EVALUATION OF NERC CENTRES 2020: UK CENTRE FOR ECOLOGY & HYDROLOGY EVIDENCE SUBMISSION

Submitted February 2020

1. List of research outputs

Type of output	Title of output	Year	Journal title	DOI
D - journal article	A combined geochemical and hydrological approach for understanding macronutrient sources	2013	Journal of Hydrology	10.1016/j.jhydrol.2013.07.006
D - journal article	A multiyear assessment of air quality benefits from China's emerging shale gas revolution: Urumqi as a case study	2015	Environmental Science & Technology	10.1021/es5050024
D - journal article	A national-scale seasonal hydrological forecast system: development and evaluation over Britain	2017	Hydrology and Earth System Sciences	10.5194/hess-21-4681-2017
D - journal article	A new widespread subclass of carbonic anhydrase in marine phytoplankton	2019	ISME Journal	10.1038/s41396-019-0426-8
D - journal article	A novel probabilistic risk analysis to determine the vulnerability of ecosystems to extreme climatic events	2013	Environmental Research Letters	10.1088/1748-9326/8/1/015032
D - journal article	A synthesis of empirical plant dispersal kernels	2017	Journal of Ecology	10.1111/1365-2745.12666
D - journal article	A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands	2014	Global Change Biology	10.1111/gcb.12580
D - journal article	A trait-based approach for predicting species responses to environmental change from sparse data: how well might terrestrial mammals track climate change?	2016	Global Change Biology	10.1111/gcb.13271
D - journal article	Acidity promotes degradation of multi-species environmental DNA in lotic mesocosms	2018	Communications Biology	10.1038/s42003-017-0005-3
D - journal article	Adaptive and plastic responses of Quercus petraea populations to climate across Europe	2016	Global Change Biology	10.1111/gcb.13576
D - journal article	Adaptive responses of animals to climate change are most likely insufficient	2019	Nature Communications	10.1038/s41467-019-10924-4
D - journal article	Advanced methods for uncertainty assessment and global sensitivity analysis of an Eulerian atmospheric chemistry transport model	2019	Atmospheric Chemistry and Physics	10.5194/acp-19-2881-2019
D - journal article	Advancing projections of phytoplankton responses to climate change through ensemble modelling	2014	Environmental Modelling & Software	10.1016/j.envsoft.2014.01.032
D - journal article	African tropical rainforest net carbon dioxide fluxes in the twentieth century	2013	Philosophical Transactions of the Royal Society (B)	10.1098/rstb.2012.0376
D - journal article	Age, oxidative stress exposure and fitness in a long-lived seabird	2015	Functional Ecology	10.1111/1365-2435.12578
D - journal article	An assessment of the global impact of 21st century land use change on soil erosion	2017	Nature Communications	10.1038/s41467-017-02142-7

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D - journal article	An interyear comparison of CO2 flux and carbon budget at a commercial-scale land-use transition from semi-improved grassland to Miscanthus x giganteus	2017	Global Change Biology Bioenergy	10.1111/gcbb.12323
D - journal article	Assessing contributions of agricultural and nonagricultural emissions to atmospheric ammonia in a Chinese megacity	2019	Environmental Science & Technology	10.1021/acs.est.8b05984
D - journal article	Assessing patterns in introduction pathways of alien species by linking major invasion data bases	2017	Journal of Applied Ecology	10.1111/1365-2664.12819
D - journal article	assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover	2014	Journal of Hydrology	10.1016/j.jhydrol.2014.04.011
D - journal article	Assessing the mode of action of Phoslock® in the control of phosphorus release from the bed sediments in a shallow lake (Loch Flemington, UK)	2013	Water Research	10.1016/j.watres.2013.05.017
D - journal article	Assessing the skill of the UK Hydrological Outlook	2019	Hydrological Sciences Journal	10.1080/02626667.2019.1679375
D - journal article	Bending the rules: exploitation of allochthonous resources by a top-predator modifies size-abundance scaling in stream food webs	2018	Ecology Letters	10.1111/ele.13147
D - journal article	Biochar suppresses N2O emissions while maintaining N availability in a sandy loam soil	2015	Soil Biology and Biochemistry	10.1016/j.soilbio.2014.11.012
D - journal article	Bumblebee family lineage survival is enhanced in high-quality landscapes	2017	Nature	10.1038/nature21709
D - journal article	Can biochar reduce soil greenhouse gas emissions from a Miscanthus bioenergy crop?	2013	Global Change Biology Bioenergy	10.1111/gcbb.12052
D - journal article	Canopy-scale flux measurements and bottom-up emission estimates of volatile organic compounds from a mixed oak and hornbeam forest in northern Italy	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-7149-2016
D - journal article	Carbon budgets for 1.5 and 2°C targets lowered by natural wetland and permafrost feedbacks	2018	Nature Geoscience	10.1038/s41561-018-0174-9
D - journal article	Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO2	2014	Proceedings of the National Academy of Sciences	10.1073/pnas.1222477110
D - journal article	Catchment properties and the photosynthetic trait composition of freshwater plant communities	2019	Science	10.1126/science.aay5945
D - journal article	Catchment-scale biogeography of riverine bacterioplankton	2015	ISME Journal	10.1038/ismej.2014.166
D - journal article	Changes in hedgerow floral diversity over 70 years in an English rural landscape, and the impacts of management	2013	Biological Conservation	10.1016/j.biocon.2013.07.033
D - journal article	Changing climate both increases and decreases European river floods	2019	Nature	10.1038/s41586-019-1495-6
D - journal article	Changing climate shifts timing of European floods	2017	Science	10.1126/science.aan2506

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D - journal article	Characterising phosphorus and nitrate inputs to a rural river using high-frequency concentration-flow relationships	2015	Science of the Total Environment	10.1016/j.scitotenv.2014.12.086
D - journal article	Cleaning up nitrogen pollution may reduce future carbon sinks	2017	Global Environmental Change	10.1016/j.gloenvcha.2017.10.007
D - journal article	Climate change and river flooding. Part 2, Sensitivity characterisation for British catchments and example vulnerability assessments	2013	Climatic Change	10.1007/s10584-013-0726-3
D - journal article	Climate change impact modelling needs to include cross-sectoral interactions	2016	Nature Climate Change	10.1038/nclimate3039
D - journal article	Climate change impact on available water resources obtained using multiple global climate and hydrology models	2013	Earth System Dynamics	10.5194/esd-4-129-2013
D - journal article	Climate-driven variability in the occurrence of major floods across North America and Europe	2017	Journal of Hydrology	10.1016/j.jhydrol.2017.07.027
D - journal article	Climate-induced phenology shifts linked to range expansions in species with multiple reproductive cycles per year	2019	nature communications	10.1038/s41467-019-12479-w
D - journal article	Clinical measures of disease in adult non-CF bronchiectasis correlate with airway microbiota composition	2013	Thorax	10.1136/thoraxjnl-2012-203105
D - journal article	Closing the global ozone yield gap: quantification and cobenefits for multistress tolerance.	2018	Global Change Biology	10.1111/gcb.14381
D - journal article	Combined impacts of future land-use and climate stressors on water resources and quality in groundwater and surface waterbodies of the upper Thames river basin, UK	2018	Science of the Total Environment	10.1016/j.scitotenv.2018.03.052
D - journal article	Community history affects the predictability of microbial ecosystem development	2013 (2014 imprint)	ISME Journal	10.1038/ismej.2013.150
D - journal article	Comparison of soil greenhouse gas fluxes from extensive and intensive grazing in a temperate maritime climate	2013	Biogeosciences	10.5194/bg-10-1231-2013
D - journal article	Comparison of the HadGEM2 climate-chemistry model against in situ and SCIAMACHY atmospheric methane data	2014	Atmospheric Chemistry and Physics	10.5194/acp-14-13257-2014
D - journal article	Compensatory water effects link yearly global land CO2 sink changes to temperature	2017	Nature	10.1038/nature20780
D - journal article	Complementary imaging of silver nanoparticle interactions with green algae: dark-field microscopy, electron microscopy, and nanoscale secondary ion mass spectrometry	2017	ACS Nano	10.1021/acsnano.7b04556
D - journal article	Consequences of human modification of the global nitrogen cycle	2013	Philosophical Transactions of the Royal Society (B)	10.1098/rstb.2013.0116
D - journal article	Contrasting vulnerability of drained tropical and high-latitude peatlands to fluvial loss of stored carbon	2014	Global Biogeochemical Cycles	10.1002/2013GB004782

