Theme D Natural Resources

Lay Summaries of Projects

Contents

Topic Line: D1 Air Quality

Topic Lead: Andrea Britton, andrea.britton@hutton.ac.uk

Plain English Summary: Clean air is essential to the health and wellbeing of people and the environment. While substantial progress has been made towards improved air quality in recent decades, through tighter controls on industrial and domestic emissions, air pollution continues to harm human health and the environment in Scotland. Air pollution is a complex issue involving multiple pollutants and their interactions and affects not only air quality but also the functioning of terrestrial and aquatic ecosystems, thereby contributing to both the climate change and biodiversity emergencies. To support further improvements in air quality across Scotland for the benefit of people and nature, new scientific evidence is needed to enable policy makers to formulate workable solutions. These need to balance economic, environmental, and public health priorities and account for the complex interdependencies between air quality, climate change and biodiversity.

The nine research questions identified in the Invitation to Tender for Grant Funding for Strategic Research Programme 2022-7 (SRP 2022-7) address three key areas where additional research and evidence is needed to support appropriate interventions. These are: (1) risks, impacts and mitigation of urban air pollution, (2) monitoring and mitigating agricultural emissions, (3) understanding impacts of air pollution and climate change on natural ecosystems. Research in this Topic Line addresses all three areas with the aim of providing evidence and practical tools to underpin development of policy, enable the commercial sector to make necessary changes, and thus benefit civil society through improved air quality and reduced environmental harm.

SRUC-D1-1 Air quality: livestock farming and ammonia
PI: Gemma Miller, gemma.miller@sruc.ac.uk

Ammonia emissions are problematic: they lead to indirect emissions of nitrous oxide when redeposited on soils from the atmosphere; N deposition leads to soil and water acidification and can affect plant biodiversity. Ammonia also binds with other gases in the atmosphere to form fine particules which damage health when inhaled. A recent US report (Domingo et al, 2021) found that ammonia emission from beef production was the biggest agricultural contributor to human deaths attributable to poor air quality.

In Scotland, ammonia emissions have only reduced by 16% since the 1970s, with agriculture currently responsible for 92%, and ruminants contributing 52% of ammonia emissions from agriculture (DEFRA Inventory, 2019). Good practice measures to reduce ammonia emissions from ruminant farming are well established, but uptake is low. This may be due to low public pressure (compared with the high public profile of methane emissions), lack of farmer awareness of the impacts and/or causes, and for economic reasons. In a working group underpinning the review of the Clean Air for Scotland (CAfS) strategy, NFUS and farming industry representatives highlighted a scarcity of information for farmers and identified the lack of quantified linkages as a key barrier to the implementation of ammonia mitigation measures. Ammonia emissions have distinct seasonal variation, with high emissions in spring and autumn associated with manure and fertiliser application. Hence, implementing low-cost actions when there is a risk of high ammonia emissions could have a big benefit. Providing farmers with decision support tools to identify sources of ammonia emissions and their effects will raise awareness and help drive uptake of mitigation actions. As part of the UKRI Strategic Priority Fund for Clean Air programme, commissioned through the UK Met Office, a project developing the UK Emission Modelling System (http://www.uk-ems.org.uk/) has among its aims the delivery of a module for calculating ammonia emissions from agriculture in high spatial and temporal resolution, taking into account meteorological parameters. The work in this project will draw on this development to generate specific ammonia emission calculations for Scotland.

In ruminants, there may be a trade-off between intensively housed systems with lower methane but higher ammonia emissions (e.g., from manure/bedding, and diets containing cereals and silages, both of which require N fertilisation) and extensive systems with higher methane emissions per kg of meat or milk, but lower ammonia emissions. It is important to understand these trade-offs to develop management practices that provide a balance between these two gaseous emissions.

SRUC-D1-2 Air quality: domestic biomass burning and fine particulate emissions
PI: John Newbold, john.newbold@sruc.ac.uk

Recent UK studies have suggested that biomass burning makes a very significant contribution to PM2.5 (e.g., Allan et al., 2010; Fuller et al., 2014; Crilley et al., 2015; AQEG, 2017; Font et al., 2017). Even in a smoke-controlled area such as London, 10% of the winter PM10 has been attributed to wood smoke (Fuller et al., 2014). The contribution to PM2.5 is larger and can exceed that from tailpipe emissions. Comparatively little is known for the Scottish context, where solid fuel combustion is used both as a traditional heat source (open fireplaces, coal combustion) as well as increasingly as a renewable heat source, encouraged by policies such as the Renewable Heat Incentive, Feed-in Tariffs and the Merton rule for on-site renewable heating for new builds. The only measurement evidence for the proportion of PM2.5 from biomass burning in Scotland comes from the UK's black carbon network (currently

Auchencorth Moss; Glasgow High St; Glasgow Townhead), from which a wood burning proxy can be derived as brown carbon from aethalometer measurements (Font et al., 2017). Winter contributions of wood smoke to total PM10 ranged 3-6% at background sites (Auchencorth) to 6-8% at urban sites (Edinburgh and Glasgow). The relative contribution to PM2.5, although the more relevant current metric, could not be established using those older data, but is likely to be significantly larger. No information currently exists for populated regions outside of smoke-controlled areas (e.g., rural village settings) where solid fuel use likely lies above the UK average. For example, Scotland, making up 8.2% of the UK population accounts for 30% of the UK's domestic RHI biomass installations (ONS, 2021). This work will focus on the quantification of biomass burning in domestic and institutional settings which dominate pollution episodes during stable winter conditions, rather than biomass combustion as part of industrial processes, in agriculture, muirburn or outdoor pleasure fires (e.g., bonfires, barbecues, etc.).

Particulate air pollution, especially PM2.5, is highly correlated with various adverse health impacts. The Cleaner Air for Scotland 2 (CAFS 2) Strategy indicates a need for evaluation of the effect of PM2.5 arising from biomass burning on health outcomes, as well as a need for quantification of the spatial effect of biomass burning on air quality in urban and rural centres. This work will focus on quantifying the spatial distribution of PM2.5 levels that are generated by biomass burning and their effect on human health outcomes across Scotland.

JHI-D1-1 Nitrogen deposition Impacts in Natural Ecosystems (NINE)

PI: Andrea Britton, andrea.britton@hutton.ac.uk

Scottish natural ecosystems supply essential goods and services upon which our society and economy depend. Effective safeguarding of natural capital and ecosystem service supply in Scotland in the face of continuing N deposition and increasing impacts of climate change requires a thorough understanding of the way in which these two drivers impact on biodiversity and ecosystem processes and their potential interactions, across a wide range of natural ecosystems. This project will review the evidence for N impacts on Scottish ecosystems in the context of climate change and will build on research conducted under the 2016-2021 Strategic Research Programme and research commissioned by CAMERAS partners and UK agencies, to enhance our understanding of interactive effects of climate and N deposition on biodiversity and ecosystem function in Scottish habitats and the potential for mitigation of these impacts. Work in this project is arranged in two work packages (WPs) addressing the requirements of RQs 8, 9 and 10 in the ITGF.

