1}$) than the 40-cm (852 ± 432 mg CH$_4$m$^{-2}$d$^{-1}$) and 60-cm traps (540 ± 426 mg CH$_4$m$^{-2}$d$^{-1}$).

In addition to the direct evidence from Fletcher Fen, there are many studies from a range of peatlands where bubble buildup and loss have been recorded in samples of upper peat (i.e., samples excluding deep peat) [e.g., Baird et al., 2004; Beckwith and Baird, 2001; Christensen et al., 2003; Comas and Slater, 2007; Kellner et al., 2006; Laing et al., 2008; Ström et al., 2005; Tokida et al., 2005]. Given such evidence, we suggest that bubble formation and ebullition may be common across the upper 1 m of peat soils. Indeed, the upper 1 m may represent at least as important a source of bubble flux to the atmosphere as middle-depth and deep peats. However, direct studies of free-phase gas dynamics in deep and middle-depth peats across a range of sites are needed to confirm this assertion. We propose as Figure 2 a new conceptual model that emphasizes the importance of CH$_4$ production in the upper parts of a peat deposit and that formalizes the strong direct evidence that this zone is one in which bubbles may accumulate in large volumes even in the absence of woody layers of peat. We accept that more work needs to be done on bubble dynamics in shallow peats, in particular on variation between peat types. It is also important to note that the model does not exclude the possibility of

**Figure 1.** “Deep peat” ebullition model of Glaser et al. [2004].
deep and medium-depth zones of CH₄ production and bubble formation but suggests that their contribution is uncertain. A key purpose of our model is to act as a stimulus for further research, especially on the partitioning of ebullition between steady losses and episodic and cyclic events and how this may be affected by peat type.

The ranges for rates of production, consumption, and efflux that we have included in the model are necessarily wide, partly because they encompass studies done on different peat types and partly because we still lack detailed data on ebullition under a wide range of conditions such as during the passage of low-pressure weather systems, through diurnal cycles, and during prolonged drought. Noting our rationale for proposing the shallow peat conceptual model, we focus in the rest of the chapter on the upper 1 m of peat.

1.3. Vascular Plants and Ebullition

It has been suggested that the presence of vascular plants reduces the importance of ebullition. This suggestion may partly explain why the deep ebullition model has been preferred by some researchers; that is, if it is assumed that vascular plants prevent or substantially reduce bubble buildup in the rooting zone, then ebullition is only ever likely to be a deep-seated phenomenon. It should be emphasized that such an argument is not made by Glaser et al. [2004], but it is an argument that may explain the popularity of the model.

Chanton [2005] notes that because of the role of vascular plants as transporters of CH₄ to the atmosphere, their presence means that pore water concentrations of CH₄ may be lowered by as much as 50%, leading to the formation of fewer bubbles and lower rates of ebullition. Indeed, Chanton [2005, p. 755] suggests that, “if vascular emergent macrophyte plants [sic] inhabit a wetland, plant transport will be the primary mechanism of CH₄ transport from the wetland.” Vascular plants may also lower pore water CH₄ concentrations via rhizospheric oxidation, i.e., the diffusion of oxygen from the shoots to the roots and rhizomes, which can promote bacterial methanotrophy in pore waters around roots and rhizomes [cf. Ström et al., 2005; Waddington et al., 1996]. Most studies on the effects of vascular plants on ebullition have looked at inundated mineral sediments (e.g., billabong sediments and paddy fields) and it is not clear how vascular plants affect ebullition in peats. In this respect, it is worth again noting the study of Tokida et al. [2007] where it was found that ebullition from a peatland containing vascular plants was more important than diffusion and plant-mediated transport combined. In our study at Fletcher Fen (see section 1.2), we also examined the influence of vascular vegetation on CH₄ bubble dynamics by comparing ebullition rates and CH₄ concentrations in both pore water and gas lost via ebullition between the aforementioned marl flat site and two sedge-dominated sites (Carex livida (Wahlenb.) Willd. and Scirpus cespitus L.) in August 2007. Gas volumes collected in gas traps were not significantly different (p < 0.05) between the Carex and marl flat sites (Scirpus data not available). While there was no significant difference (p < 0.05) in bubble CH₄ concentration (12–52%) between the three sites, the 20- to 40-cm pore water CH₄ concentration at the Scirpus site (2.1 ± 0.4 mg L⁻¹) was significantly lower than at the Carex (4.9 ± 0.9 mg L⁻¹) and marl flat (5.3 ± 0.4 mg L⁻¹) sites.