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D - journal article	Country-scale greenhouse gas budgets using shipborne measurements: a case study for the UK and Ireland	2019	Atmospheric Chemistry and Physics	10.5194/acp-19-3043-2019
D - journal article	Country-specific effects of neonicotinoid pesticides on honey bees and wild bees	2017	Science	10.1126/science.aaa1190
D - journal article	Coupling high-frequency stream metabolism and nutrient monitoring to explore biogeochemical controls on downstream nitrate delivery	2018	Environmental Science & Technology	10.1021/acs.est.8b03074
D - journal article	Crop flower visitation by honeybees, bumblebees and solitary bees: behavioural differences and diversity responses to landscape	2013	Agriculture, Ecosystems and Environment	10.1016/j.agee.2013.03.005
D - journal article	Crop pests and predators exhibit inconsistent responses to surrounding landscape composition	2018	Proceedings of the National Academy of Sciences	10.1073/pnas.1800042115
D - journal article	Declining resilience of ecosystem functions under biodiversity loss	2015	Nature Communications	10.1038/ncomms10122
D - journal article	Decreased atmospheric sulfur deposition across the southeastern U.S.: when will watersheds release stored sulfate?	2014	Environmental Science & Technology	10.1021/es501579s
D - journal article	Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes	2013	Nature	10.1038/nature11818
D - journal article	Defining ecologically relevant water quality targets for lakes in Europe	2014	Journal of Applied Ecology	10.1111/1365-2664.12228
D - journal article	Detecting macroecological patterns in bacterial communities across independent studies of global soils	2018	Nature Microbiology	10.1038/s41564-017-0062-x
D - journal article	Determination and prediction of zinc speciation in estuaries	2018	Environmental Science & Technology	10.1021/acs.est.8b04372
D - journal article	Developing a list of invasive alien species likely to threaten biodiversity and ecosystems in the European Union	2019	Global Change Biology	10.1111/gcb.14527
D - journal article	Developing surface water flood forecasting capabilities in Scotland: an operational pilot for the 2014 Commonwealth Games in Glasgow	2018	Journal of Flood Risk Management	10.1111/jfr3.12281
D - journal article	Diel surface temperature range scales with lake size	2016	PLoS ONE	10.1371/journal.pone.0152466
D - journal article	Different routes, same pathways: molecular mechanisms under silver ion and nanoparticle exposures in the soil sentinel Eisenia fetida	2015	Environmental Pollution	10.1016/j.envpol.2015.07.010
D - journal article	Direct isotopic evidence of biogenic methane production and efflux from beneath a temperate glacier	2018	Scientific Reports	10.1038/s41598-018-35253-2
D - journal article	Discrete wetland groundwater discharges revealed with a three-dimensional temperature model and botanical indicators (Boxford, UK)	2015	Hydrogeology Journal	10.1007/s10040-015-1242-5

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D - journal article	Divergent national-scale trends of microbial and animal biodiversity revealed across diverse temperate soil ecosystems	2019	Nature Communications	10.1038/s41467-019-09031-1
D - journal article	Diversity enhances carbon storage in tropical forests	2015	Global Ecology and Biogeography	10.1111/geb.12364
D - journal article	Do concentrations of ethinylestradiol, estradiol and diclofenac in European rivers exceed proposed EU environmental quality standards?	2013	Environmental Science & Technology	10.1021/es4030035
D - journal article	Does nature conservation enhance ecosystem services delivery?	2016	Ecosystem Services	10.1016/j.ecoser.2015.12.001
D - journal article	Dynamic modeling and target loads of sulfur and nitrogen for surface waters in Finland, Norway, Sweden, and the United Kingdom	2019	Environmental Science & Technology	10.1021/acs.est.8b06356
D - journal article	Earlier seasonal onset of intense mesoscale convective systems in the Congo Basin since 1999	2018	Geophysical Research Letters	10.1029/2018GL080516
D - journal article	Earthworm uptake routes and rates of ionic Zn and ZnO nanoparticles at realistic concentrations, traced using stable isotope labeling	2015	Environmental Science & Technology	10.1021/acs.est.5b03413
D - journal article	Ecological network analysis reveals the inter-connection between soil biodiversity and ecosystem function as affected by land use across Europe	2016	Applied Soil Ecology	10.1016/j.apsoil.2015.08.006
D - journal article	Eddy-covariance data with low signal-to-noise ratio: time-lag determination, uncertainties and limit of detection	2015	Atmospheric Measurement Techniques	10.5194/amt-8-4197-2015
D - journal article	Effect of ocean acidification on organic and inorganic speciation of trace metals	2016	Environmental Science & Technology	10.1021/acs.est.5b05624
D - journal article	Effects of changing climate on European stream invertebrate communities: a long-term data analysis	2018	Science of the Total Environment	10.1016/j.scitotenv.2017.11.242
D - journal article	Effects of habitat composition and landscape structure on worker foraging distances of five bumblebee species	2015	Ecological Applications	10.1890/15-0546
D - journal article	Effects of multiple stressors on cyanobacteria abundance vary with lake type	2018	Global Change Biology	10.1111/gcb.14396
D - journal article	Effects of rotational prescribed burning and sheep grazing on moorland plant communities: results from a 60-year intervention experiment	2018	Land Degradation & Development	10.1002/ldr.2953
D - journal article	Effects of urban density on carbon dioxide exchanges: observations of dense urban, suburban and woodland areas of southern England	2015	Environmental Pollution	10.1016/j.envpol.2014.12.031
D - journal article	Emergent constraint on equilibrium climate sensitivity from global temperature variability	2018	Nature	10.1038/nature25450