Topic Line: D2 Water (inc. flooding)

Topic lead: Mark Wilkinson, mark.wilkinson@hutton.ac.uk

Plain English Summary: Four interlinking and complementary projects have been developed in Topic Line D2. These projects will help to support the management of Scotland's water resources in the face of a Climate and Biodiversity emergency and increasing pressures on land use. Projects have been created with close engagement with policy and practice (see project level text). Two of the projects are led by the James Hutton Institute (JHI) (inc. BioSS and Napier University as CO-I's) which account for 90% of topic resource. These projects are Emerging Water Futures (EWF) and AiM NBS (NBS). Scotland's Rural College, SRUC (Coastal Community Vulnerability - CCV) and Moredun Research Institute, MRI (Protozoan Parasites - PP) lead two smaller projects, which link to specific elements of certain RQs.

Relevant issues and policies in Scotland	NBS	EWF	CCV	PP
Hydro Nation Strategy				
Scottish Climate Change Plan				
Climate Change Adaptation Programme				
Green Recovery (inc. Nature-Based approaches)				
Water Resources Management Plans				
National Water Scarcity Plans				
Flood Risk Management Strategies				
Scotland's Third Land Use Strategy				
Regional Land Use Partnerships				
River Basin Management Plan (RBMP)				
Future SRDP/agri-environment measures/funding				
EU Water Framework Directive (recast)				
Drinking Water Regulations				
Scottish One Health National AMR Action Plan				

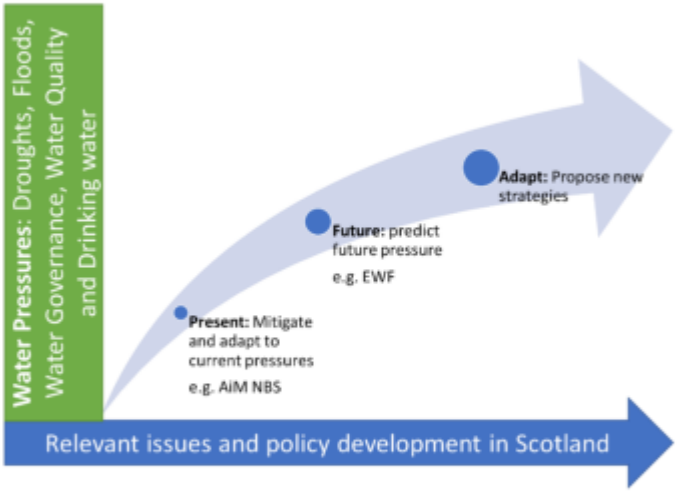

Table 1 (left): Key issues and policies in Scotland as addressed by the four projects (shaded cells). Figure 1 (right) how projects address elements of these issues/policies from the present state to data-based predictions of future state to future responses.

The projects address a range of water related issues (and associated policies) in Scotland (Table 1), informed by our consultations on project alignment with key Scottish Government needs for improving water management. Projects address similar policies but cover different aspects. For example, AiM NBS looks at ways to mitigate and adapt to current pressures whilst Emerging Water Futures looks to predict the impact of future environmental change and societal challenges on water resources (qualityy and quantity) in Scotland, including climate change related impacts and emerging contaminants (Figure 1). All projects provide valuable scientific insights to aid with adapting policy and practice in the face of current and future water related challenges. Projects inform the new research

aims and objectives, often by consolidating and building on data, cases, and findings from the SRP 2016-22 to maximise the evidence strength on water quantity (e.g., hydroclimatic extremes) and quality (nutrients, emerging contaminants); an example being how longer-term change informs new predictive capabilities.

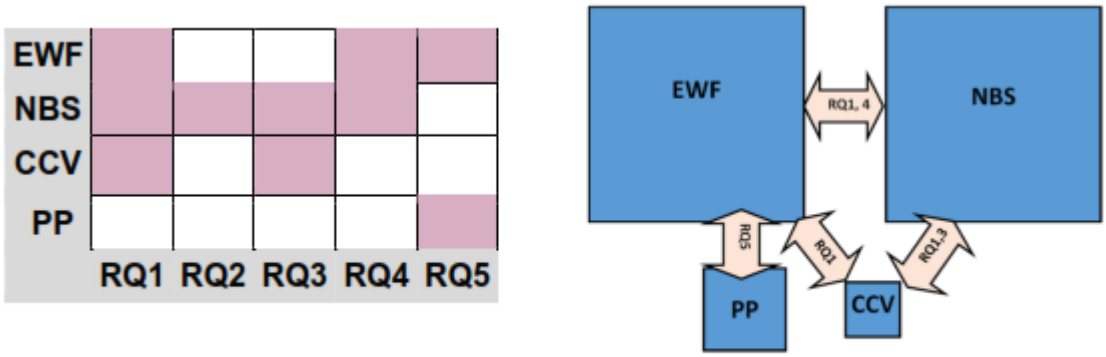

Figure 2 (left) Schematic highlighting which RQs are being addressed by each project (acronym as above). (right) Highlights the knowledge sharing between projects for each RQ to ensure research is complementary and supporting one another (Area of the blue block denotes the size in resource allocated to the project.)

Projects will engage closely with each other and jointly with relevant policy/practice teams to ensure effective communication of results. Three projects (EWF, NBS, CCV) cover multiple research questions (RQs), are cross-cutting research and deliver across water management issues. When multiple projects address a RQ this is in a complementary way (not duplicating) e.g., addressing one sub-area of a RQ or delivering to a different core aim (Figure 2). Project research direction will be reviewed constantly through engagement with: (a) stakeholder coordination groups; (b) advisory groups (in which a staff member contributes to), (c) continuing engagement and projects through the Centre of Expertise for Waters (CREW), and (d) done in co-ordination with the relevant RESAS contact (Dr Helen Jones). Hence, our new specific stakeholder groups, plus long running, tested fora for networking at national strategy to practitioner levels ensure the projects deliver to the latest policy and wider stakeholder needs.

JHI-D2-1 Emerging Water Futures

PI: Miriam Glendell, mirimam.glendell@hutton.ac.uk

In their draft strategy for Environment, Natural Resources and Agriculture Research, the Scottish Government recognises the challenges around managing water resources in the context of future environmental change, including drought and risks from emerging contaminants (ECs). This project was developed in consultation with SG Water Environment Policy team, SEPA Water and Land Unit, Scottish One Health National AMR Action Plan (SOHNAP) group, DWQR and Scottish Water (Microbiology) to support development of a proactive approach to water management under future environmental change. The project will: 1. Develop methods and use climatic projections, to understand a) the vulnerabilities of Scotland's water resources to drought (RQ1) and b) future risks to water quality from nutrients and ECs (pharmaceuticals, microplastics, antimicrobial resistance genes (ARGs)) (RQ4, RQ5) 2. Establish a baseline of ECs across Scotland to inform future response (RQ4) 3. Develop and apply trans-disciplinary approaches to evaluate options to monitor, mitigate and adapt to future threats to water scarcity and quality (RQ1, RQ4, RQ5) The key drivers of this research are the needs of policy makers and managers to:

- Have tools to predict where and when drought may occur in Scotland.