Our findings suggest that the statement by Chanton [2005] may be too general because a key confounding factor when
examining the effect of vascular plants on ebullition is that many species of vascular plants are thought to enhance CH$_4$ production through their root exudates, which act as substrates for methanogens [cf. Ström et al. 2003; Waddington et al., 1996]. Thus, on the one hand, plant-mediated transport/rhizospheric oxidation might lower pore water concentrations of CH$_4$ and rates of bubble formation, while on the other hand, enhanced rates of CH$_4$ production from root exudates could increase rates of bubble production and the relative importance of ebullition [Christensen et al., 2003]. Indeed, it is possible that dense vascular plant root mats may be zones of both intense CH$_4$ production and also bubble trapping. It would be extremely useful to separate these effects to gain a clearer picture of how vascular plants influence ebullition, and such work is underway in the second author’s laboratory. Currently, the evidence from the study of Tokida et al. [2007] and the new data from Fletcher Fen suggest that the presence of vascular plants in peatlands does not necessarily mean that ebullition is unlikely or less likely. It is also worth noting that high rates of CH$_4$ flux attributed to vascular plants in some previous studies [e.g., Waddington et al., 1996] may actually be partly because of an increased bubble flux (where the bubbles were lost as a continuous stream) caused by enhanced CH$_4$ production in the rooting zone.

1.4. Bubble Trouble: Simulating Ebullition in Peatland CH$_4$ Models

The way in which bubbles are trapped within peat will affect how the bubbles are released and the subsequent movement of CH$_4$ through the zone above the water table. Ebullition is either ignored or treated very simply in almost all existing peatland CH$_4$ models [cf. Cao et al., 1996; Froliking et al., 2002; Gedney et al., 2004; Grant and Roulet, 2002; Kettunen, 2003; Walter et al., 1996, 2001a, 2001b; Zhang et al., 2002]. Those models that do explicitly allow for ebullition, such as that of Walter et al. [2001a, 2001b], assume that bubbles are not trapped in peat but are lost directly to the water table, after which the gas moves slowly via diffusion through the zone above the water table where the CH$_4$ within it may be consumed by methanotrophic bacteria. However, if bubbles build up and are then released in one go (i.e., episodically or cyclically), they will displace gas already present in the zone above the water table or move through that zone as mass flow so that methanotrophic processing is bypassed or overwhelmed, leading to more CH$_4$ being lost to the atmosphere than if the same quantity of bubbles had been lost as a steady stream over a longer time period. Therefore, the nature of bubble transport to the zone above the water table is important for how much CH$_4$ escapes to the atmosphere from the peatland surface [Rosenberry et al., 2006]. This is a key point which apparently has not been appreciated by authors of wetland CH$_4$ models.

The buildup and release of bubbles from peat will depend on a range of factors, including rates of CH$_4$ production, the location of hot spots of production, the transport of dissolved CH$_4$ to and from bubbles through pore water, and the physical properties of the peat. Ebullition occurs when the buoyancy of bubbles overcomes the forces that keep them in place (in particular, surface tension) [cf. Fechner-Levy and Hemond, 1996; Corapcioglu et al., 2004; Strack et al., 2005]. It has been suggested recently that a threshold bubble volume must be reached to trigger episodic or cyclic ebullition [e.g., Beckwith and Baird, 2001; Baird et al., 2004; Strack et al., 2005]. The concept of the threshold was formalized by Kellner et al. [2006] in a simple model. The model is based on the idea that ebullition occurs when the bubble content rises above the threshold, the amount of gas lost in a model time step being the difference between the amount of free-phase gas in the peat and the threshold content. The model accounts for changes in bubble volume caused by changes in temperature and pressure by employing an iterative solution to Henry’s law (exchange of gas between bubbles and surrounding pore water (the gaseous and aqueous/dissolved phases)) and the ideal gas equation (direct changes in bubble volume due to pressure and temperature). It also includes a production term. Comparisons of the model with laboratory data suggest it is capable of reasonable predictions of ebullition events ($r^2 = 0.66$) [Kellner et al., 2006]. However, problems of the model have been noted by the model’s authors. In particular, they suggest that the threshold is “fuzzy”; in other words, on occasion, the model predicted ebullition when none occurred and vice versa. Another way of thinking about this fuzziness is that ebullition sometimes occurs when the gas content is below the threshold, and sometimes it does not occur until the gas content has risen substantially above the threshold. Fuzziness can arise for a number of reasons, but perhaps the most important concerns the fact that the threshold is largely an empirical concept. In particular, the model (1) takes no account of the variations in bubble content with depth in the peat profile, (2) takes no account of bubble movement and redistribution within the peat profile, and (3) lacks a secure physical basis in terms of how different peat/pore structures cause and promote, respectively, the trapping and release of bubbles. Indeed, it may be argued that a general problem of existing ebullition studies is that the physical properties of the peat have not been described in detail; at best, these studies have looked at bulk density and degree of decomposition using an “in-the-hand” assessment. Thus, there remains a need for a better description of bubble accumulation and loss from near-surface peats.
1.5. CFD or Not CFD: That Is the Question

