

Institution: University of Manchester
Unit of Assessment: 7 (Earth Systems and Environmental Sciences)
<p>1. Unit context and structure, research and impact strategy</p> <p>1 a) Research structure and strategy:</p> <p>Based in the Department (formerly School) of Earth and Environmental Sciences (DEES), University of Manchester (UoM) the Unit research combines the natural sciences to create novel discovery-led understanding of Earth systems, and deliver solutions to some of society's most pressing challenges, such as climate change, biodiversity loss, and resource sustainability. The world-leading excellence of our 73 researchers (70.78 FTE) is evidenced by 1,889 papers in the REF period (238 in Nature Index Journals) with an average 17.9 citations (18% in top 10% in the field), 3 Clarivate Highly Cited Researchers, 259 graduating doctoral students, GBP70,600,000 of competitively acquired research funding, and global collaborations spanning 113 countries. We've led major advances since REF2014 across atmospheric processes, sub-surface energy geoscience, planetary science, ecology and evolution, mineralogical and biogeochemical controls in the Earth's critical zone, and the biochemistry of extinct species.</p> <p>For example, we have:</p> <ul style="list-style-type: none"> • demonstrated that the silicate Earth is not more depleted in halogens than in other elements of similar volatility by determination of their solar system abundances in chondritic samples; • provided a research platform for Sellafield Ltd. to enhance treatment of radioactive effluents, reducing discharges of alpha-emitting radionuclides to the environment saving GBP25,000,000 in treatment costs; • made novel measurements of black carbon to explain quantitatively how absorption is enhanced by addition of condensing species, and assessed how this varies globally; • explained the long-standing puzzle of how low viscosity basaltic magma fragmentation produces highly hazardous explosive eruptions compared with normal basaltic activity; • delivered improved global hydrocarbon exploration and development success for our major industrial partners in petroleum geoscience and carbon capture and storage, and demonstrated how deep-water sedimentary processes govern global microplastics distribution; • revealed that climate extremes have significant and persistent impacts on soil bacterial networks, which are less stable than previously thought, with implications for ecosystem functioning and responses to future disturbances, and • revealed the nature and extent of biotic disruptions taking place following the Chicxulub impact, when the meteorite that caused the most recent mass extinction hit Earth. <p>Since REF2014, research within the Unit has evolved and grown, increasing staff numbers by 54%, PhD students by 63% and UKRI funding by 62%. The Unit has developed strategically, consolidating areas of strength with key appointments and proactive succession planning. Our discipline base was broadened through incorporation of the Ecology and Evolution research group in 2016, with 14 academic staff, formerly submitted within UoA5, strengthening synergies between biological sciences and our existing strengths. This has enabled novel multidisciplinary collaborations across the Unit, resulting to-date in 39 co-authored outputs. Interdisciplinarity was further enhanced in 2019 in a reorganisation that saw DEES join a new School of Natural Sciences (SNS), with Chemistry, Physics and Astronomy, Maths and Materials Science, facilitating multidisciplinary across the natural sciences, whilst maintaining collaborations with the School of Engineering (SE) which sits alongside SNS within the Faculty of Science and Engineering (FSE).</p> <p><u>Review of REF2014 Objectives</u></p> <p>At REF2014, the Unit's research had consolidated into 3 multidisciplinary research groups: Planetary and Earth Science, Molecular Environmental Science, and Atmospheric Science which</p>

we envisaged, alongside key new appointments, would enable expansion of RCUK, overseas and industry research funding. We anticipated, and have delivered, growth in nuclear waste disposal, quantification of recent climate change, genomics for geomicrobiology applications, analysis of samples from extra-terrestrial exploratory missions, stratigraphic prediction, water pollution, large-scale atmospheric modelling, aerosol-cloud-dynamics-radiation interactions and remote sensing. Since 2016, our broadened discipline base enabled greater ambition, delivering research in 7 restructured multidisciplinary groups: Isotope Geochemistry and Planetary Science; Molecular Environmental Science; Atmospheric Science; Geosciences; Basins, Stratigraphy & Sedimentary Processes; Ecology & Evolution; and Ancient Life, whilst introducing cross-cutting challenge themes in Earth & Planetary Science, Environment & Society, and Life on Earth. This facilitates the strategic alignment with UKRI and industry, and with societal needs, that were embedded in our REF2014 plans. This organisational structure (**Figure 1**) has enabled us to surpass our objectives.

Our themes align with societal grand challenges, reflected in our ability to attract considerable Official Development Assistance (ODA) funding (>GBP5,000,000). We have realised our envisaged growth in UKRI funding: awards increased from GBP5,800,000 in 2014 to GBP9,400,000 in 2020 with income/FTE increasing from GBP188,000/FTE 2013-14 to GBP232,000/FTE in 2018-19. In 2019-20 UoM received the largest share of NERC awards (14) and income (GBP8,600,000) of all UK institutions. At REF 2014, we had used the “clear alignment of our research activities with societal and commercial challenges”, partnering with teams in China, Brazil, USA and India to establish international research leadership. Consequent substantial expansion of our ODA portfolio during REF2021 with continued work in China and India, and expanded partnerships in Myanmar, Bangladesh, Vietnam and Indonesia has consolidated this leadership.

We have significantly diversified and grown beyond our 2014 plans, through reorganisation, replacement of retired staff and appointment of Early Career Researchers, targeting growth areas and supported by both internal and externally funded Fellowships. Strategic inclusion of the Ecology and Evolution group has added a substantial BBSRC portfolio, complementing notable NERC success and sustained STFC support for planetary science. Rapid growth and strengthening of volcanology and petrology was enabled by key hires and Fellowship success.

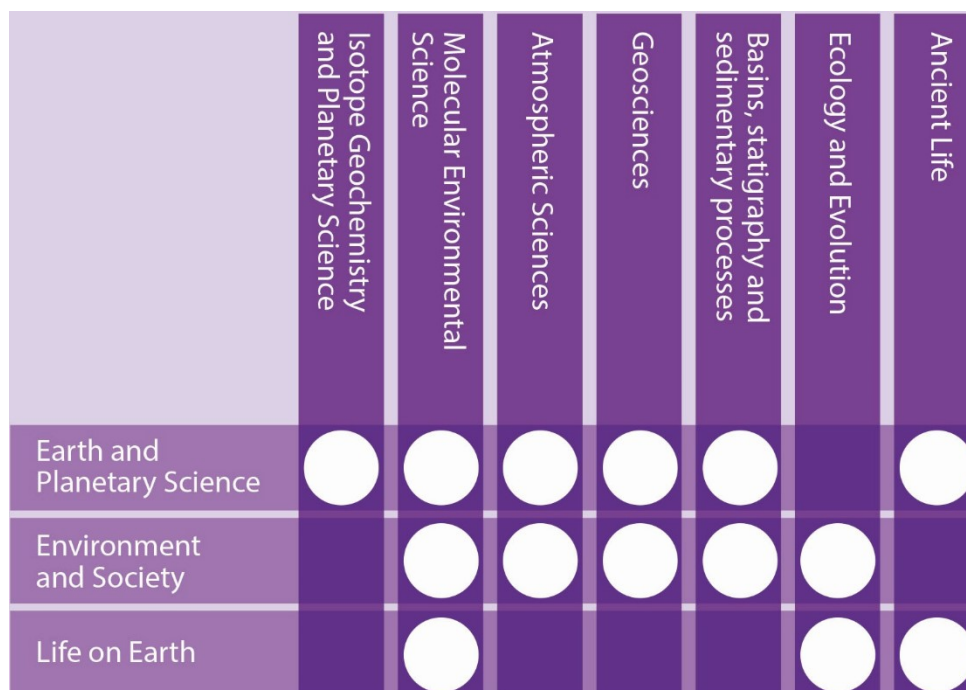


Figure 1: Relationship between our research groups and themes, circles indicating research group activity alignment with the themes.

Research Structure and Achievements

We are a world-leading centre for research into the physical, chemical and biological processes underpinning Earth and Environmental sciences, through measurement, theory, and application using combinations of cutting-edge laboratory, field and modelling techniques.

Challenge Themes

Our three challenge themes coalesce staff from multiple research groups (**Figure 1**) to influence and respond to major scientific and societal challenges. Each has a champion, who coordinates direction, and flexible membership, providing agility to respond to opportunity and evolving interests (examples in Section 3) and a platform to frame research in emerging areas.

Earth & Planetary Science: aims to understand the origins and evolution of the Earth, its atmosphere, oceans and life, and other planets and minor bodies in the Solar System. We use multidisciplinary approaches to study processes that formed the Earth and other planets, investigating fundamental questions, providing a framework to address future challenges for humanity.

Environment & Society: addresses challenges that societies are facing now and in the future. Collaborating with academic, industry, government and NGO partners, we investigate processes underpinning sustainable use of the Earth's resources, and examine the resilience of our planet and society in the face of rapid change. This research leads to both academic advances and substantial positive impact on people's lives.

Life on Earth: seeks to quantitatively understand the origins and evolution of life on Earth and its interactions in contemporary ecosystems. We study all kingdoms of life, examining how they evolved, and how they survive and interact with each other and their environment. We work at molecular to planetary scales, across diverse habitats, and tackle both applied and fundamental questions.

Research Groups

Our seven multidisciplinary research groups underpin our challenge themes (**Figure 1**), each comprising a critical-mass of REF-returned staff with complementary expertise and shared interests, infrastructure and tools.

Isotope Geochemistry & Planetary Science (IGP, 8 staff) studies the earth and solar system through mission involvement, sample analysis and remote sensing using the latest techniques of isotopic and elemental analysis. Their interests range from the prehistory of the Solar System through the formation and evolution of minor bodies and terrestrial planets.

Molecular Environmental Science (MES, 12 staff) has global research programmes on arsenic groundwater poisoning, improved water quality in distribution networks, nuclear environmental science and conversion of waste metals into high-value nanomaterials for use in industrial catalysis, healthcare and remediation.

Atmospheric Science (AS, 12 staff) conducts field, remote-sensing, laboratory and modelling studies of atmospheric processes including cloud microphysics, air pollution, bioaerosols, dynamic meteorology, surface-atmosphere interactions, greenhouse gas fluxes and ultra-violet radiation. The group hosts 9 NERC National Centre for Atmospheric Science (NCAS) staff, enhancing world-leading capabilities in remote sensing, atmospheric aerosol and cloud physics.

Geosciences (GEO, 12 staff) volcanology, petrology and rock mechanics research includes work on high-pressure high-temperature kinetics of crystal growth, satellite remote sensing of volcanic degassing, impact of dust on aircraft engines, investigation of volatiles and mantle dynamics, grain-boundary sliding and the viscosity of the mantle and shale properties.