- Understand where vulnerabilities to drought lie in our environment, economy and society.
- Understand future changes in water quality in Scottish catchments; what drivers of change are and how this impacts ecosystem services and water users.
- Improve and monitor rural drinking water quality and increase awareness of potential health risks from their water supplies.

Policy drivers include the RBMP 2021-27 and recast Drinking Water Directive (rDWD) (increased focus on ECs and requirement for novel coliphage test for drinking water); SEPA National Water Scarcity Plan and Water Resources Management Plan.

JHI-D2-2 Achieving Multi-Purpose Nature-Based Solutions (AiM NBS)

PI: Mark Wilkinson, mark.wilkinson@hutton.ac.uk

In the context of the climate and biodiversity emergencies, there is a need not only to mitigate against these changes (e.g., reduce CO2 levels) but also adapt to current and future water-related environmental pressures (e.g., flooding, drought, water quality); action (based on evidence) is needed now. Nature-Based Solutions (NBS) have been promoted as a way to help address these emergencies and support Scotland's Green Recovery. NBS are defined as "solutions to societal challenges that are inspired and supported by nature". NBS are central to global debates about sustainable natural resource management. In particular they have been identified as one solution to many water related environmental pressures. They are being considered more by many policy (e.g., Scottish FRM Act 2009, WFD), industry and practice sectors but the widespread rollout of NBS is slow to address the pressing emergencies and mitigate water-related pressure. Scientific evidence and guidance are needed to support implementation through the Scottish Government's 'Green Recovery'. Coupled with this, greater focus must be given so that these solutions can provide many more ecosystem services and there are potentially ways to maximise these benefits further in managed landscapes. We must also assess the conditions of some of our core land units (e.g., riparian zones) and look at ways to protect these systems. Also, consideration of the wider benefits, how to value these and promote these to catchment planners, industry, and practice is required. However, getting beyond small-scale pilots and isolated best practices rarely occurs; we need to explore how to work at scales and across sectors to deliver NBS that make a significant contribution to meeting society's needs. With these above drivers in mind, this project aims to: a) Develop a multi-scale empirical understanding of the impact of NBS based on hydrological, hydro-geomorphic, biogeochemical and ecological observations; b) Assess the water-related ecosystem services of a selection of NBS approaches on our landscapes and suggest ways in which the benefits can be enhanced; c) Assess the state of river corridors and their role in combating climate change, via ES impact indicator groups; d) Understand how to achieve transformative change via NBS that deliver multiple benefits and works across multiple sectors and scales. Four interconnected research Work Packages (WPs) address four driving Research Questions (RQs): 1, 2, 3, 4 under Topic D2.

MRI-D2-1 Rapid & specific tests for the identification of protozoan parasites in Scottish drinking water

PI: Frank Katzer, franz.katzer@moredun.ac.uk

This research proposal aims to develop improved, sensitive and specific diagnostic techniques that can be integrated into the current protocols used by the water industry to detect and enumerate (potentially zoonotic) protozoan parasite oocysts/cysts within raw and drinking water. There is a need

to test for these parasite oocysts/cysts as they are extremely robust and can survive for prolonged periods in the environment, including in watercourses and reservoirs. In addition, the oocysts/cysts are resistant to disinfection and can survive many of the commonly used inactivation procedures implemented by water treatment plants, including chlorination and ozone treatment. Current detection methodologies for protozoan parasites (Cryptosporidium & Giardia) in raw and drinking water used by the water industry rely on the filtration of particulate matter, including parasite oocysts/cysts, from large volumes of water. These particulates are then subjected to immunomagnetic separation (IMS), using antibodies specific for either Cryptosporidium oocysts or Giardia cysts, to bind and concentrate the parasites away from other particulate matter. The parasite oocysts/cysts are then stained with fluorescently labelled monoclonal antibodies and the parasites are visualised using fluorescent microscopy, which is difficult, time consuming and can be subjective. Currently there is no IMS available for the concentration of Toxoplasma oocysts. The proposed work will utilise parasite resources that are held and maintained within Moredun, which is supported by underpinning capacity funding.

SRUC-D2-1 Vulnerability of remote coastal communities to water challenges: Perception, valuation and coping mechanisms

PI: Carly Maynard, carly.maynard@sruc.ac.uk

Coastal communities experience some unique water-related challenges (e.g., balancing limited access to potable water, with too much of the 'wrong type' of water (i.e., saline intrusion, coastal and pluvial flooding). This research will aim to determine what drives the response of remote coastal communities to existing and anticipated water challenges in Scotland, addressing the risk of low flows and water scarcity, as well as high flows. It will draw on behaviour theory and knowledge of perceptions, values and understanding, to evaluate and enhance the ways in which water challenges can be managed in the future. In doing so, we will address Research Questions D2.1 (vulnerability and
resilience in the context of water scarcity) and D2.3 (governance). By determining how coastal communities perceive, value and respond to water scarcity we will be able to identify examples of good practice and opportunities for sharing of knowledge and support mechanisms. Through the assessment of the connectivity of organisational and community scale approaches to water management, we will be able to advise on how to better connect policy and practice with specific community needs.