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D - journal article	Enhanced global primary production by biogenic aerosol via diffuse radiation fertilization	2018	Nature Geoscience	10.1038/s41561-018-0208-3
D - journal article	Environmental DNA metabarcoding of lake fish communities reflects long-term data from established survey methods	2016	Molecular Ecology	10.1111/mec.13660
D - journal article	Environmentally relevant exposure to an antidepressant alters courtship behaviours in a songbird	2018	Chemosphere	10.1016/j.chemosphere.2018.07.074
D - journal article	Evaluating year-to-year anomalies in tropical wetland methane emissions using satellite CH4 observations	2018	Remote Sensing of Environment	10.1016/j.rse.2018.02.011
D - journal article	Evaluation of regional-scale soil moisture-surface flux dynamics in Earth system models based on satellite observations of land surface temperature	2019	Geophysical Research Letters	10.1029/2019GL082962
D - journal article	Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO2 trends	2013	Global Change Biology	10.1111/gcb.12187
D - journal article	Evidence for a persistent microbial seed bank throughout the global ocean	2013	PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	10.1073/pnas.1217767110
D - journal article	Evidence for a weakening relationship between interannual temperature variability and northern vegetation activity	2014	Nature Communications	10.1038/ncomms6018
D - journal article	Experimental evidence for sustained carbon sequestration in fire-managed, peat moorlands	2019	Nature Geoscience	10.1038/s41561-018-0266-6
D - journal article	Exploiting monitoring data in environmental exposure modelling and risk assessment of pharmaceuticals	2014	Environment International	10.1016/j.envint.2014.07.018
D - journal article	Exploring taxonomic and phylogenetic relationships to predict radiocaesium transfer to marine biota	2019	Science of the Total Environment	10.1016/j.scitotenv.2018.08.343
D - journal article	Exploring the ecological constraints to multiple ecosystem service delivery and biodiversity	2013	Journal of Applied Ecology	10.1111/1365-2664.12085
D - journal article	Extinction risk from climate change is reduced by microclimatic buffering	2018	Nature Climate Change	10.1038/s41558-018-0231-9
D - journal article	Extreme rainfall affects assembly of the root-associated fungal community	2018	New Phytologist	10.1111/nph.14990
D - journal article	Fast and flexible Bayesian species distribution modelling using Gaussian processes	2016	Methods in Ecology and Evolution	10.1111/2041-210X.12523
D - journal article	First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble	2014	Proceedings of the National Academy of Sciences	10.1073/pnas.1302078110
D - journal article	Fish diversity in European lakes: geographical factors dominate over anthropogenic pressures	2013	Freshwater Biology	10.1111/fwb.12167
D - journal article	Food choices, health and environment: effects of cutting Europe's meat and dairy intake	2014	Global Environmental Change	10.1016/j.gloenvcha.2014.02.004

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D - journal article	Frequency of extreme Sahelian storms tripled since 1982 in satellite observations	2017	Nature	10.1038/nature22069
D - journal article	From meteorological to hydrological drought using standardised indicators	2016	Hydrology and Earth System Sciences	10.5194/hess-20-2483-2016
D - journal article	Functional trait composition of aquatic plants can serve to disentangle multiple interacting stressors in lowland streams	2016	Science of the Total Environment	10.1016/j.scitotenv.2015.11.027
D - journal article	Global change effects on plant communities are magnified by time and the number of global change factors imposed	2019	Proceedings of the National Academy of Sciences	10.1073/pnas.1819027116
D - journal article	Global distribution of earthworm diversity	2019	Science	10.1126/science.aax4851
D - journal article	Global phenological insensitivity to shifting ocean temperatures among seabirds	2018	Nature Climate Change	10.1038/s41558-018-0115-z
D - journal article	Global rise in emerging alien species results from increased accessibility of new source pools	2018	Proceedings of the National Academy of Sciences	10.1073/pnas.1719429115
D - journal article	Global trade networks determine the distribution of invasive non-native species	2017	Global Ecology and Biogeography	10.1111/geb.12599
D - journal article	Global variability in leaf respiration in relation to climate, plant functional types and leaf traits	2015	New Phytologist	10.1111/nph.13253
D - journal article	Handling a messy world: lessons learned when trying to make the ecosystem services concept operational	2018	Ecosystem Services	10.1016/j.ecoser.2017.08.001
D - journal article	Heavy metal and nitrogen concentrations in mosses are declining across Europe whilst some "hotspots"□ remain in 2010	2015	Environmental Pollution	10.1016/j.envpol.2015.01.036
D - journal article	Helminth burden and ecological factors associated with alterations in wild host gastrointestinal microbiota	2017	ISME Journal	10.1038/ismej.2016.153
D - journal article	High-resolution global topographic index values for use in large-scale hydrological modelling	2015	Hydrology and Earth System Sciences	10.5194/hess-19-91-2015
D - journal article	Historical nectar assessment reveals the fall and rise of floral resources in Britain	2016	Nature	10.1038/nature16532
D - journal article	Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain	2014	Global Change Biology	10.1111/gcb.12603
D - journal article	How will climate change modify river flow regimes in Europe?	2013	Hydrology and Earth System Sciences	10.5194/hess-17-325-2013
D - journal article	Human influence on climate in the 2014 southern England winter floods and their impacts	2016	Nature Climate Change	10.1038/nclimate2927
D - journal article	Hurricane Maria tripled stem breaks and doubled tree mortality relative to other major storms	2019	Nature Communications	10.1038/s41467-019-09319-2
D - journal article	Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment	2013 (2014 imprint)	Proceedings of the National Academy of Sciences	10.1073/pnas.1222473110

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D - journal article	Hydrological forecasts and projections for improved decision-making in the water sector in Europe	2019	Bulletin of the American Meteorological Society	10.1175/BAMS-D-17-0274.1
D - journal article	Identifying multiple stressor controls on phytoplankton dynamics in the River Thames (UK) using high-frequency water quality data	2016	Science of the Total Environment	10.1016/j.scitotenv.2016.06.239
D - journal article	Impact of temperature, feeding preference and vaccination on Schmallenberg virus transmission in Scotland	2014	Scientific Reports	10.1038/srep05746
D - journal article	Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity	2015	Environmental Research Letters	10.1088/1748-9326/10/11/115004
D - journal article	Impacts of neonicotinoid use on long-term population changes in wild bees in England	2016	Nature Communications	10.1038/ncomms12459
D - journal article	Implications of improved representations of plant respiration in a changing climate	2017	Nature Communications	10.1038/s41467-017-01774-z
D - journal article	Implications of land-use change to short rotation forestry in Great Britain for soil and biomass carbon	2015	Global Change Biology Bioenergy	10.1111/gcbb.12168
D - journal article	Improving the science-policy dialogue to meet the challenges of biodiversity conservation: having conversations rather than talking at one-another	2014	Biodiversity and Conservation	10.1007/s10531-013-0607-0
D - journal article	Increased sensitivity to climate change in disturbed ecosystems	2015	Nature Communications	10.1038/ncomms7682
D - journal article	Increased soluble phosphorus loads to Lake Erie: unintended consequences of conservation practices?	2017	Journal of Environmental Quality	10.2134/jeq2016.07.0248
D - journal article	Indexing butterfly abundance whilst accounting for missing counts and variability in seasonal pattern	2013	Methods in Ecology and Evolution	10.1111/2041-210X.12053
D - journal article	Inertia in an ombrotrophic bog ecosystem in response to 9 years' realistic perturbation by wet deposition of nitrogen, separated by form	2014	Global Change Biology	10.1111/gcb.12357
D - journal article	Institutional challenges in putting ecosystem service knowledge in practice	2018	Ecosystem Services	10.1016/j.ecoser.2017.07.019
D - journal article	Integrating methods for ecosystem service assessment: experiences from real world situations	2018	Ecosystem Services	10.1016/j.ecoser.2017.10.014
D - journal article	Interacting effects of climate change and habitat fragmentation on drought-sensitive butterflies	2015	Nature Climate Change	10.1038/nclimate2746
D - journal article	Interactive biotic and abiotic regulators of soil carbon cycling: evidence from controlled climate experiments on peatland and boreal soils	2014	Global Change Biology	10.1111/gcb.12585
D - journal article	Lake responses following lanthanum-modified bentonite clay (Phoslock®) application: an analysis of water column lanthanum data from 16 case study lakes	2013	Water Research	10.1016/j.watres.2013.07.016

