Towards a microbial process-based understanding of the resilience of UK peatland systems: *Workshop 3 on modelling and remote sensing peatland microbial processes: 4th October, Manchester*

This document provides a summary of the discussions and outcomes of the above workshop. It is organised in relation to the workshop sessions. Participants at the workshop were split into two groups and swapped between Session A and B during the day.

Session A Microbial processes and peatland modelling

The workshop considered the question:

'Can enhanced understanding of microbial controls on peatland growth and decay improve our modelling of peatland systems?'

Discussion focussed around three main responses to this question namely 1) whether it is desirable to incorporate microbial processes into peatland modelling, 2) whether it is possible to do so, and 3) what additional research would be required to make this possible.

Key points are summarised below:

Is it desirable to incorporate microbial understanding into peatland modelling?

The following reasons why the incorporation of microbial process understanding into peatland modelling approaches would be a step forward were outlined:

- Current modelling approaches are driven by physical variables such as temperature or water table. These parameters are correlated with peatland function (e.g. organic matter decomposition rates) because of the control of these variables on microbial activity. However, if climate change produces no-analog conditions, we do not know the degree to which currently known statistical relations will be stationary.

A number of further points which are elaborations of this fundamental problem were also discussed:

- Measurement of gas flux from peatland surfaces derived from microbial decomposition of organic matter, commonly demonstrates localised hotspots of production, which are not explained by macro-level variation in physical parameters. Micro-scale drivers of microbial metabolism may be important here, which would be best understood through a focus on the microbial system.
- Models which base carbon dynamics on water table typically use long term mean water tables (monthly or annual) as drivers. Synoptic scale change in hydrometeorological conditions (flood /drought) and particularly changes in the frequency of these events, may

not be properly represented by these input variables. Changes in carbon metabolism can occur at these shorter timescales and microbial processes can introduce lags into the system (e.g. enzyme latch mechanism). Similarly, there was discussion of the scale of lags in methanogenesis which might be induced through microbial dormancy during drought periods. Models which directly incorporate microbial dynamics could address this limitation.

- Dealing with systems ”hitting the buffers”. This is the extreme version of the basic case. Where environmental change pushes system behaviour beyond the current natural variability, it may be difficult to model carbon cycling using proxy drivers. Modelling approaches based on understanding of microbial dynamics may be more robust. An example which was discussed was the potential that long term lower water tables in peatlands would lead to cracking of surface peats, so that potentially measured water tables do not relate linearly to peat moisture at the micropore level which is experienced by microbes. This would be a non-linearity in the relations between water table and gas flux, which an understanding of direct microbial response to changing water balance might help to unravel.
- Peat decomposition by microbes may be driven by pulses of substrate and/or pulses of toxins, driven by peatland hydrology. Understanding microbial response to key substrates and toxins provides an alternative approach to understanding decomposition dynamics.
- Incorporating understanding of microbial growth rates would allow modelling of non-linear changes in gas fluxes and short-term rates of change.
- A key requirement is that peatland models accurately partition gaseous carbon losses between methane and CO_2 (and also include plant-mediated transfer). In non-stationary conditions microbial information such as methanogenesis-methanotroph ratios may be required to achieve this.
- It was discussed that whilst microbial understanding might not directly appear in modelling approaches, it was essential to give confidence that response curves in models are appropriate across a range of conditions

What is possible now?

Two main areas of discussion

1) Surprisingly, it may be easier to introduce microbial processes into large scale earth system models such as JULES (Joint UK Land Environment Simulator) because they run at shorter timesteps. Peatland models with higher spatial resolution, but annual timesteps are more of a challenge. Where models are running at appropriate timesteps it is possible to incorporate some routines which are based on microbial understanding – One workshop participant presented some very promising work introducing understanding of methanogen activity into JULES routines.
2) The rapid evolution of microbial techniques for studying gene expression through RNA analysis was identified as a current research frontier, which has the potential to develop understanding of microbial control of carbon cycling to the point where model incorporation is possible.

What research is needed to make this happen?

- Experimental evidence is required to define peatland function response curves outside the envelope of current environmental conditions.
- This experimental work needs to be supported by long term monitoring to identify peatland systems that are moving out of their functional envelope.

- Tracer studies and sensing of fluxes and chemical conditions (e.g. redox and electron acceptor concentrations) are required to understand drivers of microbial response.
- Functional gene studies are required alongside measurement of drivers.
- A clearer understanding of what hydrological drivers, microbial communities respond to is needed. Should we be studying soil moisture or water table (or both)?
- We need to take advantage of rapidly evolving genetic techniques to increase our understanding of microbial variability in space and with depth in soil systems.
- Recovery from fire and peatland restoration are useful study cases for peatlands outside their natural functional envelope (but we also need to capture a possible point beyond no return – such as water repellency after prolonged peat cracking).