Basins, stratigraphy & sedimentary processes (BSSP, 8 staff) has research foci including stratigraphic prediction of siliciclastic and carbonate depositional and metasomatic processes, palaeoenvironmental reconstruction and multi-scale imaging of pore networks in sedimentary rocks. We apply seismic geophysics to inform understanding of subsurface fluid flow, essential for carbon sequestration studies.

Ecology & Evolution (EE, 12 staff) explores responses of species and ecosystems to environmental change that is pivotal for biodiversity conservation and sustainable ecosystem management. The group works on novel mechanisms underpinning plant stress tolerance, adaptation of microalgae to environmental pollution, environmental impacts on wildlife populations, microbial evolution, and relationships between soil biodiversity and ecosystem functioning under global change.

Ancient Life (AL, 7 staff) examines soft-tissue preservation and the survival of biomolecules, invertebrate morphology and evolution, evolutionary linkages of extinct vertebrates, evolution of the human hand and new methodology for identifying bone tissues, including novel spectroscopic imaging and extracting proteomics data from difficult materials.

Overarching objectives for the next 5 years are to:

- develop, nurture, support and lead cross-university multidisciplinary collaborations to produce solutions to global challenges (see Sections 1b and 1c)
- provide development, support and inspiration for our world-class researchers to enable our staff to maximise their capability, ambition, drive and vision to transform our understanding of the solar system and the lithosphere, biosphere and atmosphere of the Earth (see Section 2)
- contribute to the continuous improvement and optimal use of our departmental, university, national and international research infrastructure (see Section 3).

As general measures of success we expect our research income per FTE and proportion of publications in the top 1% and top 10% in their field, to be comparable with those of top-five UK Units.

We are well-placed to respond to societal challenges in the forthcoming Covid recovery. We align our challenge-theme activities with the UK Government Research and Development Roadmap, 2020 and the Delivery Plans of UKRI and its Councils (our major funders), and will continue to take advantage of University Institutes and structures (see Section 1b below and the institutional statement (IS) 2.iii). UoM recently launched its Sustainable Futures Platform to stimulate cross-University collaborations, at the core of our Unit activities. Our research has been strengthened by the Feb 2021 appointment of Chris **Jackson** as Chair of Sustainable Geoscience, and we envisage expansion of our nuclear waste remediation work, research on sustainable soils and biodiversity, and in environmental pollution during the low carbon transition, with emphasis on health impacts. Digital environmental research, including into Future Cities, will expand, aligned with the newly awarded NERC Digital Solutions programme and the UoM Digital Futures platform.

1 b) Interdisciplinary research:

Interdisciplinary research lies at the heart of the Unit. We have made use of our new thematic structure, staff growth, the Faculty restructure and pan-University research institutes to transform how we manage, nurture and promote our multidisciplinary research portfolio.

The creation of SNS and SE has enhanced interactions and enabled greater coherence of strategic multidisciplinary research across **FSE**. Our staff have played a leading role in driving this agenda (**Taylor** is SNS Research Director; **Nixon** is Faculty Business Engagement Clean Futures Lead) and examples of success include: building drone capacity for environmental monitoring with the Department of Mechanical, Aerospace and Civil Engineering (MACE); leading the first UK meteorite recovery expeditions to Antarctica (2019-20) with the Department of Maths; leading the

first X-ray absorption spectroscopy analysis of plutonium at the UK's Diamond Light Source with the Department of Chemistry; and conducting 4-D X-ray microtomography experiments under magmatic conditions with Department of Materials.

Across the University, a network of institutes has been developed to drive interdisciplinary research (IS 2.2), the most important for the Unit being:

1. **Manchester Environmental Research Institute (MERI)** brings together researchers from across UoM to provide evidence and solutions for the challenges of our changing environment (led from the Unit);
2. **Dalton Nuclear Institute (DNI)** addresses major challenges associated with nuclear power, such as plant life extension, new nuclear build, decommissioning and radioactive waste management (led from the Unit);
3. **Manchester Institute of Biotechnology (MIB)** develops new biotechnologies with applications in human health, the energy economy, food security and the environment;
4. **Institute for Data Science and Artificial Intelligence (IDSAI)** acts as an access point to, and enables interactions between researchers and problem holders in, data science and artificial intelligence, part of the University's Digital Futures platform (IS 2.iv);
5. **Manchester Urban Institute (MUI)** enables urban research and stakeholder engagement, training and impact-generation with the next generation of urban activists, decision-makers and researchers.

UoM also hosts national institutes that facilitate our research including the **Henry Royce Institute (Royce)** (accelerating commercial exploitation and impact of innovations in materials) and **Tyndall Centre for Climate Change** (researching energy systems, carbon budgets and pathways, the water energy food nexus, communities, and circular economy).

Unit staff have leadership roles within our institutes (**Coe** MERI Director; **Johnson** MERI theme leader; **Livens** DNI Director; **Heath, Morris**, DNI co-directors; **Topping** IDSAI Management Board; **Buckley** MIB Group leader). Examples of Unit-led research benefiting from the leadership and capacity provided by the institutes include (see also Section 3): **MERI** led the GBP2,300,000 UKRI Clean Air Wave 1 Strategic Programme Fund (SPF) project OSCA, a 7-institute consortium, that delivered air quality data and analyses for the Programme and facilitated collaborative high-profile investigation of processes governing geographical distribution of environmental pollutants such as microplastics. **DNI and Royce** fostered major NERC, EPSRC, EU and industry-funded research programmes led from the Unit, delivering high-impact publications on the fate of radionuclides in natural and engineered environments, and multi-million pound cost-savings for decommissioning and remediation to the UK nuclear sector. **IDSAI** jointly held the UK's first summit on Environmental Intelligence with the Alan Turing Data Science Institute, enabling integration of **AS** activities in a Turing-Health-programme-funded project (GBP157,000) and a Met-Office-funded collaboration on developing a new agent-based model of exposure (GBP188,000).

Beyond the University, our national and international collaborations are driven through a combination of shared common interest and alignment with research-funder priorities and societal needs, ensuring the relevance and sustainability of our research base. We actively encourage researchers to explore all appropriate cross-sector mechanisms to enable this including: (1) engagement with and development of interdisciplinary research clusters across Universities (e.g. N8 AgriFood programme); (2) participation in funding body solutions-driven initiatives (e.g. UKRI Clean Air SPF wave 1 and 2 programme consultations); and (3) redirection of expertise and resource to urgent societal needs (e.g. Covid-related engagement with health professionals); collaborations illustrating each mechanism detailed in Section 4.

1 c) Enabling impact:

Our Unit's research is interwoven with societal and environmental challenges, providing opportunities for substantial impact. Researchers are encouraged to engage directly with industry, government and other beneficiaries, taking advantage of University, Faculty, School and Departmental structures and mechanisms to realise impacts of their research. The Faculty Business Engagement team promotes events enabling development of stakeholder connections and the Unit organises outreach activities within the research Institute interdisciplinary networks (see Sections 1b and 3). Our Faculty Impact Officers provide signposting to extensive networks and activities across Faculty and Unit impact activities are steered and encouraged by School and Department Impact Champions. Section 2 describes how staff impact activities are enabled and incentivised.

We have actively developed collaborations with stakeholders and sought impact funding, winning 11 EPSRC, 9 NERC, 2 BBSRC Impact Accelerator Awards (IAA), and attracting 5 Impact Fellowships funded through the EPSRC IAA and Dean's awards to develop impact in the REF period. This has enabled impact via: (1) embedding our researchers within stakeholder organisations, leading to impact cases in nuclear industry (**Morris**) and jet engine management (**Williams**); (2) co-design of research with stakeholders leading to impact cases in vitamin D health policy (**Webb**); and (3) research leading to impact cases with the petroleum industry (**Redfern**) and arsenic pollution mitigation (**Polya**).

BBSRC IAA awards were coordinated via UoM's allocation of Global Challenge Research Fund (GCRF) QR as part of the UK's official development assistance (ODA), supporting development of impact in areas such as groundwater remediation in SE Asia (**Richards, Polya, Lloyd, van Dongen**) and sustainable solutions to grassland degradation in China (**Bardgett**). Beyond GCRF, we have partnered with ODA collaborators worldwide (e.g. Bangladesh, China, India, Indonesia, Iraq, Kenya, Myanmar, Vietnam, Papua New Guinea, see Section 4). ODA-compliant local stakeholder engagement ensured direct benefit to host countries.

Direct engagement of our staff with partners and stakeholders implementing policy has ensured sustained responsiveness and vitality of our impact. Examples include leadership of the High-Level Skills Sub-Group of the Cross-sector Nuclear Skills Strategy Group (**Heath**); acting as Deputy Chair of the DECC/BEIS Committee on Radioactive Waste Management and Chair of the Defra CBRN recovery Scientific Advisory Group (**Livens**); and roles on the Foreign Office Scientific Advisory Committee for volcanic risk (**Burton**) and as a Trustee of the Mersey River Trust (**Boult**). Engagement with key beneficiaries including those leading to our impact case studies is detailed in Section 4b.

1 d) Open research environment:

Open Research and Open Access (OA) publishing are institutional commitments (IS 2.v), and >99% of our Unit output submission is OA compliant. Library staff streamline our OA procedures through a web-based system, pay APC fees (GBP714,470 in REF period for 376 OA papers), and manage embargoes with minimal academic effort. The UoM OpenAccess+ scheme uses a Media Relations team to produce press releases and professionally edit media articles. Our OA culture extends to PhD and MSc theses, which are OA with a 1-year maximum embargo.

The UoM New Academics Programme (NAP, Section 2) provides training in OA and the transition to an open research environment. This principle is further embedded in induction workshops delivered by the Unit Head of Research. All submitted grant proposals must have a data management plan ensuring secure storage space for datasets. Many researchers generate and use large environmental datasets and frequently use OA National and EU data archival services. The NERC Digital solutions platform (co-led by **Topping**) is working with the Sustainable Software Institute (SSI) to bridge stakeholder engagement with private and public bodies and the NERC data centres to ensure open data-compliant curation.

1 e) Research integrity:

We follow the UoM Code of Good Research Conduct (IS 2.v), aligning with the UUK Concordat to Support Research Integrity. Robust organisational structures promote a culture of integrity. A mandatory Research Integrity training course is repeated by all academics and PGRs every 3 years and 95% of our researchers are currently compliant. Unit-focussed NAP (Section 2) induction and the “Ethics in Research” course reinforce research integrity. Unit-specific good practice is achieved by sharing outputs prior to publication and internal pre-submission review of funding proposals. Conduct is reinforced through a quarterly University-wide Ethics and Integrity e-Newsletter and a regular one-day course on “Introduction to Data Ethics”, coordinated by IDSAI.