An alternative to the threshold approach is one where bubble dynamics (movement, break up, and coalescence) are described or modeled in great detail through a known pore structure. Somewhat surprisingly, experimental work on bubble dynamics in simple pores is ongoing, and we have found no work on bubble movement through individual pores with complicated cross-sectional shapes or through branching pores. Thus, although understanding of bubble dynamics has improved steadily over the last 20–30 years [e.g., Borhan and Pallinti, 1999; Chaudhari and Hoffmann, 1994; Das and Pattanayak, 1994; Schwartz et al., 1986], new information on processes such as the coalescence of two moving bubbles of different sizes within uniform capillary tubes is still being discovered [e.g., Almatroushi and Borhan, 2006a, 2006b]. This suggests that we are some way from being able to model satisfactorily the detail of bubble dynamics in individual pores or pore networks. Nevertheless, computational fluid dynamics (CFD) models have been developed for bubble reactors and are able to predict bubble dynamics at the bubble population level. For example, the model of Jia et al. [2007] is able to predict local gas holdups (defined as the fractional bubble content within a section of a reactor or bubble column) and fluid velocities in bubble columns containing three phases (solid, liquid, and gaseous). However, it is clear that such models require further development and testing; the correspondence between the model of Jia et al. and experimental data was modest at best. Additionally, to our knowledge, such approaches have not been applied to three-dimensional, two-phase fluid flow in porous media such as peats.

One hurdle to application of CFD methods to two-phase fluid transfer in peats is a lack of information on pore structures in different peat types. X-ray computed tomography (CT) promises, in part at least, to remove this hurdle. Studies by Blais [2005] and Kettridge and Binley [2008] have demonstrated that it is possible to extract information on pore size and pore continuity from X-ray images. The latter study also shows that individual bubbles can be imaged (see Figure 3) and that bubble population properties (such as the probability density function of bubble size and shape) can be derived. Despite these advances, it is unlikely that such detailed information will be used in larger models of peatland CH₄ dynamics. CFD models are computationally expensive, and their incorporation into models such as that of Walter et al. [2001a, 2001b] for a range of peat types would prove a huge task. In any case, there are good arguments for keeping models as simple as possible [cf. Baird, 1999; Wainwright and Mulligan, 2004a, 2004b], while avoiding the problem of simplistic (naively simple) models. Below, we present a modeling approach that we believe combines the simplicity of the threshold approach with some of the physical realism of a CFD model.

![Figure 3](image_url)

Figure 3. X-ray computed tomography images of bubbles in a sample of poorly decomposed Sphagnum fuscum (Schimp.) Klinggr. peat/litter. The bubbles are shown in gray against a black background, with water and peat fibers rendered transparent. Reprinted from Kettridge and Binley [2008], with permission of John Wiley.
2. A NEW APPROACH TO MODELING CH₄ BUBBLE BUILDUP AND EBBULLITION: UPSIDE DOWN AVALANCHES

There is a significant gap between the two approaches to modeling ebullition described in section 1. The threshold approach is strongly empirical, which necessarily limits its applicability to simple peat profiles in which depth variation in, for example, bubble accumulation and the factors that affect bubble dynamics (pore structure) can be ignored. Neither does it account for depth variation in CH₄ production and solubility. Such variability is almost certainly partly responsible for the threshold exhibiting fuzziness. However, some fuzziness may be an intrinsic property of peat-bubble interactions, such that even a uniform peat might display complex ebullition behavior (i.e., a fuzzy threshold). We have also argued in section 1 that CFD models are too complex, at least for nesting within existing peatland CH₄ models.

With the problems of existing approaches in mind, we have started to explore the possibility of using “reduced complexity” models to simulate bubble dynamics in peat. What may be termed an “Occam’s razor” approach involves building simple numerical approximations of bubble movement and storage within a porous medium that allow us to explore how variations in factors such as pore structure, CH₄ production, and exchanges of CH₄ between the aqueous and gaseous phases can influence ebullition.