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D - journal article	Land use driven change in soil pH affects microbial carbon cycling processes	2018	Nature Communications	10.1038/s41467-018-05980-1
D - journal article	Land-use emissions play a critical role in land-based mitigation for Paris climate targets	2018	Nature Communications	10.1038/s41467-018-05340-z
D - journal article	Large microplastic particles in sediments of tributaries of the River Thames, UK - abundance, sources and methods for effective quantification	2017	Marine Pollution Bulletin	10.1016/j.marpolbul.2016.09.004
D - journal article	Large sensitivity in land carbon storage due to geographical and temporal variation in the thermal response of photosynthetic capacity	2018	New Phytologist	10.1111/nph.15100
D - journal article	Leaf aging of Amazonian canopy trees as revealed by spectral and physiochemical measurements	2016	New Phytologist	10.1111/nph.13853
D - journal article	Legacy effects of grassland management on soil carbon to depth	2016	Global Change Biology	10.1111/gcb.13246
D - journal article	Long-range forecasts of UK winter hydrology	2015	Environmental Research Letters	10.1088/1748-9326/10/6/064006
D - journal article	Long-term accumulation and transport of anthropogenic phosphorus in three river basins	2016	Nature Geoscience	10.1038/ngeo2693
D - journal article	Long-term changes to the frequency of occurrence of British moths are consistent with opposing and synergistic effects of climate and land-use changes	2014	Journal of Applied Ecology	10.1111/1365-2664.12256
D - journal article	Macroinvertebrate community responses to river impoundment at multiple spatial scales	2019	Science of the Total Environment	10.1016/j.scitotenv.2018.09.264
D - journal article	Mapping ecosystem service and biodiversity changes over 70 years in a rural English county	2013	Journal of Applied Ecology	10.1111/1365-2664.12093
D - journal article	Meta-analysis reveals that pollinator functional diversity and abundance enhance crop pollination and yield	2019	Nature Communications	10.1038/s41467-019-09393-6
D - journal article	Meteorology, air quality, and health in London: the ClearfLo project	2015	Bulletin of the American Meteorological Society	10.1175/BAMS-D-12-00245.1
D - journal article	Microbial community composition explains soil respiration responses to changing carbon inputs along an Andes-to-Amazon elevation gradient	2014	Journal of Ecology	10.1111/1365-2745.12247
D - journal article	Microbial responses to warming enhance soil carbon loss following translocation across a tropical forest elevation gradient	2019	Ecology Letters	10.1111/ele.13379
D - journal article	Microplastic particles reduce reproduction in the terrestrial worm Enchytraeus crypticus in a soil exposure	2019	Environmental Pollution	10.1016/j.envpol.2019.113174
D - journal article	Modeling soil moisture-precipitation feedback in the Sahel: importance of spatial scale versus convective parameterization	2013	Geophysical Research Letters	10.1002/2013GL058511

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D - journal article	Modelling agro-forestry scenarios for ammonia abatement in the landscape	2014	Environmental Research Letters	10.1088/1748-9326/9/12/125001
D - journal article	Modelling future impacts of air pollution using the multi-scale UK Integrated Assessment Model (UKIAM)	2013	Environment International	10.1016/j.envint.2013.09.009
D - journal article	Modelling the introduction and spread of non-native species: international trade and climate change drive ragweed invasion	2016	Global Change Biology	10.1111/gcb.13220
D - journal article	Multigenerational exposure to silver ions and silver nanoparticles reveals heightened sensitivity and epigenetic memory in Caenorhabditis elegans	2016	Proceedings of the Royal Society B: Biological Sciences	10.1098/rspb.2015.2911
D - journal article	Multimodel assessment of water scarcity under climate change	2013 (2014 imprint)	Proceedings of the National Academy of Sciences	10.1073/pnas.1222460110
D - journal article	Multisectoral climate impact hotspots in a warming world	2013 (2014 imprint)	Proceedings of the National Academy of Sciences	10.1073/pnas.1222471110
D - journal article	Nano silver and nano zinc-oxide in surface waters - exposure estimation for Europe at high spatial and temporal resolution	2015	Environmental Pollution	10.1016/j.envpol.2014.10.022
D - journal article	National patterns of functional diversity and redundancy in predatory ground beetles and bees associated with key UK arable crops	2013 (2014 imprint)	Journal of Applied Ecology	10.1111/1365-2664.12171
D - journal article	National-scale analysis of simulated hydrological droughts (1891-2015)	2017	Journal of Hydrology	10.1016/j.jhydrol.2017.05.018
D - journal article	Nitrogen and phosphorus constrain labile and stable carbon turnover in lowland tropical forest soils	2015	Soil Biology and Biochemistry	10.1016/j.soilbio.2014.09.012
D - journal article	Nitrogen deposition and plant biodiversity: past, present, and future	2017	Frontiers in Ecology and the Environment	10.1002/fee.1528
D - journal article	Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots	2018	Nature Communications	10.1038/s41467-018-03540-1
D - journal article	No increase in global temperature variability despite changing regional patterns	2013	Nature	10.1038/nature12310
D - journal article	No saturation in the accumulation of alien species worldwide	2017	Nature Communications	10.1038/ncomms14435
D - journal article	Nutrient fluxes from domestic wastewater: a national-scale historical perspective for the UK 1800â€“2010	2016	Science of the Total Environment	10.1016/j.scitotenv.2016.02.037
D - journal article	Observational evidence for cloud cover enhancement over western European forests	2017	Nature Communications	10.1038/ncomms14065
D - journal article	Organic aerosol components derived from 25 AMS data sets across Europe using a consistent ME-2 based source apportionment approach	2014	Atmospheric Chemistry and Physics	10.5194/acp-14-6159-2014