Unit researchers influence the codes of conduct of, and upholding of, professional standards within learned societies via committee membership, leadership, and membership (Section 4).

Research Ethics Committees (REC) across the Institution report to the University REC (UREC). Departmental Leads (Director of Research and Head of Department) act as gateway to procedures, with five levels of approval, from departmental (low-risk PGR projects), to UREC (high risk staff/PGR projects), to national regulations, facilitated by an online Ethical Review Manager platform.

Export control, data compliance, radiation protection licensing, animal and plant licences and other legal obligations applicable to research are centrally managed and cascaded as necessary through research support and the DEES Health and Safety Committee with compliance officers in each area. Appropriate training is provided and where necessary, attendance is monitored to assure compliance.

The Head of Research and Head of Department act as Academic Malpractice Officers, responding, as required, to reports of malpractice in the Unit, conducting initial investigations and inputting to Faculty and University research malpractice processes.

2. People**2 a) Staffing and recruitment policy**

The Unit currently has 73 researchers, including 11 tenure-track fellows. In addition, we have 27 technical staff, 20 professional support staff (9 operational, 4 research, 7 T&L), 49 post-doctoral research associates / non-tenure track fellows and 186 PhD students. Faculty administrative teams support research activities through financial administration, training and organisation of review committees.

DEES has witnessed significant growth in academic staff from 48 in 2014 to 74 in 2020 (**Figure 2**), driven by our REF 2014 research strategy, integration of **EE** and university tenure-track fellowship opportunities. 95% of category A staff have permanent contracts and the gender balance in the Unit is 30% female, 70% male.

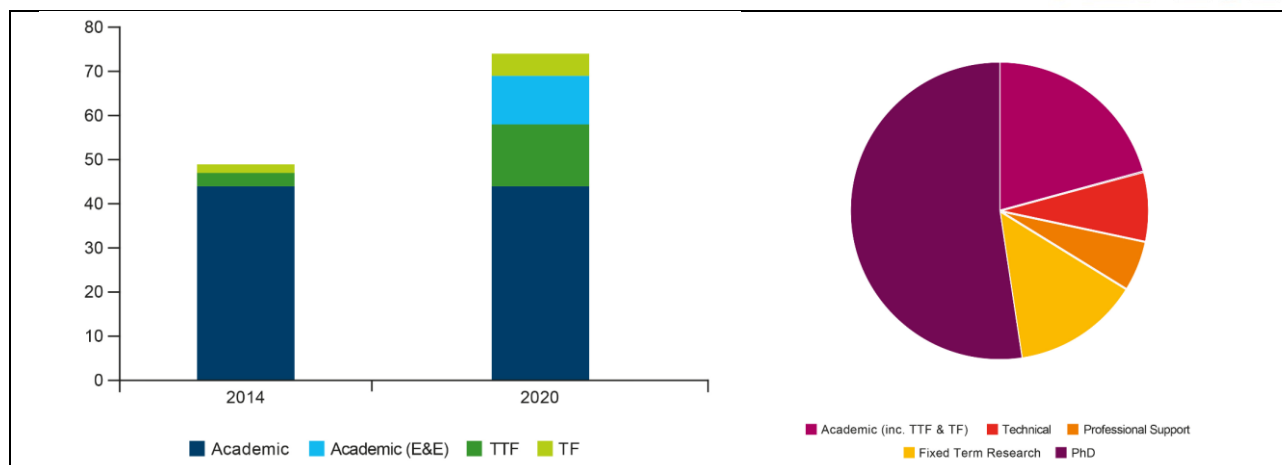


Figure 2: DEES Staff profile: Left, Academic staff numbers 2020 cf. 2014. E&E = 2015 staff intake of Ecology & Evolution Research Group; TTF = Tenure Track fellows; TF = Teaching Focussed academics; Right, Full staff profile 2020.

We appointed high profile researchers (e.g. **Burton, Johnson, Di Toro**) to enhance leadership in areas we wished to grow a larger critical mass (e.g. volcanic geoscience, plant-soil ecology), successfully attracting increased PGR and ECR researchers in these areas. In addition, our nuclear environmental science sub-theme area has been strengthened by welcoming Heath and Livens.

We have strengthened our academic pipeline by recruiting nine tenure-track research fellows through Faculty and University schemes (Dame Kathleen Ollerenshaw (DKOF) and Presidential Fellowships) and UKRI Future Leadership Fellowships (FLF), many of whom have already attracted significant external funding. These include Presidential Fellows **McCormick-Kilbride** (gas geochemistry), **Neave** (NERC Fellowship, magmatism) and **Jones** (Royal Society Fellowship, vertebrate evolution); DKOFs **Tartese** (isotope geochemistry, STFC fellowship), **Legg** (arthropod palaeontology), **Richards** (soil/water pollution) and **Nixon** (environmental biotechnology, NERC Industrial Innovation Fellowship, BBSRC fellowship); UKRI FLFs **Cox** (fungal diversity), **Clay** (volatile origins). **Farrell** was awarded a Leverhulme ECF (high-temperature rock dynamics). These are in addition to staff with Royal Society fellowships: **Buckley** (ancient Biomolecules), **Shultz** (mammal ecology) and **Joy** (meteorites).

The Unit replaced retiring staff and made strategic hires, strengthening multiple areas. **AS** appointed four new staff: **Garcia-Carreras** (atmospheric modelling Lecturer) and **Topping** (digital environment Reader) transferred from NCAS, while **Allan** (aerosol science Reader) and **Crosier** (cloud microphysics Reader) have each taken 50% NCAS and 50% Department roles. **Semchenko** (soil ecology Lecturer) was appointed to support **EE**. **BSSP** was enhanced with the appointment of **Kane** (Reader) from petroleum industry. **GEO** appointed **Hartley** (igneous petrology, promoted to Senior Lecturer 2019) and **Polacci** (volcanology Senior Lecturer). **Jones** (meteorites) and **Joy** (lunar/meteorites) were appointed as Readers in **IGP** in 2015.

An annual planning cycle allows each research group and degree programme to produce a three-year plan, highlighting where strategic hires would reach departmental goals. Revisions to research group and degree programme structures are considered before hiring priorities are proposed to the School of Natural Sciences and considered against the School and Faculty strategy and financial position. Additionally, opportunistic new appointments can be proposed, allowing for agility in achieving Unit, School and Faculty goals.

2 b) Staff development strategy:

In 2020 we re-structured departmental management to improve leadership, role-rotation and staff support. Research Group Lead and line management roles were separated, and all leadership

positions are now openly advertised and held for a defined period. This immediately increased the diversity of the leadership team. Each member of staff has a line manager who conducts regular informal meetings to discuss performance, probation/promotion targets and well-being. A formal annual performance and development review defines annual targets and develops training and development plans. Each line manager has ≤10 reports, permitting personalised support. Staff are mentored by a senior academic and belong to a research group (Section 1), providing community and inspiration throughout their careers.

Induction and probation

New academic staff (including TTF) are assigned to an appropriate research group and (decoupled) line manager, and follow an induction introducing the Departmental/University structures and processes. Three-year probation targets are defined with their line manager, following School-wide policies on research income (GBP300,000 in three years for ECR) and publications (1-2 senior-authored publications per year). A mentor is selected to guide probation and career development. A senior mentor oversees probationers' development, coordinating the Faculty-run New Academics Programme (NAP), which comprises 300 hours of training and development focussed on research, innovation, impact, and postgraduate research supervision. New staff have a reduced teaching load, with duties increasing through probation as they pass through teaching elements of NAP. TTFs are awarded a Department-funded PhD studentship at the start of their fellowship, ensuring PhD supervisory experience.

Formal annual review by the Departmental Promotion Committee assesses progress towards probation goals and highlights potential shortfalls, allowing extra support to be provided. TTFs are line-managed by the Deputy HoD which allows cohort development and social bonding of fellows who are distributed across the research groups.

Staff training and well-being

Staff development is vital to the success of both individual staff and the entire Department. The extensive University staff development portfolio covers both essential training and optional development opportunities to ensure that all staff benefit from the University's strong ethos of social responsibility to its staff and the wider community. Examples include safety training, ethical development (e.g. unconscious bias), and personal development (e.g. leadership skills).

We have a continuum of training and development opportunities, beginning with PhD students (see Section 2c) and continuing through ECRs (PDRAs, fellows and junior academics) to senior staff. We fully support the ethos of the Researcher Development Concordat and recognise the need to provide the best chance of securing employment both within, and outside, academia. PDRAs and ECRs are well-served by specific programmes for research staff including *Teaching for Researchers*, *Research into Management* and *Impact Training for Researchers*. PDRAs and fellows welcome the opportunity to contribute to teaching (up to 0.1 FTE) and we provide bespoke teacher-training, while they gain experience of supervision and project management through co-supervision of PGR, PGT and UG student projects. Higher Education Academy fellowship accreditation can be gained through the University Leadership in Education Awards Programme (LEAP). Senior staff aspiring to major leadership roles have followed the university Headstart programme (6 current staff). and more recently the externally run Inspiring Leaders Programme (9 completed, 5 in progress).

All academics and probationers are given development opportunities and are encouraged to consider leadership roles, as appropriate to their development needs. This policy has enabled relatively junior staff to step-up to management tasks and gain experience, supported by more experienced leadership team members. The Unit offers mentors to PDRAs, fellows, junior staff, and the University offers external mentoring and mentor coordination opportunities.

Staff well-being is actively supported, with regular social activities organised by research groups and department. The University invests GBP227,000 p.a. in comprehensive wellbeing services

offered to all staff and students. Our line management processes, and recently revised workload model, ensure fair distribution of responsibilities and help staff manage life-work balance. All students and staff have full access to support from the University counselling and mental health service.

Promotions

An annual promotions round is open to all staff. Clear progression criteria are circulated by Faculty who provide workshops on preparing promotion cases. Line managers discuss individual cases with each of their staff, encouraging development of a promotion case where likely to succeed. Line managers are trained in equality, diversity, inclusion and access (EDIA) and ensure that promotions are encouraged equally and meritoriously regardless of protected characteristics. Applications are reviewed by the departmental promotions committee and feedback is provided, allowing staff to revise and strengthen their case before final review. Faculty promotions committee review and make a final decision. Our promotion application and success rates (80%) are the same regardless of gender over the reporting period.

Impact leave/sabbatical leave

All academics are eligible to apply for academic leave (one semester/year after six semesters/years or pro rata part-time leave) for a major research, impact or teaching project by submitting an application and detailed plan for the leave period. Examples of leave-enhancing research and impact include **Hodgetts** who recently began a 2 year leave of absence to develop a spin-out company developing software for 3D visualisation of geological features; **Polya** won GBP1,600,000 in funding and co-authored 20 publications during a sabbatical year; **Hollis** significantly increased the number and quality of outputs, strengthened research impact and started a new collaborative project with Texas A&M University.

