Towards a microbial process-based understanding of the resilience of UK peatland systems: *Workshops 1 and 2 on peatland function and microbial processes: 20th-21st May, Manchester*

This document provides a summary of the discussions and outcomes of the above workshop. It is organised with relation to workshop themes across the two days.

What is resilience *and in what ways does understanding of the microbial system underpin it?*

This session focused on the concept of resilience and how peatlands currently are and could be manipulated to be resilient. As major stores and potentially sources of carbon the role peatlands play in regulating climate, the nature of their functional response to climate change, and the ways in which peatland management can mediate this response is an important component of climate resilience in the UK. Resilient peatlands maintain the long term carbon sequestration function of these ecosystems and also mitigate the risk of degradation of the peatland carbon store which would be a significant source of carbon to the atmosphere.

Discussions focused on the concept of the 'resilience basin' (Walker et al. 2004). Walker et al. (2004) discusses resilience as having four aspects: latitude, resistance, precariousness and panarchy. The latitude of the system (depth of basin) is the maximum amount the system can change before it reaches inability to recover. The resistance (steepness of sides) is the ease in which the system may change. Precariousness (how far up the side of the basin) is the proximity of the system is in relation to its limit or threshold. Panarchy (interactions below and above the basin) refers to interactions with external systems or dynamics.

There may be a number of basins in which a system moves between which we can refer to as alternative stable states. A new stable state could be defined by climate change and could either be within a safe operating space, or represent something completely different and alien. These concepts are highly relevant in the context of UK peatlands. These are highly modified ecosystems (due to a range of anthropogenic impacts and consequent erosion). They are also systems where extensive restoration and rehabilitation is under way. Participants discussed whether new work should focus on restored systems which are arguably outside of the envelope.

Peatlands are naturally resilient systems as evidenced by their persistence in the UK uplands despite numerous external pressures (panarchy). However we know that bioclimatic envelope suitable for peatlands is moving (Gallego-Sala et al. 2010). We do not know whether all peatland functions are resilient. We need to work on defining their carbon resilience, microbiological resilience and hydrological resilience. In relation to microbiology- are some microbiomes more resilient than others? We need to define lag times for recovery (return to bottom of the well if possible) after events e.g. drought or fire. Does a future outside the climatic envelope lead to less functional resilience? There was discussion around a cascade of failures and what may be the first 'resilience' to fail.

In restored systems, could we modify or support the microbiome to become peat forming? One promising approach would be to 'define' a core microbiome by investigation of the 'best' and 'worst' systems. Considering peatlands as to be 'carbon storage ecosystems' requires that they are actively peat forming and therefore this is a key component of resilience. The ideal vegetation in peatlands for carbon accumulation was considered. For example *Ericacea* has a high lignin-cellulose ratio and therefore may be considered as more resistant to decomposers. *Sphagnum* also produces recalcitrant litter and therefore is less susceptible to attack by white-rot decomposers. The importance of interactions between the plant and microbial systems was emphasised in this context. Is it possible to manipulate vegetation and the microbial system independently?

Timescales of microbial response to changes in the peatland system and the nature of microbial behaviours on the rate of response

Discussions in this session focused around timescales of change and timescales of operation of key peatland processes. A wide range of timescales were discussed including: daily; monthly; seasonal (wet and dry); longer-term (decadal). Much of the discussion in this session emphasised the importance of lags and tipping points. One key thread in the discussions seemed to be that we know about some microbial behaviours in response to environmental changes in some systems, but not as well in peatland ecosystems. A key question is whether knowledge can be transferred from other systems or whether peatland characteristics, behaviours and challenges make them unique.

Defining the timescales that matter is important. Are rapid transformations or longer-term changes more important with regards to peatland ecosystem function? At daily timescales there is an understanding surrounding the behavior of water tables and dissolved organic carbon (DOC) fluctuations. But there is a lack of understanding about microbial behavior at this short timescale. Consequently the importance of short term change as a component of long term resilience is poorly understood.

Seasonal change in microbial communities was identified as being complex to understand as there is lots of interconnectivity. Long-term timescales were noted as important, as for example short-term drawdown in water tables is commonplace, but long-term drought is an entirely different process. Concepts such as the enzyme latch mechanism indicate that significant lags in ecosystem function to these events are possible. The responses of microbial communities to these changes and the ways in which they control or mitigate lagged responses is an area of interest. Peatland systems are complex and may react slowly to stressors. For example there is some research suggesting lag times in response to drought from work on testate amoebae and vegetation community change may be in the order of decades. However, microbiological communities may react more rapidly to environmental changes.

The resilience of peatlands, their tipping points and reaction to long-term climate change is unknown, particularly when factoring in multiple stressors. Tipping points may include extreme droughts, flooding, extreme pollutant events and fire. Recovery responses of peatlands to pollutant deposition including S and N, and the recovery of peatlands after management are becoming increasingly well known, but the microbiological response is less so. The palaeo-record may be important to understand longer-term change. Testate amoebae, diatoms, microbes and biomarkers and DNA were discussed here.