Topic Line: D3 Soils

Topic lead: Eric Paterson, eric.paterson@hutton.ac.uk

Plain English Summary: Soils provide environmental and societal benefits; including supporting crop production, biodiversity, and C-sequestration. If in good condition and effectively managed, soils also mediate impacts on effective water filtration (including removal of contaminants), resistance to wind/water erosion, and have significant capacity to store additional carbon from the atmosphere. Topic level research aims to provide robust scientific understanding to policy makers, regulators, and land managers to support decisions on governance of Scotland's soils. Currently, governance for protection of soils is not captured within any single policy instrument, but rather is intrinsic to a broad range of primary and secondary legislation within the National Performance Framework and to Scottish Government strategies relating to environmental protection, water quality, climate change, pollution, waste, land use and planning. Project outputs will thus inform relevant key policies including the Scottish Climate Change Plan, Scotland's National Peatland Plan, Scottish Climate Change Adaptation Programme, Land Use Strategy, Climate Change (Emissions Reduction Targets) (Scotland) Act 2019, Scotland's Forestry Strategy, National Planning Framework (NPF4), UK GHG Inventory reporting, Scotland's Environment Strategy 2020, post-CAP agriculture strategy and agri-support mechanisms, nature-based solutions (NbS), Natural Flood Management, Good Food Nation, Scottish Biodiversity Strategy. Given the diverse benefits provided by soils, and their importance to multiple policies, a challenge for topic level research to address is to generate integrated outputs that explicitly identify impacts across these and other relevant policy areas. This is achieved through, (i) building on previous SRP research and reports to focus priorities, identify synergies and potential trade-offs of managements to promote specific soil functions, (ii) co-construction of the research proposed with policy, land management and regulatory stakeholders (RESAS, Scottish Government Policy, (Agri-environment, Climate Change, Biodiversity), SEPA, Nature Scot including Peatland Action, (iii) making explicit research connections to Underpinning Capacity and related SRP topics including A1, B1, B3, C3, C5, D2, D4, D5 to enable coordinated outputs across policy areas, (iv) creation of a KE hub, embedded within the Topic with specific responsibility for co-ordinating communication and discussion of soils related research outputs. This will be achieved through maintaining engagement with stakeholders via the creation of a Scottish Soils Network. Research in D3 Soils is structured as two interlinked projects (CentrePeat and Healthy Soils), that in combination address all the Research Questions set out in the SRP tender document. CentrePeat is focused on peatlands informing peatland restoration strategies and aims to provide the underpinning analysis for a Peatland Monitoring Framework, enhance the Peatland Code and improve Natural Capital accounting. Healthy Soils will strengthen the evidence base to support and inform decision-making, practice and uptake for sustainable management and minimization of degradation and loss of Scotland's soils through a deeper understanding of the multifunctionality of soils, identifying novel sustainable soil management practices and assessing metrics of change. Both projects will generate data to support the establishment of a National Soil Monitoring Framework for Scotland. Both D3 projects will be led by experienced PIs and their respective management teams. Project progress will be monitored through regular meetings attended by workpackage leads to update achievements and identify any issues as they arise. Progress will be formally recorded via instruments as indicated by RESAS (e.g., ResearchFish).

JHI-D3-1 Healthy Soils for a Green Recovery

PI: Roy Neilson, roy.nielson@hutton.ac.uk

This innovative programme of work aims to strengthen the evidence base to support and inform decision-making, practice and uptake for sustainable management and minimization of degradation and loss of Scotland's soils, considering both their intrinsic value and the benefits (ecosystem services) that they provide. Society depends on healthy soils to deliver a broad spectrum of benefits (Figure 1). However, human-mediated activities including a changing climate threaten soils, reducing their function and ability to deliver these benefits. As the interim report of the EU Mission Board for Soil health and food states "Soils provide us with nutritious food and other products as well as with clean water and flourishing habitats for biodiversity. At the same time, soils can help slow the onset of climate change and make us more resilient to extreme climate events such as droughts and floods. Soils preserve our cultural heritage and are a key part of the landscapes that we all cherish. Simply put, healthy living soils keep us, and the world around us, alive." Thus, there is an imperative to protect soils, improve soil health and identify the roles and contributions of Scotland's soils in delivering key beneficial services. Although improving, full knowledge on the mechanistic understanding of how the complex interactions of soil deliver individual and interlinked functions is lacking. Also, the definition of soil function and the determination of its boundaries is not a simple task. Soil functions can be described as the flows and transformations of mass, energy, and genetic information that connect soil to the wider critical zone, transmitting the impacts of human activity at the land surface Figure 1. Multifunctioning soils for ecosystem delivery (source The Challenge of Feeding the World Sustainably: Summary of the US-UK Scientific Forum on Sustainable Agriculture, 2021) and providing a control point for beneficial human intervention. Thus, the soil functional outcome is a result of interactions among physical, chemical, biological including human factors. For Scotland's soils we will advance our knowledge of the complex interactions that deliver societal benefits through four interlocking work packages (WP) addressing seven Research Questions (RQ), that seek to: a) maintain soil ecosystem delivery through understanding the multifunctionality of soils (WP1); b) protect soils through development of new management practices (WP2); c) identify and validate metrics that support the monitoring of Scotland's soil health and measure the vulnerability of Scottish soils to existing and future perturbations (WP3); and d) offer nature-based solutions for remediation and protection of soil to stakeholders through coordinated Topic-level proactive KE (WP4).

JHI-D3-2 CentrePeat

PI: Rebekka Artz, Rebekka.artz@hutton.ac.uk

Protecting and enhancing soil health, particularly in peatlands given that they store nearly 50% of all Scotland's soil carbon, is key to reaching Scotland's net zero target by 2045. Peatland health, or condition, is dependent on physical, hydrological, and ecological factors, which influence each other in various self-regulating feedbacks to produce resilience over millennial timescales to climatic variation. Much of Scotland's peatland area, however, has been damaged to such a degree that this self-regulation no longer functions. In net terms, the degraded peatlands lose so much carbon (estimated between 8.8-9.7 Mt CO2 y^{-1}) that they completely offset the entire forest carbon sink in Scotland as well as having lost other vital ecosystem functions such as water filtration/storage. The realisation of the scale of this issue has led to the inclusion of peatland restoration targets in the Land Use Strategy. The Scottish Government's Climate Change Plan has a 250,000-ha restoration target by 2030. As the majority (>70%) of Scotland's approximately 2.4 million ha of peat is degraded, targeting the most cost-effective sites for restoration is necessary. This project will provide spatially explicit

information about where and when restoration should be considered, and how much benefit could be achieved at each restoration site and across all of Scotland to achieve net zero by 2045. Wider than just restoration issues, we also still do not have clear estimates of how degraded our peatlands are, or how to cost-effectively monitor the overall health or condition of our 2.4 million hectares of peatland. Addressing 5 specific research questions with peatland components in the Soils topic, through 5 interlocking WPs and in collaboration with key stakeholders, we will provide underpinning and integrated research for: (i) emission factor updates and activity data for the UK Greenhouse Inventory (WP1), (ii) the development of a specific Peatland Monitoring Framework and road map to wider Soil Monitoring (WP1&2), (iii) improved Natural Capital accounting across a range of ecosystem services (WP3), (iv) further development of the Peatland Code to incentivise private investment into restoration efforts (WP4), and (v) improved carbon auditing tools that include climate risk assessments.

Topic Line: D4 Biodiversity

Topic lead: Ruth Mitchell, ruth.mitchell@hutton.ac.uk

Summary: Biodiversity is the variety of life and is important in its own right, as well as providing society with essential services, e.g., food, water quality, carbon capture, and many other important societal benefits. However, biodiversity is currently in crisis with species abundance and diversity declining at unprecedented rates. It is therefore vitally important that we understand what biodiversity is present in Scotland, the changes it is undergoing and what is driving these changes, develop tools to record and monitor it, and identify what can be done to further protect biodiversity and what impact these changes will have on ecosystems and on people. To do this we need to improve our ecological understanding and our socio-ecological understanding of how humans value biodiversity, and how this impacts on decisions of how biodiversity is managed and governed. Summary of research and links to key policies/reports: NatureScot identified 22 research questions (RQs) to be addressed in this Topic driven by a range of key policies (Fig. 1). All these RQs are addressed in the research proposed, which has grouped the RQs into eight related projects in order to develop substantial pieces of work (Fig. 1).