Here we present one prototype model which is based upon a single key assumption: that a (relatively) constant production of CH₄ (or of CH₄-containing bubbles) can give rise to nonsteady releases of bubbles. We assume that (in the field) the timing of ebullition events is not regular, nor are the events necessarily of the same size, so the peatland system generates a nonlinear frequency and magnitude output from a relatively linear input. Although detailed ebullition data sets are sparse, there is evidence of such dynamics in shallow peats, as we show later (see also section 1.1).

Such behavior can be found in many other natural systems, in particular geomorphic systems where relatively steady inputs are transformed into episodic outputs. Examples include earthquakes (constant tectonic pressure leads to sudden release) and river catchment sediment systems (relatively steady rates of sediment production but episodic releases of sediment from the catchment outlet). Perhaps the best documented examples of this behavior are landslides, in particular the strikingly simple sandpile model of Bak et al. [1987]. Bak et al. [1987] developed a cellular automaton in which sand is added, grain by grain, to a surface to form a pile. When local slopes become too steep, a collapse occurs, moving sediment to neighboring cells, which too can collapse if the adjusted slopes are too steep. Bak et al. [1987, 1988] noticed that the addition of a single grain could cause a cascade of local collapses whose size could vary from a single cell (grain) to that of the whole length of the surface. They also found that the magnitude-frequency distribution of these cascades follows an inverse power law. After a collapse, and with the addition of more grains of sand, the system would self organize back to a critical state where the addition of a single grain of sand could again cause a cascade of collapse. The model reached its critical state through a series of positive (sand grains building up to create a pile) and negative (avalanches destroying part of the sandpile) feedbacks.

Bak et al. [1987, 1988] suggested that their model was a good analogue of natural sandpiles [cf. Jaeger et al., 1989; Held et al., 1990; Rosendahl et al., 1993] and referred to the tendency of a system to “evolve” toward a dynamic equilibrium around a critical state as “self-organized criticality” (SOC). Here we are not concerned with SOC systems per se; however, the dynamics of the numerical sandpile appear to have some useful similarities with the dynamics of the peat-bubble system in that a small and constant input may lead to output that is highly variable in magnitude and frequency.

Our prototype model is similar to an inverted sandpile model, where, instead of grains of sand falling, we have bubbles rising. The peat profile is represented in the model as a 2-D cellular grid or lattice. Cells within this lattice may be of three types (or have one of three states): peat (solid), water (liquid), or bubble (gas). The model grid is set up as a column of water that contains obstacles or “shelves”; together, these represent the pore network of a peat soil. Therefore, by altering the size, disposition, and density of shelves, we can represent a range of different types of pore structure or network. Into the base of this column, single small “bubbles” are introduced at a constant rate (one per model iteration) but at random locations (across the base). This process represents CH₄ production; in other words, our example model assumes that pore water is already CH₄ saturated so that production translates immediately into bubbles. This is obviously oversimple, but our purpose here is to demonstrate the model’s capability and simplicity rather than a realization of a particular peat type at a given time of year. Suffice it to say, the model can easily be altered so that bubble production can vary through time and model space.

During each model iteration, every bubble rises up through the column one cell until it reaches either a shelf or another bubble trapped below a shelf. When it reaches another bubble, its subsequent movement is dictated by a range of eight simple rules (as described in Figure 4) that determine whether it stops or moves around the obstacle (shelf). This allows the small bubbles to build up or coalesce into larger bubbles: in analogy, a series of upside down sandpiles. The
bubble accumulations grow until they are large enough to shed bubbles around the side of the shelf through upward “avalanching.” Similar to the sandpile model, the size of these “avalanches” bears no relation to the size of the input, so the addition of a single bubble can trigger an “avalanche” of a much larger bubble.

The model’s operation is illustrated in Figure 5, where large bubbles develop beneath the shelves, leading eventually to the episodic release of different size “bubbles” represented by chains of individual bubbles. The model is written in Visual C# and may be obtained from the first author. The model allows the user to add or subtract shelves, which enables investigation of how different types of “pore network” affect ebullition. The size of the bubbles reaching the surface (the length of the “landslides”) can be recorded by the program. To illustrate the capability of the model, we conducted three simple runs among which the width and number of shelves varied (i.e., representing different pore structures). Run 1 contained 11 shelves, each, on average, 7 cells wide. Run 2 contained five shelves, on average, 14 cells wide. Run 3 contained three shelves, on average, 22 cells wide. Bubble inputs were kept at the same rate for all three runs.