Staff exchange programmes

Staff are encouraged to widen experience through career breaks and staff exchanges with international research institutes and industry: **Semchenko** is taking a two-year career break through a Marie Skłodowska Curie fellowship at the University of Tartu, Estonia; **Manning** took a 25% position while working on a USA palaeontological project (2016-18). Conversely, we hosted 15 overseas and industrial researchers e.g. JSPS fellow Kazahaya, Tokyo University, which yielded four papers from 1 year hosting in 2019; a 3-month visit from Wang, Fudan University, leading to a visiting professorship in Fudan for **Coe**; and an honorary professorship for Rory Clarkson of Rolls-Royce, facilitating thriving mineral dust/ jet engine research.

Support and rewards for developing impact

Developing beneficial societal impact from Unit research is a priority, and embedded within all procedures. It is supported by previously discussed activities (e.g. outreach training for PDRAs, promotions, sabbatical leave, secondments and staff exchanges). The Department has an Impact Officer to assist development of impact activities, and 3 of our impact case leads won Faculty funding for impact fellows= support. Success in developing impact is recognised in two ways: it is one of several criteria upon which promotion is based, through knowledge exchange; and it meets University commitments to Social Responsibility through research with impact.

2 c) Research students

We have a diverse community of PhD, MPhil and MSc research students involved in all groups and themes within the Unit. Our PGR students drive inter-disciplinary, cross-faculty and cross-institutional research through collaborative programmes and doctoral training partnerships, including our NERC DTP, EPSRC CDT in Nuclear Energy (GREEN), NERC Oil/Gas CDT and NCAS/EPSC Aerosol CDT. They provide substantial, high quality research outputs; research papers from the Unit that include at least one PGR author increased from 232 in 2014 to 462 in

2018. Our impact cases have major contributions from PhD researchers, with two impact cases, examining radioactivity management at Sellafield and arsenic contamination in Asia, involving significant contributions from 6 and 7 PGRs respectively.

We recruit students in an open and transparent process regardless of gender, ethnicity, disability and sexual orientation, on the basis of excellent academic quality, research potential and strategic fit to the Research Group in which they will be based. PGRs are recruited to advertised projects or apply with their own project proposals. Applicants are interviewed by a panel of two or more academic staff, who have completed Diversity in the Workplace and Unconscious Bias training. PGR numbers in the Unit have grown by 63% since 2014, with 186 currently active PGRs, giving a PGR/staff ratio of 2.6. We attract ~60% Home and ~40% Overseas PGRs. The gender balance has remained stable while our PGRs are now more ethnically diverse (**Figure 3**).

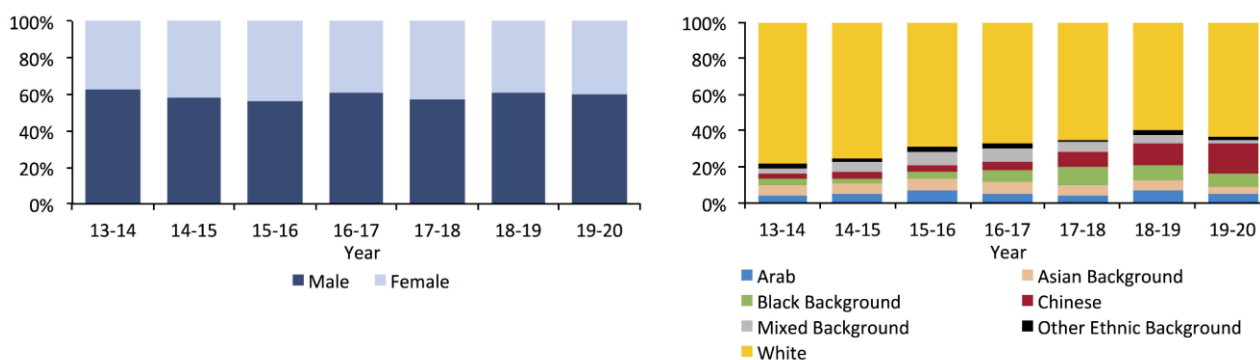


Figure 3: Gender (left) and Ethnicity (right) characteristics of Unit PGRs for each academic year cohort

On average, 50% of the annual student cohort is funded through UKRI scholarships (via EPSRC, BBSRC, STFC and NERC) or other UK funders such as the Royal Society. We also attract industry funding from Sellafield, National Nuclear Laboratory, Met Office, Rolls Royce, various energy companies (e.g. BP, Equinor), and many others, such that >35% and >80% of our NERC and EPSRC studentships, respectively, have an industry partner. The remaining PGRs are funded through university scholarships (including 2 to 5 students per year from highly competitive President's and Dean's scholarships), various overseas funding agencies, or are self-funded.

All PGRs have a supervisory team of two or more academic staff and a pastoral advisor. All supervisors are approved by the Head of PGR to ensure that collectively the team has proven supervisory experience, provides an excellent research training environment that is relevant to the project, and is complemented by the wider research groups, such as through group research seminars.

Online student progression monitoring enables recording of attendance, completion of key milestones, and a written record of academic engagement, training completion, progression problems and resolutions. This allows provision of support and academic intervention, as needed, to assist PGRs towards on-time submission and completion (recorded within 5 years for full-time study). Counselling and well-being services are University provided and signposted through the supervisory team or the Department's qualified mental health first-aider. Additional support comes through the Disability Advisory Support Service (DASS) where needed. As such, we can demonstrate excellent PGR performance, with >95% routinely passing end of year progression assessments at first attempt and reporting a high level of satisfaction (2019 PRES survey: 82% of the Unit's PGRs were satisfied with their experience). We are achieving strong completion statistics, with a mean of 82.8% during the REF period, with >80% of PGRs gaining an award with no or minor revisions at first submission. All PGR programmes allow flexible working and can be taken on a full-time or part-time basis. Efficient special circumstances processes allow flexibility

to changing situations, such as extensions for Covid delays, interruptions for long-term sick leave, maternity/paternity leave, or interruptions for professional development.

All PGRs discuss and agree a bespoke training programme with their supervisory team, which is reviewed regularly. There is mandatory induction and training in transferable skills including research ethics and integrity, alongside extensive training options available from the Faculty Researcher Development programme and elsewhere (e.g. data science, science dissemination, research impact). Unique training opportunities are available through DTPs, CDTs and internships, providing experience with industrial and employability relevance. The excellence of our training environment is evidenced by high employability of our PGR graduates: after graduation, 52% follow academic careers, 12% public sector and 36% private sector.

2 d) Equality, diversity and inclusion

UoM is unique in placing Social Responsibility (including EDI) alongside research and teaching as one of the three equal pillars of its strategy. The University provides mandatory EDI and unconscious bias training, and EDI is central to everything the Unit does, evidenced by major changes instigated through our Athena Swan Action Plan, and we have held Athena Swan Bronze status throughout the period. For example, all leadership positions are fixed-term and openly advertised, with staff from underrepresented groups being actively encouraged to apply. Our leadership team has gone from being entirely white male 5 years ago to having a composition reflecting our diversity (see Table 1 below). Our active Equality, Diversity, Inclusion and Accessibility (EDIA) committee proposes initiatives based on lived experiences, which are actioned through our Department Leadership Team. Recent initiatives include having EDIA observers on all appointment panels and complementing mandatory training with targeted activities in Department meetings.

Staff from under-represented groups are targeted for leadership training. For example, staff nominated to complete the UoM "Inspiring Leaders Programme" have been disproportionately women. We lead the Women in Environmental Sciences network, hosted by MERI and aligning with the UN sustainable development goals (UN SDGs). The network engaged women from culturally and professionally diverse backgrounds at two workshops held in the UK in 2018 and 2019. We are acting to increase fieldwork accessibility for students and staff with disabilities and improving support for students from different cultures. Our Widening Participation committee has the goal of increasing diversity, particularly BAME representation, amongst staff and students. This has led to an increase in BAME representation across research students from 24% in 2014 to 37% in 2020 and staff from 6% to 9%. LGBTQ+ and disabled students and staff from UoA7 are contributing to Faculty initiatives to improve equality and diversity across the institution.

Table 1: Distribution of research academic staff by career stage, role and gender in 2014 and 2020.

RGL -Research Group Lead, LM – Line Manager

DEES	Gender	All	Fellow	Lecturer	Senior Lecturer	Reader	Professor	RGL	LM
2014	Female	16%	20%	13%	33%	29%	8%	0%	0%
	Male	84%	80%	88%	67%	71%	92%	100%	100%
2020	Female	30%	55%	44%	33%	30%	18%	29%	29%
	Male	70%	45%	56%	67%	70%	82%	71%	71%

The Unit recognises the challenges faced by staff due to personal circumstances, including those with disabilities and caring responsibilities. All staff may request flexible working and such requests are automatically respected in teaching timetables. Currently, 8 staff have flexible contracts. All meetings occur within core hours (10am-4pm, excluding lunch) and agendas/minutes allow absent staff to contribute to discussions. Staff on leave have regular meetings with line managers and can apply for PDRA or teaching replacement for up to 6 months. Remote working is encouraged. In response to COVID we followed procedures described in the Institutional Statement on Covid

mitigations. Staff with childcare responsibilities can request support for childcare when attending conferences. The Unit has a policy of actively developing the careers of part-time and fixed term employees and has an excellent record of developing staff onto permanent positions where this fits with their own career aspirations.

All staff involved in the REF output and impact submission undertook EDI and unconscious bias training, and selection of submissions was analysed for possible bias, resulting in 33% female-led impact cases in REF2021, reflecting the Unit gender balance. Unit outputs submitted by male, female, white, BAME and disabled staff closely follow our actual distribution of protected characteristics, with 29% female and 71% male submissions.

3. Income, infrastructure and facilities

3 a) Research funding and strategies:

Our REF2014 strategy for growing research income identified 3 goals that align with the UKRI strategic landscape, and an increasing emphasis on solutions-based research from multiple funding agencies.

(i) Further growth of our fundamental research capacity: We have achieved significant uplift in our—research funding base over the REF period measured in volume and income/FTE, increasing from GBP36,400,000 (GBP760,000/FTE) in REF2014 to GBP72,595,656 (GBP981,022/FTE) in REF2021. We have also maintained our balance of income across all streams since REF2014 but have increased our market share across UK Earth and Environmental Science HESA cost centres from 4.6% to 7% (**Figure 4**).