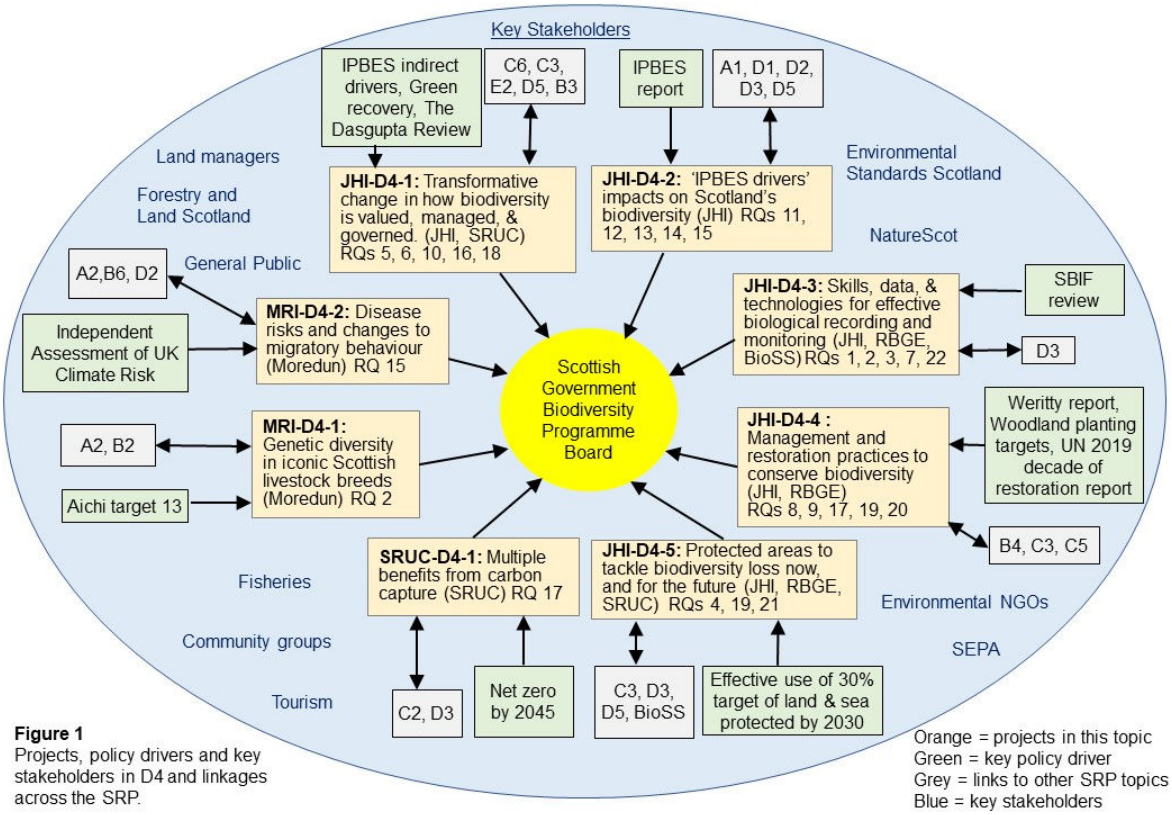

Figure 1
Projects, policy drivers and key stakeholders in D4 and linkages across the SRP.

Project JHI-D4-2 seeks to better understand how the direct drivers of biodiversity loss identified by The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) impact on biodiversity, and project MRI-D4-2 focusses on microbial risks related to climate-driven changes in biodiversity. Project JHI-D44 seeks to better understand how moorland and woodland management may benefit biodiversity, while project SRUC-D4-1 assesses how management can benefit biodiversity and help achieve Scotland's target of net-zero carbon emissions by 2045. Work in JHI-D4-5 looks at how our protected areas can conserve biodiversity both now and under future climates. All this work is set within the context of a Green Recovery post Covid-19 and how we transform human behaviour and expectations from the natural environment, project JHI-D4-1. Finally, taking forward

recommendations identified by the Scottish Biodiversity Information Forum (SBIF) review and Achi target 13 we need to know what biodiversity we have, including genetic diversity, project MRI-D4-1, and how to record and hold that data, given the new and novel data capture methods that currently exist, project JHI-D4-3.

JHI-D4-1 People and Nature
PI: Kate Irvine, kate.irvine@hutton.ac.uk

The Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) [1] concluded that addressing biodiversity loss requires urgent transformative change in the way our economy and governance systems operate. This was recently echoed by the Edinburgh Declaration calling on parties of the Convention on Biological Diversity to 'take strong and bold actions to bring about transformative change... in order to halt biodiversity loss'. This is fundamental if we are to address the limitations of finite growth and move towards values, structures and institutions that promote a "good life" with a focus on ecological and social wellbeing. In the project we will deal with the indirect drivers of biodiversity loss - social values and behaviours - focusing on key leverage points identified by the IPBES report; i) Embrace diverse visions of a good life, ii) Unleash values and action, iii) Reduce inequalities, iv) Practice justice and inclusion in conservation, v) Internalize externalities and tele-couplings and vi) Promote education and knowledge generation and sharing. The bringing together of diverse knowledge creation systems and greater democracy has long been recognised within sustainability concepts [2]. These concepts recognise the importance of public and civil society knowledge creation alongside academic, economic, and political knowledge systems This is supported by evidence that increasingly suggests that conservation and biodiversity measures succeed best when a plurality of voices and diverse forms of knowledge can be engaged in the co-development of management solutions [3,4]. Further developments propose that sustainability will be best achieved when new knowledge and know-how is in balance with nature. This supports the need to transform how nature and the economy are currently framed and measured [5,6] and thus lead to more just and sustainable ways of living with our natural world. The main aim for the project is to identify and evaluate interventions, research approaches and processes which can facilitate the transformative change of how biodiversity in Scotland is framed, valued, managed, and governed, and how the benefits associated with Scotland's biodiversity can be harnessed and more equitably distributed by engaging with a plurality of voices and values. We will do this by conducting interdisciplinary and transdisciplinary biodiversity research with stakeholders; from land managers, community residents and policy makers, as well as evaluating novel mechanisms and interventions. Our research will be co-constructed to embrace a plurality of actors and knowledges, specifically identifying and facilitating the inclusion of voices often marginalised in biodiversity research and management.