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D - journal article	Ozone pollution will compromise efforts to increase global wheat production	2018	Global Change Biology	10.1111/gcb.14157
D - journal article	Parental age influences offspring telomere loss	2015	Functional Ecology	10.1111/1365-2435.12630
D - journal article	Persistence of dissolved organic matter explained by molecular changes during its passage through soil.	2019	Nature Geoscience	10.1038/s41561-019-0417-4
D - journal article	Personal exposure monitoring of PM2.5 in indoor and outdoor microenvironments	2014 (2015 imprint)	Science of the Total Environment	10.1016/j.scitotenv.2014.12.003
D - journal article	Phenological sensitivity to climate across taxa and trophic levels	2016	Nature	10.1038/nature18608
D - journal article	Phenology predicts the native and invasive range limits of common ragweed	2013	Global Change Biology	10.1111/gcb.12380
D - journal article	Phosphorus retention and remobilization along hydrological pathways in karst terrain	2014	Environmental Science & Technology	10.1021/es405585b
D - journal article	Plant diversity increases soil microbial activity and soil carbon storage	2015	Nature Communications	10.1038/ncomms7707
D - journal article	Plant functional traits have globally consistent effects on competition	2016	Nature	10.1038/nature16476
D - journal article	Potential landscape-scale pollinator networks across Great Britain: structure, stability and influence of agricultural land cover	2018	Ecology Letters	10.1111/ele.13157
D - journal article	Predicting nitrogen and acidity effects on long-term dynamics of dissolved organic matter	2013	Environmental Pollution	10.1016/j.envpol.2013.08.023
D - journal article	Predicting soil moisture distribution, dry matter, water productivity and potato yield under a modified gated pipe irrigation system: SALTMED model application using field experimental data	2017	Agricultural Water Management	10.1016/j.agwat.2016.02.002
D - journal article	Predicting species' maximum dispersal distances from simple plant traits	2014	Ecology	10.1890/13-1000.1
D - journal article	Predominant pathogen competition and core microbiota divergence in chronic airway infection	2014	ISME Journal	10.1038/ismej.2014.124
D - journal article	Projected flow alteration and ecological risk for pan-European rivers	2013 (2014 imprint)	River Research and Applications	10.1002/rra.2645
D - journal article	Quantifying atmospheric nitrogen deposition through a nationwide monitoring network across China	2015	Atmospheric Chemistry and Physics	10.5194/acp-15-12345-2015
D - journal article	Quantifying global soil carbon losses in response to warming	2016	Nature	10.1038/nature20150
D - journal article	Quantifying gross vs. net agricultural land use change in Great Britain using the Integrated Administration and Control System	2018	Science of the Total Environment	10.1016/j.scitotenv.2018.02.067

Type of output	Title of output	Year	Journal title	DOI
D - journal article	Radiological dose rates to marine fish from the Fukushima Daiichi accident: the first three years across the north Pacific	2015	Environmental Science & Technology	10.1021/es505064d
D - journal article	Range expansion through fragmented landscapes under a variable climate	2013	Ecology Letters	10.1111/ele.12129
D - journal article	Rapid and highly variable warming of lake surface waters around the globe	2015	Geophysical Research Letters	10.1002/2015GL066235
D - journal article	Recent trends and drivers of regional sources and sinks of carbon dioxide	2015	Biogeosciences	10.5194/bg-12-653-2015
D - journal article	Relationship between site-specific nitrogen concentrations in mosses and measured wet bulk atmospheric nitrogen deposition across Europe	2014	Environmental Pollution	10.1016/j.envpol.2014.07.016
D - journal article	Respiratory microbiota resistance and resilience to pulmonary exacerbation and subsequent antimicrobial intervention	2015	ISME Journal	10.1038/ismej.2015.198
D - journal article	Response of cyanobacteria and phytoplankton abundance to warming, extreme rainfall events and nutrient enrichment	2019	GLOBAL CHANGE BIOLOGY	10.1111/gcb.14701
D - journal article	Road verges support pollinators in agricultural landscapes, but are diminished by heavy traffic and summer cutting	2019	Journal of Applied Ecology	10.1111/1365-2664.13470
D - journal article	Role of OH variability in the stalling of the global atmospheric CH4 growth rate from 1999 to 2006	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-7943-2016
D - journal article	Satellite observations of tropospheric ammonia and carbon monoxide: global distributions, regional correlations and comparisons to model simulations	2015	Atmospheric Environment	10.1016/j.atmosenv.2015.02.007
D - journal article	Scale-dependent relationships between tree species richness and ecosystem function in forests	2013	Journal of Ecology	10.1111/1365-2745.12132
D - journal article	Selecting methods for ecosystem service assessment: a decision tree approach	2017	Ecosystem Services	10.1016/j.ecoser.2017.09.016
D - journal article	Selective environmental stress from sulphur emitted by continental flood basalt eruptions	2015	Nature Geoscience	10.1038/ngeo2588
D - journal article	Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability	2013	Nature	10.1038/nature11882
D - journal article	Sewage sludge treated with metal nanomaterials inhibits earthworm reproduction more strongly than sludge treated with metal metals in bulk/salt forms	2017	Environmental Science: Nano	10.1039/C6EN00280C
D - journal article	Short-term soil bioassays may not reveal the full toxicity potential for nanomaterials; bioavailability and toxicity of silver ions (AgNO3) and silver nanoparticles to earthworm Eisenia fetida in long-term aged soils	2015	Environmental Pollution	10.1016/j.envpol.2015.03.033
D - journal article	Siblings of patients with Crohn’s disease exhibit a biologically relevant dysbiosis in mucosal microbial metacommunities	2015	GUT	10.1136/gutjnl-2014-308896

Type of output	Title of output	Year	Journal title	DOI
D - journal article	Similarities in butterfly emergence dates among populations suggest local adaptation to climate	2015	Global Change Biology	10.1111/gcb.12920
D - journal article	Simple models to estimate historical and recent changes of total organic carbon concentrations in lakes	2015	Environmental Science & Technology	10.1021/es503170r
D - journal article	Simulated resilience of tropical rainforests to CO2-induced climate change	2013	Nature Geoscience	10.1038/ngeo1741
D - journal article	Simulating secondary organic aerosol from missing diesel-related intermediate-volatility organic compound emissions during the Clean Air for London (ClearfLo) campaign	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-6453-2016
D - journal article	Social and ecological drivers of success in agri-environment schemes: the roles of farmers and environmental context	2015	Journal of Applied Ecology	10.1111/1365-2664.12412
D - journal article	Soil bacterial networks are less stable under drought than fungal networks	2018	Nature Communications	10.1038/s41467-018-05516-7
D - journal article	Soil fungal:bacterial ratios are linked to altered carbon cycling	2016	Frontiers in Microbiology	10.3389/fmicb.2016.01247
D - journal article	Soil networks become more connected and take up more carbon as nature restoration progresses	2017	Nature Communications	10.1038/ncomms14349
D - journal article	Soil nitrous oxide flux following land-use reversion from Miscanthus and SRC willow to perennial ryegrass	2018	Global Change Biology Bioenergy	10.1111/gcbb.12541
D - journal article	Soil pH effects on the comparative toxicity of dissolved zinc, non-nano and nano ZnO to the earthworm Eisenia fetida	2014	Nanotoxicology	10.3109/17435390.2013.809808
D - journal article	Soil water content in southern England derived from a cosmic-ray soil moisture observing system - COSMOS-UK	2016	Hydrological Processes	10.1002/hyp.10929
D - journal article	Source apportionment of atmospheric ammonia before, during, and after the 2014 APEC summit in Beijing using stable nitrogen isotope signatures	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-11635-2016
D - journal article	Space Partitioning Without Territoriality in Gannets	2013	SCIENCE	10.1126/science.1236077
D - journal article	Spatial and habitat variation in aphid, butterfly, moth and bird phenologies over the last half century	2019	Global Change Biology	10.1111/gcb.14592
D - journal article	Spatial and temporal variability of urban fluxes of methane, carbon monoxide and carbon dioxide above London, UK	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-10543-2016
D - journal article	Spatial patterns and environmental constraints on ecosystem services at a catchment scale	2016	Science of the Total Environment	10.1016/j.scitotenv.2016.04.004
D - journal article	Statistics for citizen science: extracting signals of change from noisy ecological data	2014	Methods in Ecology and Evolution	10.1111/2041-210X.12254
D - journal article	Stocks and flows of natural and human-derived capital in ecosystem services	2016	Land Use Policy	10.1016/j.landusepol.2015.12.014