We collected output data from each of the model runs, and these are presented as unitless frequency distributions in Figure 6. They are compared to a frequency distribution of laboratory-measured ebullition events (data from Kellner et al. [2006]). There is a strong similarity between the frequency distribution from the laboratory experiments and the distributions from runs 2 and 3. However, run 1 produced mainly small- (size 1) and medium-sized ebullition events (size 2–3), and very few that are larger, because the shelves are not long enough to allow large accumulations of bubbles. The same volume of bubbles was introduced into the base of the “peat” in runs 1, 2, and 3. Hence, given that there were more small ebullition events in run 1, this run also produced fewer large-volume bubbles than runs 2 and 3.
Therefore, run 1 may be thought of as a poorly decomposed peat with an open pore structure in which bubbles are lost steadily (in response to CH$_4$ production) to the water table, as is assumed in, for example, the current version of the model of Walter et al. [2001a, 2001b]. We have deliberately chosen to compare frequency distributions, and the outputs from the model runs are unitless. Our aim at this stage is to show that our prototype model can produce some of the key dynamics of the real (laboratory) system, i.e., the frequency-magnitude relationship seen in the data of Kellner et al. [2006]. This parsimonious example model reveals how the distribution of bubble size can be radically altered by the form of the medium in which bubbles are trapped and from which they are released.

Our investigation of reduced-complexity models is in its early stages of development, and there are several obvious steps to explore. Different peat types (as represented by the size, number, and pattern of shelves) could easily be explored. Additional processes can also be incorporated to give the model greater realism, while retaining considerable simplicity compared to CFD approaches. For example, the avalanche rules could be altered to see what effect they have on both the pattern of bubble buildup and the frequency distribution of ebullition events. At the moment, the accumulations of bubbles look somewhat like inverted sandpiles, and it would be interesting to see how making the bubbles/piles more “sticky” and less “willing” to shed bubbles affects the shape of bubble accumulations and rates and patterns of release. Such an increase in stickiness could be seen as attempting to represent surface tension more accurately. It is also possible to add bubbles nonrandomly in different parts of the modeled peat profile, to reflect vertical differences in CH$_4$ production, for example, and to simulate exchange of CH$_4$ between bubbles and pore water. Finally, it is a relatively simple task to alter the model so that it operates in three dimensions. Ultimately, the power of the reduced-complexity approach is that it allows us to build parsimonious models; we can increase the level of detail only to that which is necessary to match experimental and observational data on ebullition dynamics. As part of this process, a key advantage of the reduced-complexity approach is that it is easy to conduct extensive sensitivity analyses on the range of main factors that control bubble buildup and release.

3. RESEARCH NEEDS

We have shown that ebullition needs to be accounted for properly in models of peatland CH$_4$ dynamics. It is not enough just to know ebullition volumes; the temporal pattern of loss also needs to be considered. Thus, we disagree with Frolking...
et al. [2002], who contend that the different modes of ebullition need not be simulated because all ebullition flux can be assumed to bypass methanotrophic processing. Such complete bypassing is unlikely to be the case in many peats. As we noted in section 1.4, CH₄ being lost via steady ebullition may, in fact, be processed in the zone above the water table, while much of that lost episodically and cyclically may not be. The fate of CH₄-containing bubbles when they reach the water table needs to be investigated empirically, but we would be surprised if there were not big differences in CH₄ efflux between a situation where a given volume of bubbles is lost via steady ebullition and one in which the same volume is lost in a single event as a large slug of gas. Although not discussed in the main body of the chapter, there is also clear evidence that bubbles may form under horizontally averaged CH₄ pore water concentrations that are substantially less than the equilibrium solubility [e.g., Baird et al., 2004], and for this reason alone, more work on bubble buildup and formation is needed; that is, existing models need revision in this respect too.

We have also shown that the recently proposed bubble threshold model of ebullition [e.g., Kellner et al., 2006] is probably too simple to account for the complexity of the process, while CFD approaches are still in their infancy and are unlikely ever to become part of a larger model of CH₄ dynamics in peat soils because of their extreme complexity. We believe our reduced-complexity approach offers a sensible way around the problem of how to model ebullition in a way that accounts for depth variability in key processes such as bubble accumulation. Obviously, there will still be a need for data on peat pore structures (collected using X-ray CT) and a requirement to turn such information into the right pattern of shelves found in the reduced-complexity model so that different peat types can be represented. The latter requirement is not trivial but can be addressed relatively simply using laboratory experimentation where relationships are established between different types of pore structure and bubble dynamics. Even with this requirement, the model will be parsimonious in its data requirements and setup compared with a full CFD description of the process. Finally, different versions of the prototype model will need thorough testing through both sensitivity analyses and model-data comparisons. We will report on such developments in due course.

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