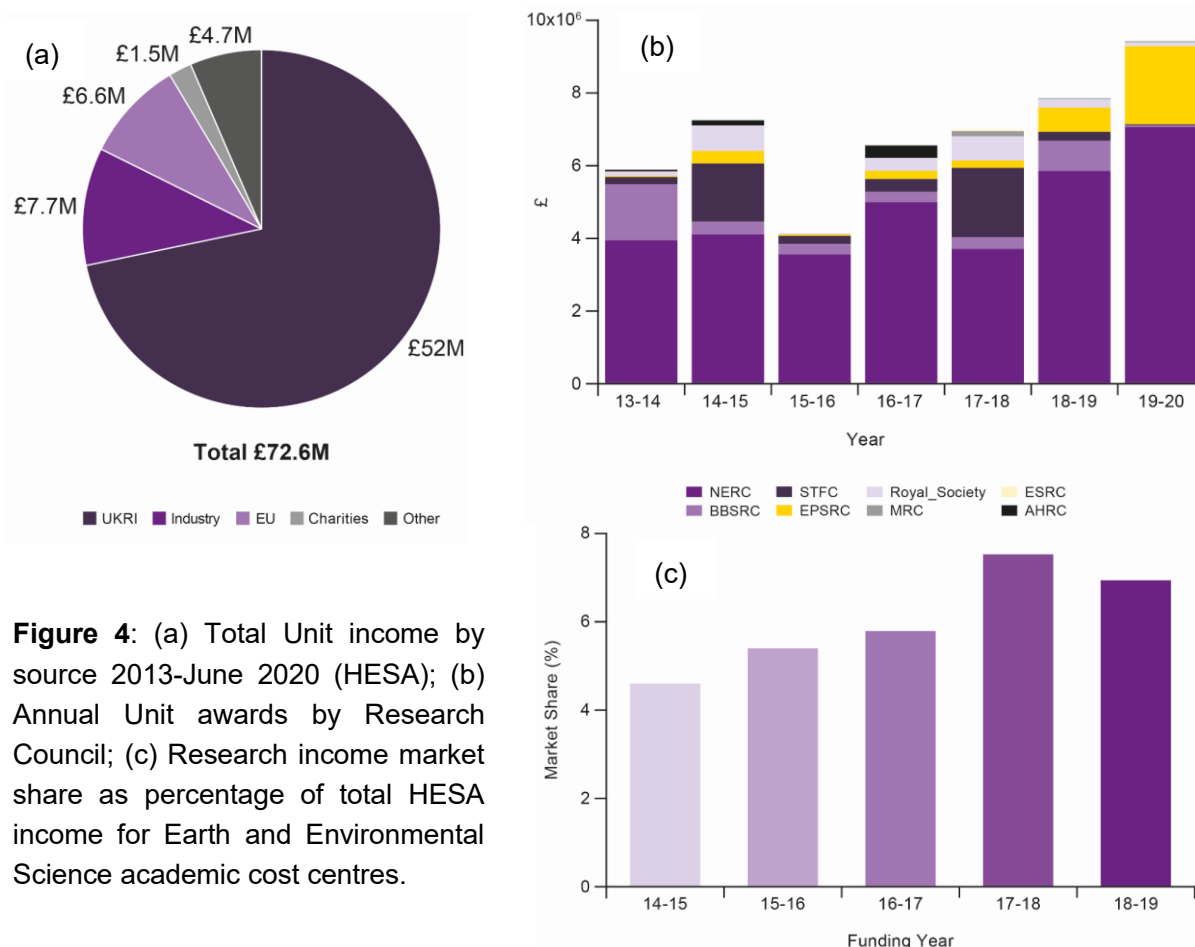


Figure 4: (a) Total Unit income by source 2013-June 2020 (HESA); (b) Annual Unit awards by Research Council; (c) Research income market share as percentage of total HESA income for Earth and Environmental Science academic cost centres.

UKRI Funding (Figure 3b): We have received GBP52,103,549 of UKRI income during REF2021, the majority (69%) from NERC. UKRI awards data for 2019-20 shows that **UoM received the largest amount of NERC funding by award value of any HEI** (GBP8,604,000, the Department led GBP5,542,000), over GBP1,500,000 more than any other. In the REF period we were awarded GBP6,737,399 from NERC to support NCAS at UoM. Notable NERC funding successes include 3 awards in the Climate Sensitivity due to Clouds programme worth GBP1,820,945 (19% of total call value) and a large grant award focussing on basaltic magma (GBP1,631,229). STFC awards of GBP4,523,937, included two consolidated awards with a combined value of GBP2,671,129. BBSRC (GBP3,577,832) and EPSRC (GBP3,751,202) awards have underpinned our sustainable agriculture, biotechnology, and environmental clean-up research. The HEFCE-funded N8 AgriFood programme supported a new Chair in Soils (**Johnson**, see Section 4).

EU income: has totalled GBP6,607,636, including ERC awards in **EE (Brown, Bardgett)** and **GEO (Burton, Mecklenburgh)** and FP7 projects on clouds, vitamin D and nutrition, nuclear remediation and disposal, paleo-biomechanics, and volcanology. We are the UK hosts for the ACTRIS (**Vaughan**) and IAGOS (**Gallagher**) European Research Infrastructures for atmospheric science and are the UK lead in the new ATMO-ACCESS programme for collaborative access to EU atmospheric infrastructures (**McFiggans**).

Industrial funding: BSSP has received GBP5,378,241 from the energy sector including BP, Shell and Equinor. Our nuclear research partnerships with Sellafield and NNL have resulted in GBP3,207,988 awards and **MES** has also been awarded GBP265,000 for work on water clean-up technologies (Evoqua and Arvia). **GEO** has worked with Rolls Royce on dust ingestion into engines, and Boots and Rolls-Royce have supported work on UV exposure and jet engine emissions respectively, that have been central to our impact cases (GBP250,000).

Since 2014, the income from 23 prestigious Fellowships (see Section 2) has totalled GBP6,178,316 from NERC, BBSRC, MRC, STFC, Leverhulme, Royal Society, Daphne Jackson, 1851, AXA, and Newton.

(ii) Encouraging growth in large, multidisciplinary research programmes: We have increased our funding from large and multidisciplinary awards (e.g. NERC large grants, EU/ERC awards, UKRI SPF) compared to the previous REF period by 90%. We have been awarded 2 UKRI Strategic Programme Fund awards (GBP650,000), over 15 NERC Research Programme (RP) and Consortium awards (>GBP13,000,000) and the EPSRC UK Collaboration for Research on Infrastructure and Cities (UKCRIC) Manchester Urban Observatory (GBP1,000,000). This has been driven by fostering integration of our researchers within our strong cross-University Institutes and alignment with UKRI themes.

(iii) Growing our International Collaborative Research: Official Development Assistance (ODA) funding growth has been a particular strength over the period. We have hosted Newton Fellowships with the Universities of Fudan and Sao Paulo, consolidating existing collaborations. Successes in 3 UKRI Air Pollution and Human Health (APHH) programmes secured GDP1,505,441 for 6 projects, improving air quality and consequent health outcomes in China, India, Vietnam and Indonesia. GBP1,252,642 ODA income has supported work on arsenic poisoning of ground waters worldwide, including FAR-GANGA (DST-NERC Newton Bhabha), and EPSRC and NERC-funded research on the controls on and remediation options for high arsenic ground waters in Cambodia, India, Argentina, Chile and Myanmar. These large multidisciplinary awards involve substantial international collaboration, which has driven a significant increase in internationally authored outputs in our return (see Section 4).

(iv) Enabling this growth: UoM has developed a comprehensive research and business engagement team, including a dedicated Research Support Manager with 4 Research Support Officers providing support in developing grant applications and contract tenders. This service includes identification of opportunities, costings, contracts, and impact advice. A Faculty team of 5 Research Strategy Coordinators provides support for writing and managing major collaborative

bids such as successful EPSRC National Nuclear User Facility (NNUF) and Radioactive Waste Management (RWM) bids.

We support delivery of our funding strategy by: (i) providing targeted information on funding opportunities; (ii) developing our less experienced staff through research leader mentors; (iii) triaging all draft proposals, including full panel assessment of NERC standard proposals (31% success rate in 2020); (iv) running mock panels for fellowship, large grants and ERC interviews using recent panel members, producing high success rates (see Section 2); (v) running regular FSE training events on Fellowship applications; (vi) providing online material for ECRs on developing grant applications; (vii) releasing staff time for grant writing through pro-active load management and sabbaticals; (viii) promoting the spin-up of new research through department-funded PhD studentships, small equipment and pump-priming new initiatives. ECRs are proactively encouraged to benefit from these initiatives.

ODA growth has been fostered through the University's Internationalisation agenda (**Flint**, AVP Internationalisation), identifying key partner universities and investing in joint programmes, visits and studentships; encouraging visiting Professorships in partner universities (e.g. **Coe**, **Lloyd** – Fudan and CUG Beijing); allowing time for our staff to help shape international programmes, such as NERC-MoES and NERC-CNSF calls; and encouraging staff to access internally distributed GCRF funding via our research office and Institutes.

3 b) Organisational infrastructure:

Our academics play major roles in UoM research institutes (Section 1b and IS 2.iii) which drive our interdisciplinary research. **MERI**, set up in 2018 and involving >300 staff, fosters interdisciplinary environmental research across all 3 faculties. **MERI** facilitated the NERC funded Air Quality supersite (GBP750,000) and, together with the Manchester Urban Institute (**MUI**), created and maintains the EPSRC UKCRIC Manchester Urban Observatory, expanding our research into environmental data science.

DNI coordinates cross-University nuclear power research, integrating >12 facilities across campus covering material science and radiochemistry, alongside access to the Dalton Cumbrian Facility (DCF). These make us the largest UK nuclear environmental research group, delivering high-profile and impactful science. Our Unit has benefitted from DNI-led capital infrastructural awards via EPSRC NNUF Radioactive Waste Management and Environmental Remediation Laboratory Refurbishment (RADER) (GBP1,855,166) and the Radioactive Waste Management Ltd. Trans-Uranium Waste Management Research Support Office (GBP2,498,634).

The Henry Royce UK National Institute for Advanced Materials, funded by EPSRC and hosted at UoM, supports advanced materials research through a network of >900 scientists and >GBP300,000,000 of facilities. One of the Royce research themes, led by Unit staff (Livens) is Nuclear Materials and supports equipment for DNI research. Imaging applications using the Royce X-ray MicroTomography and MALDI-imaging facilities are being driven by **AL** and **GEO**.