Type of output	Title of output	Year	Journal title	DOI
D - journal article	Stress exposure in early post-natal life reduces telomere length: an experimental demonstration in a long-lived seabird	2014	Proceedings of the Royal Society B: Biological Sciences	10.1098/rspb.2013.3151
D - journal article	Structural basis for therapeutic inhibition of complement C5	2016	Nature Structural & MOLECULAR BIOLOGY	10.1038/nsmb.3196
D - journal article	Structure from Motion (SfM) photogrammetry with drone data: a low cost method for monitoring greenhouse gas emissions from forests in developing countries	2017	Forests	10.3390/f8030068
D - journal article	Sub-Antarctic marine aerosol: significant contributions from biogenic sources	2013	Atmospheric Chemistry and Physics	10.5194/acp-13-8669-2013
D - journal article	Sustaining recreational quality of European lakes: minimizing the health risks from algal blooms through phosphorus control	2013	Journal of Applied Ecology	10.1111/1365-2664.12059
D - journal article	Taxonomic and functional turnover are decoupled in European peat bogs	2017	Nature Communications	10.1038/s41467-017-01350-5
D - journal article	Temperature and precipitation drive temporal variability in aquatic carbon and GHG concentrations and fluxes in a peatland catchment	2013	Global Change Biology	10.1111/gcb.12209
D - journal article	Testing copper-speciation predictions in freshwaters over a wide range of metal-organic matter ratios	2013	Environmental Science & Technology	10.1021/es304150n
D - journal article	The contrasting effects of genome size, chromosome number and ploidy level on plant invasiveness: a global analysis	2014	New Phytologist	10.1111/nph.12799
D - journal article	The contributions to long-term health-relevant particulate matter at the UK EMEP supersites between 2010 and 2013: quantifying the mitigation challenge	2016	Environment International	10.1016/j.envint.2016.08.005
D - journal article	The dark side of street lighting: impacts on moths and evidence for the disruption of nocturnal pollen transport	2017	Global Change Biology	10.1111/gcb.13371
D - journal article	The ecology of immune state in a wild mammal, Mus musculus domesticus	2018	PLoS Biology	10.1371/journal.pbio.2003538
D - journal article	The effective management of national hydrometric data: experiences from the United Kingdom	2013	Hydrological Sciences Journal	10.1080/02626667.2013.787486
D - journal article	The global carbon budget 1959-2011	2013	Earth System Science Data	10.5194/essd-5-165-2013
D - journal article	The influence of decadal-scale variability on trends in long European streamflow records	2013	Hydrology and Earth System Sciences	10.5194/hess-17-2717-2013
D - journal article	The means determine the end - pursuing integrated valuation in practice	2018	Ecosystem Services	10.1016/j.ecoser.2017.07.011
D - journal article	The rate of loss of dissolved organic carbon (DOC) through a catchment	2013	Journal of Hydrology	10.1016/j.jhydrol.2013.03.016
D - journal article	The robustness of a network of ecological networks to habitat loss	2013	Ecology Letters	10.1111/ele.12117

Type of output	Title of output	Year	Journal title	DOI
D - journal article	The role of nitrogen deposition in widespread plant community change across semi-natural habitats	2014	Ecosystems	10.1007/s10021-014-9765-5
D - journal article	The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands	2016	Aquatic Sciences	10.1007/s00027-015-0447-y
D - journal article	The sensitivities of emissions reductions for the mitigation of UK PM2.5	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-265-2016
D - journal article	The Time-Dependent Transfer Factor of Radiocesium from Soil to Game Animals in Japan after the Fukushima Dai-ichi Nuclear Accident	2016	Environmental Science & Technology	10.1021/acs.est.6b03011
D - journal article	The uncertain climate footprint of wetlands under human pressure	2015	Proceedings of the National Academy of Sciences	10.1073/pnas.1416267112
D - journal article	Toward a Generic Analytical Framework for Sustainable Nitrogen Management: Application for China	2019	Environmental Science & Technology	10.1021/acs.est.8b06370
D - journal article	Towards a climate-dependent paradigm of ammonia emission and deposition	2013	Philosophical Transactions of the Royal Society (B)	10.1098/rstb.2013.0166
D - journal article	Towards a resource-based habitat approach for spatial modelling of vector-borne disease risks	2015	Biological Reviews	10.1111/brv.12149
D - journal article	Trends and drivers of ozone human health and vegetation impact metrics from UK EMEP supersite measurements (1990â€“2013)	2015	Atmospheric Chemistry and Physics	10.5194/acp-15-4025-2015
D - journal article	Trends and variability in weather and atmospheric deposition at UK Environmental Change Network sites (1993â€“2012)	2016	Ecological Indicators	10.1016/j.ecolind.2016.01.061
D - journal article	Trends in atmospheric evaporative demand in Great Britain using high-resolution meteorological data	2017	Hydrology and Earth System Sciences	10.5194/hess-21-1189-2017
D - journal article	Trends in surface water chemistry in acidified areas in Europe and North America from 1990 to 2008	2014	Water, Air, & Soil Pollution	10.1007/s11270-014-1880-6
D - journal article	Ubiquity of organic nitrates from nighttime chemistry in the European submicron aerosol	2016	Geophysical Research Letters	10.1002/2016GL069239
D - journal article	Understanding the controls on deposited fine sediment in the streams of agricultural catchments	2016	Science of the Total Environment	10.1016/j.scitotenv.2015.12.079
D - journal article	Unique metabolites protect earthworms against plant polyphenols	2015	Nature Communications	10.1038/ncomms8869
D - journal article	Urban natural capital accounts: developing a novel approach to quantify air pollution removal by vegetation	2019	Journal of Environmental Economics and Policy	10.1080/21606544.2019.1597772
D - journal article	Use of flood seasonality in pooling-group formation and quantile estimation: an application in Great Britain	2018	Water Resources Research	10.1002/2017WR021623
D - journal article	Validated predictive modelling of the environmental resistome	2015	ISME Journal	10.1038/ismej.2014.237
D - journal article	Variability in organic carbon reactivity across lake residence time and trophic gradients	2017	Nature Geoscience	10.1038/ngeo3051

Type of output	Title of output	Year	Journal title	DOI
D - journal article	Warming effects on greenhouse gas fluxes in peatlands are modulated by vegetation composition	2013	Ecology Letters	10.1111/ele.12167
D - journal article	Water-use efficiency and transpiration across European forests during the Anthropocene	2015	Nature Climate Change	10.1038/nclimate2614
D - journal article	What does three years of hunting great cormorants Phalacrocorax carbo, tell us? Shooting autumn-staging birds as a means of reducing numbers locally	2015	Pest Management Science	10.1002/ps.3782
D - journal article	What is the most ecologically-meaningful metric of nitrogen deposition?	2019	Environmental Pollution	10.1016/j.envpol.2019.01.059
D - journal article	Widespread losses of pollinating insects in Britain	2019	Nature Communications	10.1038/s41467-019-08974-9
D - journal article	Wildlife-friendly farming increases crop yield: evidence for ecological intensification	2015	Proceedings of the Royal Society B: Biological Sciences	10.1098/rspb.2015.1740
D - journal article	Wintertime aerosol chemical composition and source apportionment of the organic fraction in the metropolitan area of Paris	2013	Atmospheric Chemistry and Physics	10.5194/acp-13-961-2013

Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH01_Control of rat poisons by underpinning policy and the UK Stewardship scheme**

Section B

1. Summary of the impact

Controlling rats is essential to protect food quality, human health, and UK infrastructure. Second-generation anticoagulant rodenticides (SGAR) are very effective rat poisons but present a significant risk to other wildlife which, if uncontrolled, would result in restrictions of SGAR use. CEH research, through its Predatory Bird Monitoring Scheme (PBMS) has underpinned the development of voluntary SGAR initiatives by UK industry and national and international SGAR regulations. Under these regulations a UK wide rodenticide stewardship scheme has been introduced and its mandatory monitoring for evaluation is provided by PBMS. This scheme avoids the restriction of SGAR use in the UK and prevents potential damage costs totalling hundreds of millions of pounds.