A key question was posed: Is everything everywhere? Or is the presence/absence/migration of microbial communities important to understanding functional responses to external stress. Are microbial communities relevant to defining tipping points of peatland function in this context? The combinations of pressures may be important in the future. Identifying if some stressors are more influential than others in creating system tipping points and whether there is a cascade effect may be key. In the light of these ideas, experiments on combination and ordering of stressors may help.

Discussions focused on the impact of restoration on microbial communities. We have started to understand the effects and timescales of response on water table, fluvial carbon fluxes, water flow and vegetation (Alderson et al. 2019) but at present we know nothing about the impact on microbial communities. To allow us to identify response to change we need to understand the baseline i.e. what does normal look like with regards to microbial communities and behavior in both intact systems and degraded systems before we can look at restored systems.

The impact on these communities when changing the pH of the soil (liming) during restoration was discussed. Sub-surface structural changes may also be important and have been shown to potentially be important in relation to water residence times (Shuttleworth et al. 2018) and production of DOC. Does this also impact on microbial communities? There is a need to compare surface versus sub-surface communities and behaviours/functions. The speed of response of microbial communities to restoration represents an important avenue of research.

Spatial scales in peatlands were also regarded as important. Small scale (sub-cm) information on microbial communities could be essential. At larger scales there is a necessity to link field plot scale measurements to landscape scale ecosystem function. This is particular important if microbial processes in peatlands are to be properly represented in climate models. We need to understand what information the modelling community requires, but in order to produce accurate models we need to understand microbial processing in order to develop predictive modelling capabilities.

What microbial processes are key to peatland function?

This session centered on the major roles of microbial communities in peatlands, focusing both on their influence on carbon dynamics, and interactions with nutrient cycling. It was noted that at present in peatland systems, more microbiological research has been based on species characterisations of bacteria, fungi and archaea, than functionality and contributions to peatland ecosystem services and resilience. The species that characterise peatlands can thrive in harsh conditions i.e. cool climate, low oxygen availability, nutrient depletion and acidity. Soil fauna (e.g. enchytraeids, protozoa) drive top-down effects on structure and function of microbial communities. Participants were keen to emphasise that it is important to differentiate microbial presence from function. Similarly, the relations between microbial biomass, biodiversity, community structure and function are complex. Peatland resilience and the relation between peatland state and microbial function are likely to be closely linked to understanding which species are active. We need to better understand controls on both the structure and function of the microbial community

The importance of conducting microbiological research in peatland ecosystems was discussed. For example, the microbiological response to environmental changes can be much more rapid than changes of plants and animals, as a consequence of short generation times and their evolutionary potential. Microbial biota and their response to external and internal stressors may therefore be important as rapid indicators as peatland systems approach tipping points. The role of substrate availability and redox conditions as drivers of change in microbial structure may assist in identifying limiting factors in peatlands.

Carbon cycling

The role of different microbial groups in the decomposition process was discussed in the context of the function of fungi vs bacteria. It was agreed that we need to know more about gradients in microbiological community structure across peat depth, vegetation types and severity of degradation. The depth gradient was discussed with regards to the acrotelm/catotelm model of peatlands and its role in the carbon balance of a peatland. Participants discussed the notion that some peatlands now display a haplotelmic model as a consequence of ecosystem disturbance. In particular the potential change in depth of electron acceptors (organic and inorganic) availability was identified as important Methane release is controlled by the balance of methanotroph/methanogens in peatlands. Vegetation gradients are a key driver for for spatial and temporal resolution of microbial communities structure and function. Vegetation mosaics change through restoration processes and have implications for re-wetting and CH_4 emissions, the balance of methanotrophs and methanogens, and substrate quality. The functional diversity in root systems of vegetation was identified as a particular unknown.

Discussions also turned to peatlands as a semi-aquatic landscape. Pools, ponds and streams are all part of the peatland ecosystem, and the microbial communities of these ecosystem components should also be investigated. This is also important as restoration practices such as gully blocking create ponds. Within the peatland soils themselves, there are likely to be very different communities under drained versus waterlogged peat, and in fact the wetting up and drawdown of the water table in peat is a natural process. We know that changes in the water table affect microbial community structures at intermediate timescales. But we do not know enough about changes over small spatial and temporal scales and more focus is required on event driven changes. Do the communities change over time and what effect does this have on production and stablisation/release of carbon based species?

We discussed whether there were essential microbial functional groups or communities for a "functioning system" e.g. for carbon accumulation. Perhaps to explore this we need to compare source versus sink peatlands? This discussion developed ideas of attempting microbial engineering for carbon resilience. If we are trying to assess an 'ideal' microbial community for a peatland we need to consider different types of peatlands e.g. bogs versus fens. In a wider sense, is it possible to achieve the microbial community of an intact peatland when restoring a degraded peatland? Some other ecosystem functions (e.g. Water table) may not be able to return to pre-degradation levels.