MIB provides state-of-the-art biological laboratories for **AL** and **MES**, and supports infrastructure and technical support for our biotechnology research, including biofuel production from algae, and energy and industrial biotechnology. The latter includes microbial systems for bioremediation, functional nanomaterial synthesis and catalysis. We make extensive use of MIB genomic/postgenomic tools including proteomics and metabolomics.

Unit researchers interface with the **Tyndall Centre** through **MERI**, investigating impacts on air quality from wood-burning stoves, biomass renewable energy, carbon budgets and pathways, and IDSAI, through the Digital Futures platform, to develop the InnovateUK Smart City project CityVerve.

3c) Support infrastructure:

Estate and facilities: Our estate of 7,433 m² surrounds the University's newly landscaped Brunswick Park. The Williamson Building houses our Environmental and Geoscience laboratories, including the Williamson Research Centre (WRC), home to our extensive environmental chemistry, isotope, mineralogical and advanced imaging facilities (Section 3f). New clean-room curation facilities house meteorite samples returned from the Antarctic by **IGP**. The Simon Building houses **AS**'s 10 m tall ice-cloud chamber and 18m³ Manchester Aerosol Chamber, both unique in the UK and part of EUROCHAMP2020 Research Infrastructure. **EE** and **AL** are co-located with the central facilities of the Faculty of Medical Biological and Health Sciences housed in the Michael Smith and Stopford Buildings. UoM has invested £2M in the "The Firs" Botanical Gardens, which includes state-of-the-art controlled environment growth facilities. Advanced equipment and IT resources are tailored to our research areas and are described in Section 3f.

Technical and Support Staff: Our research is supported by 25 technical staff: 4 senior experimental officers provide integrated technical management; 8 externally funded research technicians; 3 senior technicians; 2 computing officers; specialist technicians provide horticultural support at "The Firs" and Manchester Air Quality Supersite. The School of Natural Sciences maintains a well-equipped mechanical workshop staffed by 13 technicians, with one dedicated to this Unit. Technical staff line management is provided by a technical operations manager, with senior EOs providing line management of more junior staff. Safety and environmental sustainability of laboratories are managed by our dedicated safety advisor.

The UoM Library is detailed in IS 4.2. It provides leading research services to support our research including access compliance, data management planning, and metrics for benchmarking and informing research strategy.

IT Services supports standard University services and has a specialised team (~40 FTE) who provide research support and training across software, data engineering, access to internal and external HPC, data storage facilities, visualisation and analytics. Our researchers routinely access institutional HPC, particularly the centrally-supported Computational Shared Facility (CSF) a cluster of >9500 nodes, to which researchers contribute nodes and additional infrastructure, increasing energy efficiency. These facilities underpin work on biomechanics, fossil imaging, atmospheric modelling and subsurface geoscience. We use the N8 HPC facility and ARCHER, UK's National computing service for large-scale meteorological and air quality modelling.

Significant archives and collections: The Manchester Museum at UoM hosts a collection of over 4.5 million objects that are used by staff across the Unit and we host our own extensive rock and mineral collection, curated to museum standards.

3d) Equality and diversity:

EDIA is embedded in how we support research funding applications (IS 4.1). Awards data monitoring allows us to identify under-represented groups in applications and awards by research funders. This is used by our Faculty support team to inform design of workshops to support applications, target assistance for review and feedback, and aid building of large research teams for major bids. Post-award support includes tracking Open Access publishing and impact generation.

Access is considered through UoM's planning and operational processes. Our buildings all include disabled toilet facilities, wide-door access, accessible light switches and swipe pads. Our estates team incorporate disability access when commissioning new developments, including floor levelling and disabled toilets in the new Firs greenhouses. Disability access requirements are identified through our Disability Support Services and implemented by our technical team. Our laboratory services and facilities run an access rota and flexible working allows technicians to meet the needs of everyone using our laboratories, ensuring safety for all.

3e) Support for impact:

Our infrastructure, facilities and expertise play an important role in developing our impact. Facilities are promoted externally through our Faculty Business Engagement team (Clean Futures lead **Nixon**) and Institutes. Our aerosol instrumentation has been used to support aero-engine emissions legislation development (Impact Case); our atmospheric chambers have supported studies of diesel emissions controls (GBP28,500) and aging of cosmetics (GBP22,000). Our mineralogical facilities are helping Rolls-Royce improve helicopter servicing in dusty environments (GBP166,000), and **BSSP** infrastructure and geological datasets are used with the petroleum industry to drive exploration and production efficiency (Section 3a). Our nuclear expertise and facilities are closely integrated into the UK Nuclear Industry, underpinning effluent treatment and decommissioning strategies at Sellafield, and deep disposal of nuclear waste. WRC facilities are used to continue joint development with UoM spin-out companies, including water remediation (Arvia and Evoqua) and improvements in water distribution with Salamander, which commercialised Hydraclam®, Chloroclam® hardware (licensed to Siemens). Webb has been supported by Boots for work on UV exposure and skincare (impact case);

Our facilities underpin outreach and public engagement activities, notably the collections at the Manchester Museum and imaging facilities in the Royce (Manning).

3f) Specialist research infrastructure:

Our research groups maintain a wide range of specialist infrastructure, supported and developed through University and external funding. We have procured equipment through research grants worth in excess of GBP10,000,000 over the REF period:

AS cloud-physics research has been supported by investment in cloud and precipitation instruments, including globally unique 3D real time holographic imaging spectrometers and miniature cloud detectors integrated into Global Research infrastructure (IAGOS). Investment in novel mass spectrometry for real-time analysis of particle and gas phase compositions has driven research in our pollution theme, and investment in new technology for online bioaerosol detection is driving new research. Additional capital investment has enabled installation of these instruments onto the NERC BAe-146 aircraft, keeping us at the forefront of airborne atmospheric science. Investment in a new suite of UV sensors provides long-term monitoring for Defra. Atmospheric modelling is underpinned by recent investments in both edge and centralised computing facilities including nodes in the CSF.

MES facilities are hosted in WRC. The NNUF RADER (S3b) and the Nanoscale Imaging and Analysis Facility for Environmental Materials (GBP500,000) provide a new facility for wider community use, including new ICP-AES, ICP-MS, HPLC, GC-MS, high-throughput Illumina DNA sequencing, and a FEG-SEM with XRF/EDS and Raman spectrometers. This investment has enhanced existing WRC facilities that include EPMA, XRD, X-Ray reflectometry, imaging FT-IR, SEM and optical microscopes.

GEO also benefits from the WRC facilities, and maintain additional specialist high pressure experimental petrology and rock deformation laboratories. New investments in monitoring of volcanic gas emissions have enhanced this growth area. EPSRC-Rolls Royce funding has set up a new mineral dust laboratory, including a AJ100 Jet Mill System.

BSSP hosts a state-of-the-art high end computing facility with leading industrial applications for seismic interpretation, geophysical log analysis, 3D modelling and visualisation, and a terrestrial Lidar scanner and drone with high resolution photogrammetry facilities are used for digital outcrop modelling. It also supports a petrophysical laboratory and petrographic suite, and benefits from the WRC.

AL research has been supported by a Z+F 5010C Imager (Lidar, 190 m range) and a High Power Visualisation Workstation. We maintain a bioarchaeology facility for our comparative faunal

reference collections, as well as scanning, imaging and 3D printing facilities, a taphonomy wet laboratory for experimental decay, and dedicated simulation laboratories.

During the REF period, **IGP** received STFC investment for a state-of-the-art laser-ablation-Inductively-coupled-plasma mass spectrometer to examine processes in the solar nebula (GBP235,559). This adds to a clean room facility and a suite of mass spectrometric tools (ToF-SIMS, NG-RIMS, NI-NGMS, HELIX MC and VG5400 all operated as part of the STFC UK Cosmochemistry Analytical Network).

EE laboratories have facilities to analyse microbial and faunal community composition (including DNA extraction, amplification and analyses), stable (^{13}C) and radioisotopes (^{14}C , ^{33}P , ^{32}P), nutrient and cation concentrations, greenhouse gases (CO_2 , CH_4 , N_2O), and chemical and physical soil and vegetation properties. Two NERC Capital awards (GBP1,000,000) in 2017 funded a bespoke mobile isotopic greenhouse gas laboratory, portable CO_2 and greenhouse gas analysers and a cavity ring-down spectrometer for isotopic analyses of CO_2 and CH_4 . A newly refurbished growth room suite houses 10 climate-controlled environment chambers including some with CO_2 control and facilities to continually pulse-label large plants with ^{13}C at ambient CO_2 concentrations.

In addition to bespoke research infrastructure and our extensive use of facilities in our institutes (see 3b), our researchers draw on a range of University facilities. Notably, **EE**, which is primarily located in the Michael Smith Building, has access to extensive core facilities including a bioimaging suite, a broad range of mass spectroscopy equipment, genomic technologies, and flow cytometry available in the Faculty of Medicine, Biology and Human Sciences.

3g) Shared research infrastructure:

AS hosts NERC NCAS expertise and infrastructure for cloud physics, aerosol and remote sensing, that is delivered through the associated UK Atmospheric Measurement and Observation Facility and the NERC BAe-146 research aircraft.

Synchrotron-based research has been important across all areas of the Unit. **AL** research undertaken at synchrotron light sources (Stanford Synchrotron Radiation Lightsource, Diamond Light Source, SOLEIL, and ESRF) has made them a world leader in the imaging and quantification of the chemistry and biomarkers from fossils and ancient artefacts. **GEO** staff have been innovators in using synchrotron-based imaging, diffraction and spectroscopy to observe the behaviour of rocks and magma systems under realistic sub-surface pressure and temperature. Our UoM office at Harwell supports this work, hosting a NERC Fellow (**Ma**).

We make extensive use of observational and digital data from the British Geological Survey core repository to inform models for sub-surface rock structure and fluid behaviour, and have developed significant collaborations with BGS scientists. Awarded NERC isotope facility time (Keyworth, Edinburgh and East Kilbride) has been used to understand fluid - rock interactions and igneous geochemistry

3h) Benefits-in-kind

Use of multiple synchrotrons worldwide includes the SSRL, the Advanced Light Source, LBNL, Berkeley, the Canadian Light Source, the Swiss Light Source, and ANKA, Karlsruhe as well as at the Diamond Light Source in the UK. For the UNRI facilities use alone access equates to GBP5,544,000.

AS has flown in excess of 1150 hours on the NERC BAe-146 research aircraft in the 2014-2019 period worth >GBP13,000,000 based on FAAM costs per flight hour, not included in the UKRI income-in-kind summary data. Our Unit's ARCHER allocations exceeded 300M AUs during the period, equating to GBP168,000 at the UKRI cost rate of GBP560/MAU and has supported our atmospheric and magma ascent modelling.