2. Underpinning Research

The PBMS (https://pbms.ceh.ac.uk/) is a long-term, UK national monitoring scheme that quantifies the concentrations of pollutants in the tissues and eggs of selected predatory bird species in Britain. It uses citizen science to collect between 250-650 carcasses from the public annually.**The current case study concentrates on one aspect of PMBS work: Second Generation Anticoagulant Rodenticides (SGARs).** These poisons are highly toxic to wildlife as well as the intended targets – commensal rodents (rats and mice).

Led by Professor Ian Newton, long term monitoring of barn owls for exposure to SGARs began in 1984 because of concerns about exposure and poisoning in non-target wildlife. This work produced the first long-term dataset of its type. In 2000, the lead investigator became Professor Richard Shore. All PBMS reports, from 1984 to the latest in 2019, are published [1].

The monitoring indicated a significant rise in exposure of barn owls to SGARs (reflecting increased usage) during the 1980s and early 1990s, reaching a maximum of about 30% of individuals [2, 3]. Additional experimental work demonstrated the potential for exposure to cause secondary poisoning in owls [4]. Critically, however, newly developed analytical equipment with enhanced sensitivity revealed that exposure had been severely underestimated and, in fact, 80-90% of barn owls across Britain were exposed to SGARs [5]. Other studies initiated or involving CEH, demonstrated that exposure was not confined to barn owls but was widespread across multiple predatory bird and mammal species, many of which did not prey on commensal rodents [6, 7]. This indicated extensive and unanticipated contamination across all trophic pathways.

CEH also investigated how user behaviour, usage patterns and ecology all influence the likely severity of exposure, and resultant risk of poisoning, of non-targets [5]. With Canadian colleagues, Professor Shore also developed novel probabilistic approaches to diagnosing mortality based on measurements of liver resides [6]. This, for the first time, provided a means of estimating the extent of mortality that may occur in wildlife populations. Through this and other more traditional scientific approaches, CEH demonstrated that poisonings from SGARs do occur in barn owls and other species but can be particularly numerous in key species (such as red kites) that are heavily exposed through their diet [8]. Overall, this knowledge has provided the evidence base that indicates how and why exposure varies and can be mitigated, and which vulnerable species may be in most need of protection. CEH studies have spurred research into this issue globally (19 ISI authored/co-authored between 1990 and 2018 were cited 748 times by December 2019) and have been used as evidence by policy-makers across the world. In a series of key reviews CEH, together with key collaborators, have elucidated the worldwide state-of the art understanding (and knowledge gaps) with regards to monitoring and quantifying SGAR exposure and evaluating impacts on wildlife [9].

3. References to the underpinning work

[1] https://pbms.ceh.ac.uk/content/pbms-reports

[2] Newton, I., et al, L. Empirical evidence of side-effects of rodenticides on some predatory birds and mammals. in *Advances in vertebrate pest management* 1999, (eds D.P. Cowan & C.J. Feare), Filander Verlag, Fürth, pp. 347-367

[3] Shore, R.F., et. al., Second generation anticoagulant rodenticide residues in barn owls. CEH contract report to the Campaign for Responsible Rodenticide Use (CRRU) UK, 2018, pp. 24.

[4] Newton, I., et al., The toxicity of the rodenticide flocoumafen to barn owls and its elimination via pellets. Pesticide Science, 1994, 41, 187-193.

[5] Shore, R.F., et al., 'Monitoring rodenticide residues in wildlife', Rodent pests and their Control, 2nd edition. CAB International, Wallingford, 2015, pp. 346-365

[6] Thomas, P.J., et. al., Second generation anticoagulant rodenticides in predatory birds: probabilistic characterisation of toxic liver concentrations and implications for predatory bird populations in Canada. *Environment International,* 2011, 37 914-920 and corrigendum 40:256

[7] Shore, R.F., et al., Spatial and temporal analysis of second-generation rodenticide residues in polecats (*Mustela putorius)* from throughout their range in Britain, 1992-1999. *Environmental Pollution,* 2003, 122 183-193.

[8] *Molenaar, et al., Poisoning of reintroduced red kites (*Milvus milvus*) in England. *European Journal of Wildlife Research,* 2017, 63 *94.* https://doi.org/10.1007/s10344-017-1152-z

[9] *Rattner, B.A., et al., Adverse Outcome Pathway and Risks of Anticoagulant Rodenticides to Predatory Wildlife. *Environmental Science & Technology*, 2014, 48, 8433-8445

4. Details of the impact

Policy & regulatory impact of work on SGARs

The table below illustrates the context of the activities and impact of the PBMS. The policy baseline is set in 1999 when Defra guidance on safe rodenticide use on farms did not consider any environmental risks. PBMS research has enabled awareness that the problem exists and has fed into policy and industrial considerations. By 2019, the main regulations on SGARs in the UK are derived from CEH research and the monitoring required is the PBMS.

Date	CEH PBMS activity and the resultant Impact
Mid 1970s -80s	SGARs introduced in UK after resistance started to render older products ineffective. The enhanced potential for SGARs to poison wildlife raises environmental concerns but there is a lack of evidence about wildlife exposure.
1984-on	Long term monitoring of SGAR exposure in barn owls and other studies by CEH (and others) demonstrated global contamination of wildlife and associated poisoning risk.
2002-2003	In the UK, SGAR environmental risk was considered by the Advisory Committee for Pesticides (ACP) Environment Panel's *Rodenticide Risk Assessment Technical (RRAT) Working group* (chaired by CEH's Professor Richard Shore). RRAT evidence included PBMS monitoring and data. Its recommendations, endorsed by the ACP, called for mitigation of exposure and assessment of outcomes [10].
2004	CEH research on SGARs formed part of the evidence reviewed in US evaluation and regulation of anticoagulant rodenticides [11].
2004-2005	UK industry responds to the ACP recommendations by establishing the Campaign for Responsible Rodenticide Use (CRRU), first in the UK and then in Ireland. PBMS worked closely with CRRU as its long-term data sets on rodenticides in barn owls are used as a baseline against which to measure future changes in exposure. CEH took part in CRRU's launch and attends annual meetings. CRRU supports continued CEH monitoring of rodenticides in barn owls. The CRRU chairman describes the PBMS contribution: '*It was looking at anticoagulants in barn owls. It became the main driver*