Nutrient cycling and pollutants

Carbon dynamics are not the only important function for microbes in peatlands. They also have a role in controlling nutrient release and uptake, which in turn relates to plant productivity and biodiversity, considered as key ecosystem services in peatlands.

Pollutants (and interactions with climate change) affect microbial diversity and function (e.g. heavy metals, nitrogen) and have knock-on effects for carbon cycling. Nutrient deposition also affects the supply of electron acceptors. On the other hand, microbial diversity can also affect the supply and form of nutrients and pollutants (e.g. nitrates/sulphates). Questions posed in relation to nutrients were: 1. Is there stimulation of white-rot *Basidiomycota* with nitrogen pollution?; 2. What happens to algae with nitrogen pollution?

pH effects were also mentioned in this session as a possible major driver of microbial community change, in relation to restoration strategies (addition of lime) and atmospheric deposition of pollutants.

Identifying research capacity **- What methods/data/field sites are available and appropriate?**

This workshop concentrated discussions on the research topics of interest defined on day 1 of the workshop. We discussed methods, data and field sites that we already had available to tackle some of the questions at hand, and speculated on what we would need to generate further knowledge. The microbiologists asked the peatland scientists what big questions do we have about peatlands that micrbiological investigation may be able to help answer?

Some of the key themes that were identified in the first three workshop sessions were related to our ability to enhance the carbon storage capacity of peatlands. This was discussed with regards to restoration measures that are already established practice, and focusing further research effort on vegetation types that are most beneficial to promote carbon fixing microbes. In order to do this, we must first be able to identify community structures and functional microbes that encourage this process in bogs that are currently functioning as carbon sinks and considered as 'intact'.

The questions here were twofold: 1. Is it possible to identify a 'healthy' and functioning bog on the basis of a microbial community or is this idea far too simplistic?; 2. Concerns were also raised about considering other ecosystem services that peatlands provide. Would it be worth creating mono-species peatlands to assist with carbon fixation goals, at the expense of biodiversity? Participants generally agreed that if we could us the microbial community to identify a healthy ecosystem, this would be extremely useful as it would enable practitioners and researchers to cut back on costly and time intensive monitoring programmes.

Another key theme was related to using microbial processes to enhance understanding of sub-surface processes. Knowledge of sub-surface processes in peatlands, and their changing nature under stress/post-restoration is lacking. Investigations of microbial communities and functions below the surface may be a way to enhance this knowledge on sub-surface functioning. This was generally in relation to understanding DOC generation and the response of peat after stress (i.e. erosion or reduction in water table depth).

In relation to appropriate methods to best answer these research questions, the general consensus was that there should be a balance between field and laboratory experiments. The microbiologists thought that methods were advancing all the time, and that the taxonomic and genetic characterisations of microbial communities in peatlands were both important. It was generally agreed that microbial survey in the field is the place to start to obtain taxonomic identity, then obtain function from pure cultures / Funguild / functional genes.

Mesocosms were thought to be important but microcosms could also be used in the laboratory with pure/mixed cultures.

Participants were particularly keen on the idea of making use of currently available datasets, including environmental data, frozen cores and microbiological datasets collected as part of other projects.

Resources we have include:

- Carbon budgets: flux tower records (on the order of 10 years)
- Hydrological data (Moor House and Bleaklow/Kinder (10 years)
- Natural England Monitoring network
- Substrate quality data- Fred Worrall?
- Global Sphagnum project (5-10 years)
- Palaeo data (immigration versus immigration of population from DNA)
- Frozen cores?

- Metagenomic microbial data from a variety of sites from Rob Griffiths
- Microbial community data linked to biogeochemistry from Global Peatland Microbiome from Erik Lilleskov (autumn 2019, close to publishing).
- Data from MAdCAP? No data from microbial community from group.

Sites

Discussions around possible sites where studies could be conducted were focused around areas where a lot of research had previously been completed; i.e. where we already have prior information on bog characteristics and behaviours that may be relevant to the study of peatland resilience and the microbiological community. Participants particularly thought sites where there was already carbon flux data i.e. a flux tower would be particularly helpful. Sites that were mentioned during discussions were as follows:

- Bleaklow and Kinder, UK (C budget, known history; also has heather & *Eriophorum* site, *Molinia* site with control sites)
- Moor House, UK
- Whim Bog, UK
- Forsinard, UK
- Stordalen, Sweden
- Mer Bleu, Canada
- Sites in Ireland

Next Steps

This workshop summary will inform discussion at two further workshops. The first will bring together some of the participants in this workshop with the modelling and remote sensing communities to consider issues of upscaling. The second 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 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.