4. Collaboration and contribution to the research base, economy and society

4 a) Research collaborations, networks and partnerships:

Our research is highly collaborative with researchers engaged in a wide range of Departmental and University-wide collaborations, national and international research projects and networks. Reflecting this, 88.5% of papers published during the REF period involve co-authors outside UoM, and 69.9% have co-authors outside the UK, covering 113 different countries worldwide (**Figure 5**).

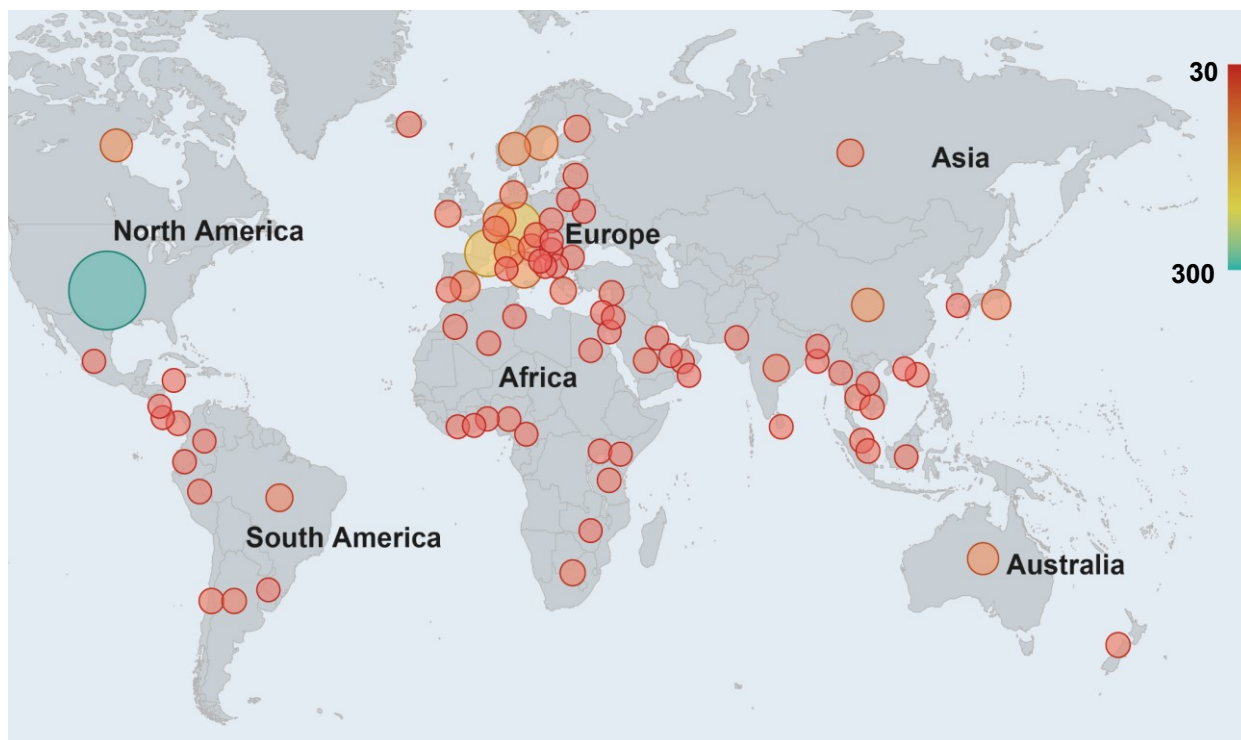


Figure 5: Global distribution and number of publications resulting from collaborations across the REF period; colour and size of marker scaled to the number of co-authored papers from each country. This indicates the global reach of our collaborations.

Our collaborative research is fostered via several mechanisms including: (i) strategic investments in staff with a remit to bolster collaborations via national research networks (e.g. **Johnson**, N8 Chair); (ii) encouragement of staff to engage in exchange programmes and to take sabbatical leave, resulting in 15 visiting international scholars with >3 month visits (Section 2); (iii) development of extensive industrial partnerships and collaboration with stakeholders, leading to significant impact (Section 4b); and (iv) via the University's flagship research institutes, especially the Manchester Environmental Research Institute (**MERI**) and Dalton Nuclear Institute (**DNI**) (Section 1 and 3). Collaborative, inter-disciplinary research is also fostered via our involvement in **NCAS**, which is a major plank of our world-leading research on remote sensing, atmospheric aerosol and cloud physics.

The success of these mechanisms is evidenced by our involvement in multiple multi-partner collaborative projects and networks, including leadership of major NERC programme grants (e.g. Drivers of Variability in the South Asian Monsoon, **Coe**; Soil Security, **Bardgett**), NERC Large Grants (e.g. Disequilibrium Processes in Basaltic Volcanoes, **Burton**; Uncertainty in Climate Sensitivity due to Clouds, **Choularton**), and international consortia in the Air Pollution and Human Health (APHH) programme (e.g. AIRPRO, **Coe**, **McFiggans**; AIRPOLL, **Allan**, **Coe**; DelhiFlux, **Allan**), fostered through NCAS. Other outcomes of our support for international collaboration include our leadership of multi-partner GCRF/Newton funded projects addressing environmental challenges related to the UN's Sustainable Development Goals, including the restoration of

degraded grasslands on the Qinghai-Tibetan Plateau, China (**Bardgett**), and groundwater arsenic remediation in the Ganga River Basin, India (**Polya**).

Our staff have also played significant roles in major national and international collaborative research networks. This includes acting as key players in major EU-funded consortia, such as ECOFINDERS, which enabled collaborative research across Europe on soil biodiversity and its role in ecosystem services (**Bardgett**) and ShaleXEnvironment, a multi-disciplinary project including academic and industrial partners on the environmental footprint of shale gas exploration (**Taylor**). Staff also have key roles in major European research networks, such as the European Network of Observatories and Research Infrastructures for Volcanology (EUROVOLC, **Burton**), bringing together the European volcanology research community, and EUROCHAMP2020 (**McFiggans**), integrating advanced European atmospheric simulation chambers into a world-class research infrastructure and leadership of commercial aircraft air sampling (**Gallagher**). Our staff also coordinate UK activities of the EU Aerosol, Clouds and Trace Gases Research Infrastructure network (ACTRIS, **Vaughan**) and have leadership roles in several international research networks, including: (i) The first UK expedition to collect and curate meteorite samples from the Antarctic in partnership with the British Antarctic Survey (**Joy**); (ii) European Space Agency's package PROSPECT involving a pan-European team measuring volatiles at the lunar South Pole (**Joy, Tartèse**); and (iii) Global Soil Biodiversity Initiative, a global community of >4k members promoting expert knowledge on soil biodiversity into environmental policy (**Bardgett**).

4 b) Relationships with key beneficiaries to develop impact:

Our extensive engagement with key users and beneficiaries is evidenced by the relationships underpinning our impact cases. Our long-standing relationship with industrial partners NNL, Sellafield, BNFL and Radioactive Waste Management (RWM) (**Morris, Shaw, Lloyd**) has had substantial mutual benefit and delivered broad impact in remediation, healthcare and the conversion of waste metals into high value nanomaterials for industrial catalysis. The provision of a research platform at Sellafield for the treatment of radioactive effluents has reduced discharges of alpha emitting radionuclides to the environment saving GBP25,000,000 in treatment costs. The substantial investment in nuclear environmental science from UKRI, EU and industry (Section 3) has enriched our research environment and delivered wider impact through the employment of research staff, including ESPRC/NERC impact fellows, and training of highly skilled postgraduates recruited to the environmental sector.

We have developed strong industrial and regulatory body relationships in the aviation sector via our emissions research with Rolls-Royce. Much of this work has been conducted through a consortium funded by the European Aviation Safety Agency. This led to involvement with the International Civil Aviation Organisation panel on particulate emissions testing, which has driven changes in emissions regulation (**Williams**). We have extensive relationships with energy companies (e.g. BP, TOTAL, Equinor, Shell) (**Redfern, Flint, Hollis, Huuse, Taylor, Schroeder, Hodgetts**) and JIPS, including North Africa Research Group (10 companies), Slope (10 companies) and PD3 (3 companies). These have delivered databases and models facilitating de-risking and decision-making of petroleum basins globally: beneficiaries include international energy companies (e.g. BP, Chevron, Repsol), national oil companies (e.g. Petrobras, Brazil; Woodside, Australia) and independent operators (e.g. Tullow Oil, Wintershall DEA, Petroceltic).

We have established an extensive set of relationships to realise the impact of our research on arsenic in groundwater and public water supplies. Notably, **Polya** was appointed as an International Advisor to the Bihar State Pollution Control Board and has undertaken knowledge transfer activities with them via the DST(India)-NERC(UK) funded FAR-GANGA Water Quality project. The impact of our research on sunlight and vitamin D benefitted from involvement of **Webb** in the Scientific Advisory Committee on Nutrition, Public Health England, and the National Health Institute for Health and Care Excellence Advisory Committee on sunlight and vitamin D. The impactful nature of this research has involved significant funding from DEFRA, EU, BUPA, CRUK, Dunhill Trust and Walgreen-Boots Alliance projects (**Webb**), and PhD projects funded by BBSRC and Saudi Government.

We have also developed partnerships with national and regional Government Agencies to advise policymakers on fracking (e.g. Environment Agency, **Allen**) and air quality (Defra Air Quality Expert Group, **Allan**; TfGM PM2.5 Task and Finish Group, **Coe**). Our partnership with Chester Zoo supports PGRs and conservation fellows working on health and management of wildlife (**Shultz, Walton, Gilman**), and we have informed government policy on forest management for wildlife in Myanmar, through engagement with its Wildlife Conservation Society (**Walton**). Our staff also engage with instrument manufacturers, including the development of detector technology with Isotopix (**Holland**) and formal collaboration agreements with Agilent to develop LA-ICP-MS technology (**Tartèse**).

4 c) Contributions to economy and society:

Our relationships with key beneficiaries have enabled delivery of substantial economic and societal benefit, extending far beyond our impact case studies. Significant societal benefits have emerged from Department of Energy and Climate Change funded research on atmospheric methane (**Allen**), delivering policy-related advice and establishing environmental baselining of methane emissions from shale gas production in the UK. Internationally, advice to policymakers during our Air Pollution and Human Health work has contributed to improved air quality in China, India, Vietnam, and Indonesia (**Allan, Coe, McFiggans**). Participation in the All-Party Parliamentary Group on Electronic Cigarettes informed revisions to the UK Tobacco and Related Products Regulations 2016 in response to the EU Tobacco Products Directive (**McFiggans**).