JHI-D4-2 Identifying the causes of biodiversity change with specific references to the IPBES drivers
PI: Robin Pakeman, robin.pakeman@hutton.ac.uk

Many species, habitats and ecosystems are in decline. This decline is the result of human activity and the overuse of natural capital. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) recognises this as the main driver of the loss of biodiversity and decline in ecosystem service supply but categorises it as an indirect driver of biodiversity loss as it acts through five direct drivers of loss: land use change, climate change, pollution, invasive species and direct exploitation. These drivers have been shown to have wide-scale impact on biodiversity and the

research in this project will focus on the first four of these and their impacts on Scottish biodiversity. Direct exploitation is restricted to a few species and is not the focus of this work. The aim of this project is to identify how the "IPBES drivers" affect key parts of Scotland's biodiversity. The research focuses at the ecosystem level, in terms of understanding how climate change is affecting system resilience and how systems can be managed to improve resilience, at the habitat level, in terms of understanding how climate change or invasive species can affect important habitats, and at the species level, in terms of understanding which drivers are resulting in changes in species' abundances. Work elsewhere in the topic (JHI-D4-3) takes a national level approach to understand how these drivers correlate to biodiversity change at a national level, but the work described will elucidate more detailed understanding of driver impacts and, especially, the interaction between drivers. Our research on the identification of which drivers are affecting different parts of Scotland's biodiversity will enable more precise identification of policies to reduce harm, mitigate impacts or enhance resilience. The research focusses on specifically addressing management needs at the large-scale, identifying the drivers of the widespread insect decline, assessing how global change is affecting iconic Scottish species and how invasive species could radically alter Scottish ecosystems.

JHI-D4-3 Scotland's biodiversity: People, Data and Monitoring
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Worldwide biodiversity is in decline and, as it supplies key ecosystem services, it needs to be conserved and restored to ensure that the world's natural capital is still available for human use in the long term as well as for its own intrinsic value. The UK and Scotland have committed to global agreements such as the Convention on Biological Diversity in response to this. Whilst Scotland is no longer part of the European Union, the legal frameworks surrounding the Birds Directive and Habitats Directive have been incorporated into law and stand alongside other legislation. These commitments have been brought together and operationalised as the Scottish Biodiversity Strategy. However, in order to deliver on the targets of the Scottish Biodiversity Strategy, there is a necessity to have accurate and current information on the status and trends of species in Scotland. This encompasses the basic question of what biodiversity Scotland has and which components Scotland has particular global responsibility for. It also requires an understanding of what is driving changes in biodiversity so that policies can be targeted appropriately to reduce pressures. This understanding has to apply at a range of scales; a national focus is necessary to get an overall picture of trends, but more detailed work is also necessary to understand the specific issues associated with the conservation of particular habitats and species. Our aim for this project is to help protect Scotland's share of global biodiversity by optimising people's skills, data, and technologies to ensure the effective recording and monitoring techniques and data flows. Three interconnected Work Packages (WP) address five Research Questions (RQs): 1, 2, 3, 7 and 22 under Topic D4 Biodiversity.

JHI-D4-4 Habitat management and restoration
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Land use change is a major driver of the biodiversity crisis. How we manage land will influence the rate biodiversity recovers or is lost. This project addresses 3 over-arching questions to answer RQs 8, 9, 17 & 20 within D4. This is urgently needed to inform current and new government policies:
1. How can public and private sector investors, at low risk, restore woodland habitats for the most multiple benefits to society in addition to increasing natural carbon capture and biodiversity, and what

land is available for this? Net Zero Emissions targets increasingly being adopted by private and public sector organisations are driving demand for investment in woodland habitat restoration to generate carbon sequestration benefits that can offset an organisations' residual emissions. Given that achieving positive net carbon sequestration rates from tree planting on Scottish soils is neither simple nor risk free, greater understanding of how to deliver high-quality woodland habitat restoration which can also deliver multiple benefits for society - and at low risk - is essential. This need is reinforced by climate change impacts which will affect tree species distributions and their net carbon sequestration rate. Derived benefits will also depend on the decision making of different woodland restoration investors, which will be based on different goals (e.g., biodiversity vs. carbon offsetting) and levels of uncertainty, and the developing regulatory context. Therefore, the risks of unintended consequences, in terms of restoration failure and reduced derived benefits, need to be assessed with respect to such decision making as well as long-term climate change. These factors are likely to determine the quality and outcome of the restoration projects and consequently the availability of land for high quality habitat restoration in the medium to long-term.

2. What is the impact of Muirburn on nature and how does this impact compare to wildfires and mechanical removal of vegetation? Muirburn (prescribed burning) is a common management practice across much of the heather dominated moorlands in Scotland where grouse shooting is a major land use. The effects of muirburn on biodiversity and how muirburn interreacts with wildfire are questions of high policy and applied relance yet the science remains unclear and contested. A greater understanding of the distribution and intensity of muirburn effects on biodiversity and interactions with wildfire incidence is needed to inform management and policy. There is an agreed need to better understand the impact of muirburn on different aspects of biodiversity, and a clear call to understand the effects and trade-offs of alternatives to muirburn such mechanical removal (cutting/mowing) in relation to biodiversity and fire risk.

3. How do our ancient woodlands function and how successful is woodland restoration? The recent Forest Research GB Science and Innovation Strategy set goals and strategies for the future sustainable management of 'trees, forests and woodlands' to 'meet the challenges of providing a healthy future for the economy, society and the environment'. Sustainable management has been used in the European sense of 'stewardship' which enhances the vitality of forests and maintains the numerous ecosystem services which they provide now and in the future. The biodiversity and climate crises are themes running throughout the strategy, and several of the recognised Areas of Research Interest highlight the need for increased understanding of the roles of woodlands in supporting biodiversity and carbon (C) sequestration, particularly soil C. We will follow the recommendations from the SIS with a focus on Scottish Atlantic Oakwoods, which are internationally important habitats supporting complex assemblages of biodiversity. 3 Although Oakwoods are renowned for their high diversity of lower plants and lichens, our knowledge of the functioning of these ecosystems is limited. In particular, the taxonomic and functional diversity of the soil biota are virtually unknown. This knowledge gap raises important questions about our ability to develop management strategies for maintaining and enhancing existing biodiversity, for restoring ecosystem services of degraded woodlands, and importantly how we monitor success of restoration management if we do not have the baseline data for healthy, functioning woodlands?

JHI-D4-5 Protected areas to tackle biodiversity loss now, and for the future.

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The choice of which areas of land and sea to prioritise for conservation protection is complex. Setting targets for the coverage of protected areas is only useful if we know what type of protection should

be implemented and where, and whether this protection is successful. We must select sites which will maximise effectiveness of biodiversity protection and deliver the most benefits. Understanding the factors which influence the distribution of species across a landscape is an essential step to identify optimal locations for protection. Protected Areas (PAs) need to be positioned within the wider landscape/seascape to provide maximum connectivity to enable species movement and to provide a buffer from the drivers of biodiversity loss occurring outside PAs. In addition, the PAs network needs to be flexible with respect to climate change. Specifically, it needs to cope with changes in species distributions due to a changing climate (which may change how the 'condition' of the protected area is perceived) while at the same time providing refugia for species with limited dispersal abilities.