Specific recommendations of the way forward

- Design experiments with direct input from modellers to define appropriate and usable peatland function response curves (what promotes and what prohibits and test relationships beyond the current parameter space; Andreas Heinemeyer).
- Address ecohydrological feedbacks in relation to microbes and C fluxes (tipping points vs resilience; Andreas Heinemeyer)
- Mesocosm studies required to shock the system and test resilience (peatlands are conservative), although as noted above restoration and fire recovery field studies will add value here.
- Studies of temporal and spatial variation of microbial communities integrated with measurement of (net) gas fluxes (and their component fluxes) are required.
- In order to understand microbial response, experiments should study DNA, microbial enzymes, gas flux and physical parameters (e.g. pH was mentioned in relation to separating fen vs bog and possible different communities and C cycle processes).
- These studies should be supported with analysis of functional genes and RNA. More progress in the cost of these approaches is required in order to undertake these analyses at useful temporal and spatial frequencies.

A key conclusion voiced by several participants is that the rapidity of the evolution of genetic techniques is both a challenge and an opportunity. The need for higher resolution studies and for the integration of studies of microbial structure and microbial function has been recognised for some years, yet there has been relatively little progress in the last decade. In part, this is because peatland scientists with interests in microbial processes have often been unable to keep up with the rapidity of change in genetic instrumentation and analysis. Therefore, progress in this area will require interdisciplinary approaches bringing together the expertise of microbial ecologists, peatland scientists and modellers.

Session B: Remote sensing of peatland environments – contributions to understanding microbial processes in peatlands

This workshop focused on the following question:

'How can we upscale our understanding of peatland microbial processes to understand the interaction of microbial processes and landscape carbon cycling?'

Discussions were split into four main parts but inevitably merged during the course of conversations. These parts were as follows a) Can we remotely sense microbial communities or processes?; b) Do remotely sensed properties map onto peatland model input variables?; c) Can we upscale peatland models using remotely sensed data?; and d) What developments if any are required in remote sensing or knowledge of peatland microbiota to upgrade our knowledge to the landscape scale?

a. Are there ways to remotely sense microbial communities or processes?

The general consensus was that we can use existing remote sensing technology and research as indirect proxies for microbial behaviours, communities and process. Remote sensing is also important in measuring peatland resilience to climate change (e.g. shrinkage and expansion rates over time/season) and monitoring recovery after stress has been applied (e.g. vegetation re-establishment or water table recovery). There is a wealth of existing and ongoing research that we may be able to draw on when we define exactly what questions we would like to ask e.g. peatland topographic data from fine-scale (e.g. LIDAR) DEMS.

Remote sensing can also be used in an alternative way in order to target sites or areas of interest for specific ground-based research, dependent on the research question e.g. identifying areas within a peatland that exhibit extreme characteristics or behaviours, and therefore may be worthy of research attention. An example of this is detecting hotspots of methane gas release (i.e. concentrations might be all that is needed, not fluxes; Andreas Heinemeyer).

There are a wide range of platforms available e.g. unmanned aerial vehicles (UAVs), aeroplanes, satellites and a lot of different techniques that could be utilised. Technology is improving and is cheaper, satellites are online more frequently, and the remote sensing community is moving rapidly in developing and applying techniques.

Approaches might include:
i description of characteristic plant-microbe assemblages

Remote sensing of vegetation variation in peatlands has made substantial progress over the last decade using hyperspectral data by studying and identifying hyperspectral properties of different types of typical moorland vegetation. Once we continue to enhance our pre-existing understanding of plant-microbial relationships in peatlands, remote sensing may(!) be a useful tool to define microbial communities based on vegetation type or characteristics, without undertaking intensive field monitoring campaigns on a regular basis. Key microbes could be linked to key vegetation components. An example was given in relation to the investigation of ericoid species vs sedges, as these may be differentiated by remote sensing techniques.

The advantage of remote sensing to provide temporal surveying was discussed and UAV research outlined as important here. The smallest resolution of remote sensing is a leaf, using a UAV with a hyperspectral sensor. There was discussion around Beth Cole's work on plant functional types in peatlands undergoing restoration work being remotely sensed. Beth used a combination of hyperspectral and LIDAR data for her work. High resolution data was used for this. If there were ways to remotely sense bog recovery post-restoration, this could save both time and expense.

Discussions centred around linking remote sensing using imaging spectroscopy with various other biochemical traits, including the chemistry and phenology of plants. The remote sensing in particular of litter quality, phenolics, pigments and lignin were discussed. Angela Harris gave particular reference about linking aspen leaf chemistry to below-ground communities (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3983929/?otool=igbumllib)

ii remote sensing of gas surface fluxes

Research is ongoing in this area- examples include a review by Lees et al. (2018) and a book chapter by Harris and Bryant (2009). Angela described how some models use FAPAR to estimate assimilation of CO_2 by plants. Discussions focused on the possibility of detecting hotspots of methane (and CO_2) by remote sensing. It was noted that measurement of methane is notoriously variable. Can we learn something about microbial behaviour by remote sensing methane fluctuations at the spatial and temporal short scale? Such short-scale methane measurements have been carried out in grasslands. We should engage with the atmospheric community surrounding this, as Angela suggested this can be carried out using drones/aircraft- there are possible links here with another group of scientists.