Substantial engagement with the aviation sector has led to near-realtime provision of cloud droplet data from a fleet of in-service commercial aircraft (including China Airlines, Lufthansa). This has enabled validation of weather prediction, leading to increased sales of cloud probes and development of cockpit safety technologies for flying through ice clouds (**Gallagher**).^[SEP] Partnerships with Rolls-Royce, the Defence Science and Technology Laboratory, and NATO on ingestion of sand and dust into gas turbine engines has influenced engine and filter testing protocols and led to a NATO Standard Agreement for compliance of engine durability in harsh environments. The work has informed cost of ownership assessment for manufacturers and end users and informed European Aviation Safety Agency policy on certification specifications for engines (**Jones**).

Our volcanology collaborations with observatories in Italy, Montserrat and Papua New Guinea have improved volcano risk management leading to improved monitoring of the dispersion of gas and ash from eruptions using satellite SO₂ imagery (**Burton, McCormick-Kilbride**). **Bardgett** was a contributing author of the UN State of Knowledge of Soil Biodiversity (2020) and EASAC's Opportunities for Soil Sustainability in Europe (2018) reports, and was "thinker in residence" for the Royal Flemish Academy of Belgium (KVAB) on Soil Natural Capital, which have informed national and international policy on soil protection.

We have demonstrated agility through research on the COVID-19 pandemic. Working with the UN Refugee Agency and Kitrinos Healthcare, we modelled COVID-19 epidemiology in refugee camps (**Gilman**) and informed a Defra report on the COVID-19 pandemic and air quality (**Coe, Allan, McFiggans**). We also contributed to collation of COVID-19 aerosol transmission related resources by the Aerosol Society (**Allan**) and with surgical clinicians we co-designed techniques for prevention of surgical COVID-19 transmission (**McFiggans, Coe, Williams**). Health-related benefits have also emerged from work with the Shillong Public Health Institute and National Vector Borne Disease Programme, India, providing guidance on infectious disease transmission (**Walton**), and the "Cloudy with a chance of Pain" research project resulted in an award-winning app and improved arthritic pain forecasting (**Schultz**).

4 d) Engagement with diverse communities and publics:

Engagement is a key part of UoM's core goal of Social Responsibility and is delivered from local to global scales. Located on an inner-city campus, adjacent to some of the most deprived areas in the UK, we make special efforts to engage with our neighbours to create a sense of involvement

with the University and its research. This includes events at Manchester Museum, showcasing research at ScienceX, our annual Faculty science festival, partnering with schools with low HE participation, using our research to inspire students to enter higher education (e.g. our annual Earth Science Matters research experience days), and participation in a coordinated Schools outreach programme between Global Action Plan, the Phillips Foundation and UoM to assess air quality in schools, which has led to guidance for head teachers on improving air quality for children. We support the Manchester Geological Association with staff members serving on Council, hosting and delivering free public lectures and leading fieldtrips.

We have developed significant engagement activities in developing countries. Notably, staff engage with local community members, leaders of rural indigenous communities, and local water authorities/operators in Cambodia, India, Chile and Myanmar on groundwater arsenic (**Polya**). Engagement with local communities has also been supported by the TIDE (Transformation in Distance Education) project in Myanmar, which provides training in environmental science and innovative pedagogical methods to 12 universities via residential schools, seminars, and training courses in Freshwater Monitoring and Statistics (**Richards, Walton, Shultz, Gilman, Polya**).

We engage regionally, nationally and internationally via different media. **AL** researchers have frequently featured on national TV and radio to promote public engagement, with appearances on BBC News and The One Show, and Discovery Channel and Channel 4/5 documentaries. The Antarctic meteorite programme (**Joy**) attracted much public interest, with press coverage from BBC Radio 4 “The Life Scientific” and BBC Today Show, and our **EE** staff have contributed to public awareness of soil biodiversity via appearances on David Attenborough’s BBC programme “Extinction: The Facts”, Science in Action (BBC World Service), “Naked Scientist”, France24 (**Bardgett**), and BBC Radio 4’s “In our Time” (**Johnson**). **GEO** volcanologists are regularly interviewed on national tv and radio. **AS** scientists have engaged with diverse publics through appearances on local/national TV to communicate research on pollution reduction in Manchester and other major cities, airborne pollution from moorland fires, and changing traffic pollution due to Covid-19 (**Coe**). They have also acted as panellist with local authority leaders on air pollution and mitigation in Manchester and engaged with MPs in the House of Commons on Air Quality policy, both via Policy@Manchester (**Coe**).

Staff have also contributed to major national public outreach events, including public talks such as the Hay and Cheltenham Science Festivals, and exhibits at the Royal Society Summer Science Exhibition. Our reach has expanded significantly via our social media portfolio, which has developed greatly during the REF period: examples include our new Cosmic Cast YouTube channel (4000 listens since 2019), the Earth and Solar System blog (15,696 views from 142 countries in 2019), and Departmental and research group-level Facebook, Twitter and Instagram, reaching an audience of > 7,000 followers.

4 e) Contribution to sustainability of discipline

Our flexible workload allocation model recognises and rewards staff involvement in external research advisory roles that help to shape the research agenda. For example, staff have served on national and international scientific advisory boards, including NASA’s Apollo Curation and Analysis Planning Team for Extra-terrestrial materials (**Joy**), the Advisory Board of the National Centre of Competence in Research Planets (**Gilmour**), Rothamsted Board of Directors and Netherlands Institute for Ecology (**Bardgett**), and on UKRI advisory committees, including The EPSRC Energy Scientific Advisory Committee (**Morris**), and the Science Strategy Board of NCAS (**Coe**). We have also contributed to development of Earth and environmental sciences through leadership of the EPSRC CDT in Nuclear Energy (GREEN) and involvement in the NERC Oil Gas CDT and NCAS and EPSRC Aerosol CDTs.

Our interdisciplinary research directly aligns to and informs environmental policy. Through our nuclear research we’ve built industrial partnerships focused on safe clean-up and disposal of radioactive waste, and established the Centre of Expertise in Effluent Treatment with the support of Sellafield Ltd and the National Nuclear Laboratory. Another example is our NERC Soil Security

research (**Bardgett, Johnson**), aligned to national (e.g. UK Government 25-year Environmental Plan) and international policy/platforms on biodiversity (e.g. IPBES); climate mitigation (e.g. COP 21) and microplastics research (**Kane**) is aligned with emerging environmental challenges. Aspects of our research also directly align with the UN's Sustainable Development Goals (SDG). Examples include research on arsenic exposure (**Polya**) with Public Health England and other agencies, which has contributed to SDG 6 on clean water and sanitation and led to changes in FAO recommendations on intake, and our GCRF research on grassland restoration on the Qinghai-Tibetan plateau (**Bardgett**), which aligns to SDG 15 on reversing of land degradation.

Our air pollution research has made a substantial contribution to the sustainability of the discipline. This is exemplified by our leadership and participation in 5 Air Pollution and Human Health projects, which address issues of direct importance to national and international policy on air quality and consequent health outcomes in China, India and SE Asia (**Allan, Coe, McFiggans**). We lead the UKRI Clean Air Strategic Priority Funded OSCA project (**Coe**), which seeks to predict changes in the atmospheric processes responsible for air pollution, informing government policy through partner Defra.

4 f) Contributions to research base:

Our wider contribution to the research base is evidenced by a number of indicators. Staff have served on NERC's peer review college (17) and funding panels (30), BBSRC funding panels (24), and as Chair of funding panels (3), including NERC peer review committees (**Choularton**) and BBSRC's Committee E, responsible for the award and mentoring of fellowships (**Bardgett**). Our staff have wider influence by serving on >50 international/national funding committees/panels (e.g. the Royal Society's Newton International Fellowships Committee, International Exchanges Committee, and Biological Sciences Grants Panel, Leverhulme Trusts Research Leadership Awards Panel), and via prominent roles on councils and committees of learned societies and Trusts: Garwood serves on council of the Palaeontological Association (2020-present); **Bardgett** served as President of the British Ecological Society (2017-2019); **Lloyd** is current President of the Mineralogical Society; **Shultz** was Chair of Publications Committee, Royal Meteorological Society (2012-2015); and **Boult** was appointed a trustee of the Mersey Rivers Trust (2021-present).

Staff contribute to and are recognised by the research base through engagement with leading academic journals: **Schultz** is Chief Editor of *Monthly Weather Review*, Kane is Chief Editor of *Sedimentology*; Gilmour is Editor-in-Chief of *Earth, Moon and Planets*; and **Bardgett** is Executive Editor of *Journal of Ecology*; 25 staff serve on editorial boards of leading journals. Staff have contributed to the research base through presenting keynote lectures at international conferences and symposia (160); including the Goldschmidt 25th Anniversary Lecture (**Morris**) and Presidential Address at the 2019 British Ecological Society Annual Meeting (**Bardgett**), and invited seminars at UK (165) overseas (221) Universities/research organisations. Unit staff have also played prominent roles in organising and/or chairing international conferences (62), including hosting international conferences, including the 7th European Lunar Symposium 2019 (**Tartèse, Joy**), the International Commission on Illumination Quadrennial Symposium 2015 (**Webb**), the Society for Molecular Biology and Evolution annual conference 2019 (**Knight, Schultz, Walton**), and Carbonate Forum 2020, an international, online conference dedicated to PGR and ECR research in carbonate geoscience, which attracted >400 academic and industrial attendees from over 40 countries (**Hollis**).

Prizes in recognition of staff research excellence include the Schlumberger Medal (**Lloyd** 2019) and Max Hey Medal (**Coker** 2019) of the Mineralogical Society, the Royal Astronomical Society Winton Capital Geophysics Prize (**Joy** 2019), the European Meteorological Society Tromp Foundation award (Schultz 2020), and an honorary doctorate, Hasselt University, Belgium (**Bardgett** 2015) and Royal Society Wolfson Merit Award (**Lloyd** 2018). Lloyd was recognised by the Science Council as one of the UK's top 100 Practising UK Scientists in 2014, **Joy** was listed on the Royal Astronomical Society's list of '21 leading women in UK astronomy and geophysics' in 2016, **Morris** was recognised by the Nuclear Institute as Women in Nuclear, Mission Possible

(2018), and **Allan** (2018), **Coe** (2018) and **Bardgett** (2014-2020) have all been recognised as Highly Cited Researchers. The contributions of staff to the discipline is recognised through fellowships from the American Meteorological Society (**Schultz** 2019), Geological Society (**Manning** 2020, **Hodgetts** 2017, **Schultz** 2019), Royal Geographical Society (**Manning** 2020), Royal Meteorological Society (**Choularton** 2017, **Coe** 2017, **Webb** 2019), Mineralogical Society (**Wogelius** 2019) and Academia Europaea (**Bardgett** 2015, **Burton** 2017).