MRI-D4-1: Assessing the impact of changing migratory patterns and population size of greylag geese on livestock and public health

PI: Eleanor Watson, eleanor.watson@moredun.ac.uk

The establishment of invasive non-native species (INNS) can introduce microbial risks, which can potentially impact on natural and farmed ecosystems as well as public health. This project aims to characterise microbial risks and pathogen circulation within an ecosystem from an exemplar migratory wild bird population which has recently become resident and expanded rapidly, namely Icelandic greylag geese on the Orkney Isles. Furthermore, the expansion of this population is postulated to be driven at least partly by changes in climate and represents a general shift in migratory patterns in other bird populations across Scotland. This research project will focus on important pathogens, which impact on animal and public health and the spread of antimicrobial resistance genes (ARGs). A further aim is to optimise methods and workflows for detection of microbial species and genes within wildlife samples, particularly remote field samples where access to a cold chain is limited, to ensure robust associative analysis between samples. Key drivers for this research include:

- A need for improved understanding of pathogen threats from newly established wildlife populations,
- Limited knowledge regarding spread of ARGs between wildlife populations, particularly relating to migratory species,
- Limited understanding of climate change-driven microbial threats within our natural and farmed ecosystems,
- A lack of case studies and roadmaps for engaging with stakeholder groups with different interests to address such issues.

This project will offer an opportunity to highlight how One Health microbial threats impact on a wide range of stakeholders (public health, conservation and farming) and the steps that must be taken to ensure that the interests of these groups are fairly represented during the course of a related study. This project will also enable the refinement of methodological pipelines to further investigate wildlife-livestock interactions and ecosystem impacts of newly established migrant populations.

SRUC-D4-1 Seeking multiple benefits from natural carbon stores in the uplands

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This work will particularly seek to address how we can maximise biodiversity benefits from natural carbon capture in upland areas while also obtaining wider societal benefits through flood mitigation. Mitigating the impacts of climate change and reversing biodiversity declines, whilst maintaining food production, is a key challenge to Scotland's agricultural industry. With nearly 60% of Scottish

agricultural land managed as rough grazing, these low-input, low-output upland livestock systems have the potential to play a crucial role in helping Scotland meet these challenges. There is however a need to identify how habitat type and management influence the multiple environmental and societal benefits that such systems provide, and to understand the interconnections among these benefits. SRUC's Kirkton and Auchtertyre 2,200 ha research and demonstration farms will provide an experimental platform to explore the environmental and wider societal benefits that upland habitats can provide, with a particular focus on carbon storage, flood mitigation and biodiversity conservation. Situated in the Loch Lomond & The Trossachs National Park, these are managed as a working extensive livestock farm, typical of the rough grazing systems that account for approximately 60% of Scotland's agricultural land. Specifically, this project aims to: 1. Explore the relationship between carbon storage, biodiversity conservation and flood mitigation to detect synergies and trade-offs and identify land management practices that optimise the benefits derived. 2. Generate evidence to inform land-use management practices in the Scottish uplands that contribute to tackling the twin challenges of biodiversity loss and the climate emergency. A range of environmental sensors of relevance to some of the data collection needs are already in place at SRUC Kirkton & Auchtertyre.

Topic Line: D5: Natural Capital

Topic Lead: Kerry Waylen, Kerry.waylen@hutton.ac.uk

Plain English Summary: Scotland is pioneering use of the Natural Capital (NC) concept as a means to mainstream sustainability in decision-making, e.g., explicitly citing it in the Scottish Government's statement on post-COVID economic recovery. However, as noted in the ITGF SRP 2022-7, tackling knowledge gaps is needed to realise the full potential of the concept. The research in this Topic Line combines multiple disciplinary perspectives to improve understanding of Scotland's NC and how climate changes create risks for Scotland's natural assets; improves data and valuation methods for NC; and provides insights about how to productively and constructively use NC concepts and data to embed sustainability in policy and private sector decisions. There are six projects designed to address all five RQs of Topic Line D5: see Figure 1. These build on the prior expertise of collaborating researchers at James Hutton Institute and SRUC. The proposals were also informed by consultations with key policy and agency stakeholders already working on NC, including Scottish Government teams working on Natural Capital and Regional Land Use Pilots, NatureScot and SEPA. The outputs of this work will be of direct use for improving accounting practices and accounts already in use by Scotland, notably the Natural Capital Asset Index (NCAI) and the ONS Natural Capital Accounts, so helping embed natural capital in support of the National Performance Framework (NPF). Improved understanding and consideration of natural capital should also support policies such as Scottish Biodiversity Strategy, Scottish Forestry Strategy, Scotland's Economic Strategy, National Planning Framework 4. The outputs will also be useful for actors, processes and sectors that do not already use or solely emphasise NC: by providing accessible maps and frameworks e.g. to aid planning for Scotland to achieve its Climate Change targets, providing guidance about constructive approaches and data to embed NC in processes, from national-level policies to Nature-based Solutions (NbS); and by identifying appropriate mechanisms to unlock financing and involvement from the private sector. We will safeguard the relevance of the work by frequent stakeholder liaison and knowledge exchange in Scotland, plus dedicated work to synthesise implications for accounting practices (SRUC-D5-2) and transdisciplinary work on NC knowledge use linked with cutting-edge practices in Scotland (JHI-D5-3). We will also interact with a wider stakeholder set through our Ecosystem & Land use Stakeholder Engagement Group and Ecosystem & Land Use Policy Engagement Group. These groups were formed in the previous SRP: at the request of stakeholders, we propose to continue these.

JHI-D5-1 Bringing in participatory approaches to widen the scope of Natural Capital Valuation

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Findings from the research conducted under the Scottish Government (RESAS) Strategic Research Programmes (SRP) 2011-2016 and 2016-2021, and overview of relevant literature sources (including policy documents) show the importance of advancing research methods and making them more relevant (e.g., case- and context-specific), accessible and effective in offering meaningful information to different audiences, such as through guiding public understanding of the consequences of NC/ES changes, and aiding decision-making. Decision support systems for participatory planning and knowledge transfer in ways that are understandable to different types of end-users need to be co-constructed involving relevant stakeholders. Innovative social science approaches are needed to help realise the potential of policy analysis and sustainable ecosystem management. The proposed research aims to address this. It is designed to widen the scope of NC and ES valuation by answering the following Research Questions (RQ2 of D5): i) What are the gaps in current NC valuation? ii) Which

of the dimensions of value would it be helpful to consider? iii) How could these values be captured/measured/valued to support more robust and end-user friendly participatory planning, knowledge transfer and decision making systems? Innovative approaches to be developed will enable a holistic understanding of ecosystem assets as complex systems and advance the knowledge of synergy effects and trade-offs between their various components. The advancement of methodology for NC valuation by bringing in participatory approaches and elaborating a mixed methods' toolset, based on the integration of techniques (e.g., participatory, analytical, visualization, digital), will enable capturing broader dimensions of value and performing concurrent assessment of a bundle of ES offered by Scottish natural assets at various scales of observation.