It was agreed such measurements should be linked to processes, allowing targeted process-based understanding. Detecting hotspots could be useful for targeted investigation of microbial communities and the environmental factors leading to enhanced microbial activity.

iii or?

Other proxies for microbial communities/processes which could be remotely sensed were discussed. Water table depth was discussed in some detail (of which participants were aware of work with several types of remote sensing). Thermal imaging for water table depth was mentioned as being currently under development (group at Exeter mentioned – Andreas Heinemeyer worked on such a proposal with Tristan Quaife). Roxane Andersen also talked about INSAR and the advantages of this technique not requiring a cloud-free atmosphere. INSAR measures ground motion, is a proxy for water table and can measure at the sub-cm level. It is complementary to remote sensing of vegetation and some useful contacts were suggested by a few members of the group. Rob Griffiths emphasised that microtopography and conditions at the micro-scale, driving the water table, are as important for microbes as for plants, and therefore this is an important measure of ecosystem health (research has already shown us this with regards to vegetation).

We discussed water in peatlands in general and that pools had been a subject of interest in the previous workshop. Pooling of water can be remotely sensed effortlessly, and spatial and temporal frequency could be measured and related back to microbes. For moisture / hydrology, how important is the stock of water compared with the movement of water? Methanogenesis causes inhibitory compounds? Water movement removes these inhibitory compounds? The presence/absence of water pooling and the linkages with microbial processes (considering timescales) is a potential research avenue and is worth exploration.

Other things that were discussed were:

- Cracking networks in peatlands and using remote sensing to detect them. Cracking can be an issue as it may cause hydrophobicity and mean that peat will not hold water as efficiently again. Links to microbial processes (Andy Baird)
- Vegetation should be linked to below-ground C inputs via exudates (sedges vs ericaceous) and impacts on (myco)rhizosphere community and C cycling (Andreas Heinemeyer)

- Pollution influx in lowland peats and their floodplains, including processes such as N deposition and the extent of saline incursion. Switching on/off of microbial processes? (Kate Heppell).

b. **How does our ability to remotely sense peatlands map onto the input variables required for peatland modelling?**

AND

c. **Can remote sensing of peatland character contribute to the effective upscaling of peatland modelling outcomes?**

The two questions above were not discussed in detail as participants felt that this was discussed broadly in Session A. Vegetation data, topographic data and hydrological data, some of which may be remotely sensed are already featured as input data into some models. Points that were made or questions that were asked were as follows:

- Input variables required for peatland models from remote sensing include: landscape topography to get water flow, plant functional types, litter quality and Leaf Area Index.
- Is microbial physiology, including the importance of the redox ladder, implemented in models?
- How does remote sensing map onto function questions?

d. **What developments in remote sensing or understanding of peatland microbiota are required to develop landscape scale understanding of the role of the peatland microbiome in peatland carbon cycling?**

Generally, the consensus was that remote sensing is developing quite fast and has been applied to explore peatlands characteristics for years. Now we need to know what we want to ask from the microbial side. What data / product do we need? Defining a set of specific research questions is important and will be the end product of this wider project. Some of the research and knowledge may need to be developed prior to the remote sensing community becoming thoroughly involved. But remote sensing may certainly help initially as a scoping tool for focused experimental research on peatlands.

The research and recommendations outlined at the end of section A are key here, and should be used as the way forward to inform how remote sensing could become entwined with the field, laboratory and modelling aspects of this research.

Other points made during the course of the duplicate sessions:

- We discussed testate amoebae as indicators of a healthy bog.
- We discussed the importance of research into microbial function and less so about communities. A point made previously in the first two workshops.
- If the characteristics of a "good bog" can be seen easily from the expertise of peatland scientists, then is it possible to remote sense this "expertise?" We discussed how many peatland scientists could go onto a particular bog and make an instantaneous judgement

about its health prior to making any quantifiable measurements. One participant used an example of the delimitation of very degraded peatland as being relatively straightforward e.g. the presence of cracking or assessment of gully density or proportion of bare peat. These things can be remotely sensed. However, the microbial component is the missing link here. An issue is also related to terminology such as ‘peat-forming’ and ‘active bog’ – this needs to be linked to monitoring impacts (e.g. C cycling) and underpinning microbial processes (Andreas Heinemeyer).

- Participants were interested in fire occurrence and prevalence and the nature of microbial communities. What happens to the microbial community after a burning event? Over what timescale does the same community recolonise, if at all? Do functional microbial processes change? Chicken and egg question of vegetation or microbial communities first.

Next Steps

This workshop summary and the previous summary from workshops 1 and 2 will inform discussion at a further workshop in January. This will bring in practitioners to co-create a policy brief on peatland microbial processes, key research questions and potential applications.

The ideas from this workshop are being brought together by the project team alongside a review of the relevant literature to develop a first draft of a state of the science paper. This will be shared with all participants for comment.