JHI-D5-2 Climate change impacts on Natural Capital
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The objective is to integrate existing knowledge, data, analytical and modelling capabilities with new methodological developments, data sources and computing capabilities to assess risks to and opportunities for Scotland's Natural Capital assets due to climate change. We will integrate biophysical modelling, new approaches to NC risk assessment with data on biodiversity (D4), water (D2, esp. JHI-2-1) and soils (D3) and social sciences assessments of risk perception, to assess the impacts of CC on NC and how this affects its supply of ES. The integrated data-modelling analysis structures will be flexible enabling consideration of all NC asset types. However, given the number and diversity of assets, the focus will be to prioritise those that are most vulnerable and/or have greater importance for livelihoods and delivery of ES (soils, water, peatlands, woodlands, arable). The project will link to research on Land Use (C3) and Large-Scale Modelling (C5) and the work undertaken to assess CC impacts on agriculture, along with Water (D2) drought risk and hydrological assessments. It will consider climate driven threats to NC, including extremes and increasing seasonal and inter-annual variability. Emphasis will be given to water and soils because of their essential roles in maintaining biological processes and ecosystem functions. There is also a clear relationship between water security and the increased risks of fire. Climate projections indicate increased likelihood of shifting spatial and temporal patterns of precipitation and more droughts, increasing the risks of ecosystems becoming drier and more susceptible to fire. These conditions separately and together will lead to a loss of ecosystem function, particularly concerning where an asset becomes a source of carbon rather than a sink, either from fire or biological release. This relates to issues of grouse moor management (D4 RQ9), other risks from flooding (D2) and erosion (D3, C5 WP2) and relationships with land tenure (E3) and land use change (C3). We will also use new Earth Observation and other remote sensed data and identify limitations of impacts assessment due to data gaps (e.g., in biodiversity records). Issues of uncertainty will be addressed in collaboration with BioSS (UNC-7).

JHI-D5-3 Galvanising Change via Natural Capital
PI: Kerry Waylen, Kerry.waylen@hutton.ac.uk

'Natural capital' refers to a concept or framing, i.e., a focus on the stocks and flows of services that nature provides to society, and also specific datasets, i.e., databases, models, maps, values. The last decade has seen growing focus on using this concept and improving the data, as it is hoped that doing so may assist in greening decision-making, in a variety sectors and venues, ranging from policy through financial investors, to farm level. Scotland is a pioneer in adoption of natural capital: a Scottish Government Natural Capital Policy team is working to embed Natural Capital into policy processes,

framed around the Four Capitals approach; whilst multiple initiatives within NatureScot's Natural Capital Pilot Programme (NCAPP) explore how to work with it with different groups and levels. Other notable initiatives directly relevant to natural capital include SEPA's One Planet Choices initiative, which uses integrated capitals assessments. The general goal of all such initiatives – and that this project seeks to both learn from and inform – is to routinely embed consideration of natural capital across sectors, policies and levels. However, natural capital is not a single, simple nor easy-actionable piece of information. It has multiple and contingent versions and interpretations; will not be the only form of knowledge used in interpretation; and furthermore, interacts with interests and institutional structures when influencing decision-making processes. These interacting factors often tend to inhibit change. Achieving transformation in support of sustainability is thus an urgent challenge but also notoriously difficult. Identifying levers of change is vital to ensure future research and practice efforts are most appropriately and effectively focused. There is a need to critically appraise how and when natural capital can support change for sustainability. Our aim is to produce constructive insights about the most productive venues (territorially and sectorally) and approaches (how and with/for whom) for using natural capital concepts and data to galvanise change for sustainability.

SRUC-D5-1 Understanding the value of Scotland's agricultural soil natural capital
PI: Alistair McVittie, alistair.mcvittie@sruc.ac.uk

Soils are the main underpinning natural capital asset of Scotland's agricultural sector. They are not currently considered as a distinct asset in metrics such as the ONS Natural Capital Accounts or the Natural Capital Asset Index. A better understanding of the value provided by soils will contribute to monitoring the sustainability of Scotland's natural capital as a National Performance Indicator, indicate where policy intervention is required, and support land management decisions. The proposed research will take a bottom-up approach to determine the main ecosystem services provided by Scotland's agricultural soils. This will evaluate the appropriate levels at which soil should be valued and monitored, i.e., as a distinct asset or part of wider system. We will then identify appropriate indicators and valuation approaches.

SRUC-D5-2 Synthesis of natural capital and valuation outcomes
PI: Alistair McVittie, alistair.mcvittie@sruc.ac.uk

Natural capital related research is proposed across multiple topics in the Strategic Research Programme. There is also ongoing initiatives and research, including by agencies and other stakeholder groups, both in Scotland and elsewhere in the UK and Europe that may be of direct relevance. The objective of this project is to collate and synthesise this research from a natural capital perspective to inform a range of end-uses and end-users. This will include evaluating the potential to use emerging metrics and indicators for a range of applications, for example:

- Natural Capital Accounting
- Natural Capital Asset Index
- Land use decision making including Regional Land Use Partnerships
- Land manager decision making and monitoring including potential use in
- future support schemes
- Nature capital investment mechanisms

SRUC-D5-3 Modelling the socio-economic, greenhouse gas and natural capital impacts of land use policy and opportunities.

PI: Alistair McVittie, alistair.mcvittie@sruc.ac.uk

Land use is a complex socio-ecological system producing benefits for land managers alongside multiple benefits for society. Land use modelling allows us to explore baselines and how changing policy and management objectives influence land use patterns and their private and societal impacts. Work package 1 will review policies influencing land use decisions using Slee et al's (2010) framework to assess policy complementarities and conflicts. This will provide an overview of the policy landscape building on Scotland's Third Land Use Strategy. This aims to support an ethos that moves "away from a sector-by-sector approach towards an overarching holistic picture of what sustainable land use in Scotland could look like", avoiding mixed messages and incentives for land managers that can be counter-productive to delivering objectives. The second work package will model combined LULUCF and Agriculture greenhouse gas emissions at a holding/business level. This approach addresses the explicit requirement of Scotland's climate change targets, that Scottish Ministers' take account of a whole farm approach to emissions accounting. It endeavours to disaggregate research undertaken for the National Atmospheric Emissions Inventory that established a national framework for sectoral emissions. Work packages 3 and 4 will apply two modelling approaches to analyse land use policy and management scenarios, how they will impact on economic outcomes in the farming sector, and wider natural capital and ecosystem services. Understanding how policy changes impact on land-based business is key to understanding the likelihood and distribution of management changes (B3) and how incentives can be targeted. The two approaches are complimentary in approaching land use scenario analysis from different perspectives. Microsimulation offers a bottom-up approach rooted in the economics of real farm businesses, extrapolated over wider geographies. Spatial Bayesian Belief Networks combine socio-economic and biophysical data to assess multiple benefits. Both allow the resulting patterns of impacts to be evaluated spatially.