	behind CRRU because it was an annual scheme. So it helped to inform the setup of CRRU and PBMS' annual reports became a bench mark for CRRU to look at' [12].
2008	Based on 2004 work, the US Environmental Protection Agency implemented a decision on rodenticides mitigation measures to reduce risks to wildlife [13].
2008-2010	The EU Standing Committee on Biocidal Products re-assesses SGARs under Directive 98/8/EC and concluded that there is unacceptable environmental risk but they can be authorised on grounds of the human health benefits derived from rodent control. PBMS work is part of the evidence base used [14].
2013	Globally, the United Nations Environment Programme (UNEP) Convention on the Conservation of Migratory Species of Wild Animals undertook a review of the ecological effects of poisoning on migratory birds which draws on PBMS data. The subsequent international workshop, chaired by Professor Richard Shore, culminated in recommendations and guidelines that include preventing poisoning risk globally from rodenticides used to protect crops [15] which are adopted by UNEP signatories.
2012 and 2013	EC Directive 98/8/EC is replaced by Regulation 528/2012 on biocidal products where authorisation of SGARs at EU level defers requirement of mitigation measures on product authorisation to individual member states. In the UK, the Health and Safety Executive (HSE) reviewed the SGAR environmental risk in which CEH/PBMS evidence is heavily used. A stakeholder consultation and meeting (involving PBMS) about possible mitigation measures was held [16].
2014	The HSE consultation resulted in a requirement for Stewardship of anticoagulant rodenticides as products were re-registered for use in 2015/16. Stewardship's primary aim is to improve best practice such as to reduce wildlife exposure. However, product authorisation was also relaxed, allowing outdoor use of all SGARs (instead of just the two least toxic) to combat developing resistance in rats; this may increase the risk to non-targets. The combined effect of implementing stewardship but relaxing product authorisation are therefore uncertain, and so assessment of subsequent changes in wildlife exposure is *absolutely critical* to meeting Regulation 528/2012. The PBMS solved this problem for the UK by outlining how it could tailor its monitoring so that it could determine whether non-target exposure reduces as Stewardship progresses. HSE commissioned CEH to develop the monitoring approach [17].
2015-2016	HSE-led Government Oversight Group (GOG) for anticoagulant rodenticides required PBMS monitoring to be part of the current stewardship programme. This monitoring is the only statistically robust means of assessing change in non-target exposure.
2016	PBMS evidence is used in European Chemicals Agency (ECHA) re-evaluation of SGARs at EU level [18].
2015 on	Product reauthorisation is completed in UK and draws on CEH data. SGAR-based products continue to be used in the UK but only under Stewardship.
2016 on	PBMS barn owl monitoring conducted as part of Stewardship. Data provided to CRRU as annual reports and findings summarised in annual stewardship reports [19]. PBMS provides data, analysis and expert advice during the year and attends the Government Oversight Group (GOG) for rodenticide Stewardship. *'PBMS provides good quality, independent external scientific data that allows the Government Oversight Group to make evidence based decisions…PBMS is the important one in measuring environmental impacts…it's the trust and communication from PBMS which makes a huge difference too'*, Head of Biocides, UK HSE [20].
2016 on	Red kites have been reintroduced into the UK but are at risk of SGAR exposure because they scavenge dead rats. The PBMS-led WILDCOMS knowledge exchange network brings together previously disparate reporting of exposure and poisoning to provide a national-scale picture. Data is reported provided annually to the GOG.

2018	European Chemicals Agency (ECHA) revise their emission scenario document [21] for rodenticides. PBMS work cited as part of the evidence base.
2020-2021	Five year GOG review of stewardship outcomes that will determine future activities and SGAR authorisations.

Beneficiaries and Value of PBMS

The use and impact of PBMS data as an evidence base globally and particularly at EU and national level has been described above. PBMS data has benefitted regulators and policy makers by providing them with the evidence base and expert input needed to recognise and weigh the environmental risks from SGAR use against the benefits, thereby having the information for balanced decision making. This, crucially, includes provision of a means of tracking the outcomes of the key UK mitigation policy of Stewardship. The Natural England Principle Specialist in this area confirms '*PBMS is the best example of wildlife monitoring and exposure that measures changes to the environment as a result of policy intervention. It's hard to think of an alternative that gives a measure of chemicals in the environment'* [22].

In the wider context, both the general public and those in occupations which are classed as professional users (primarily farmers who often do their own control) benefit from such regulation as it enables them to continue to control rodent infestations and damage but without an attendant unacceptable risk to, and potentially large-scale, wildlife mortalities.

The UK pest-control industry has been a major beneficiary as the PBMS has provided it with monitoring data, expert advice and the tools needed to inform its "Think Wildlife" campaign and to deliver the environmental monitoring evaluation of Stewardship and create innovation. The Chairman of the Campaign for Responsible Rodenticide Use summed up: '*The whole SGAR market depends on Stewardship - HSE say we will not authorise any products for use outdoors unless there is monitoring. The UK is in the best position to manage SGARs because it has the PBMS and its historical data for that monitoring – and this is not happening anywhere else'* [12]. The reach of the EU directive is wide with companies responding directly to its implementation. For example, in response to the EU legislation UK pest control company Rentokil has stated '*the business benefits…by making sure that everyone in the industry follows common codes of practice. It also makes sure that competitors cannot adopt less responsible practices*' [23].

Economic impact:

Rodent populations are controlled primarily because of their role in transmitting diseases to people and livestock, but they also damage stored foods and infrastructure. There are estimates of damage costs ($30 billion /year in the US but none exists for the UK) but it is unclear what these would be without rodent control. To give this some context, in the UK, mice and rats are thought to be responsible for 50% of farm fires through gnawing wiring (£47.5m in insurance costs in 2015).The UK market size for rat control via poison is estimated at £230 million [24]. The market value can be taken as a value of the Stewardship scheme as it is measure of business/public's willingness to pay to avoid the outcome of uncontrolled rat infestations.

Natural England have said that without the existence of PBMS '*It would have been difficult to come up with something viable. It's highly unlikely that we could have come to Stewardship without the PBMS scheme. So instead of being evidence based the decisions would be output based measured e.g. farmers getting training; But because we have PBMS we have evidence based decision making based on outcomes.*' [22]. If PBMS had not existed the UK would still have to have SGAR regulation. Below are three likely scenarios for the UK without PBMS which can be used to gauge value of economic impact of having PBMS:

1. **SGARs would not have been permitted for outdoor use**. In this scenario, it is likely that other rodent control would prove ineffective and the £230 million/year would be largely lost This is likely to be a minimum value as ineffective control would be expected to result in higher rat numbers and greater economic and health damage.
2. **Stewardship and simultaneous change in SGAR use authorisations would have been implemented (as with other products) but with no way to assess the environmental**

outcomes. The permission under stewardship to use the most toxic SGARs outdoors may lead to increased exposure and poisoning of wildlife, but conversely better usage practice promoted by stewardship may reduce wildlife exposure. Outcomes are uncertain. Monitoring provides an early alert to increasing exposure and poisoning risk. It facilitates rapid intervention to avoid mass wildlife casualties and associated cultural costs. Monitoring will also reveal any improvement in wildlife exposure associated with stewardship. If PBMS had not existed, then alternative environmental monitoring would have needed to be developed. According to the Head of Biocides at HSE '*there would have been a lag in the benchmark – that would have taken several years to build'* [20]. Subsequent establishment of *de novo* monitoring would have been against a backdrop of ongoing stewardship, and the UK would have been unable to determine what the levels of wildlife exposure were prior to stewardship.

3. **SGAR use would have been restricted to trained professionals only**, as in France and Germany, preventing domestic use or use by people who use them in their occupations such as farmers and gamekeepers. Stewardship supports the private SGAR market in the UK estimated to be £35m [24].

Wider and Future Impact of PBMS

In addition to work on SGARs, PBMS work feeds into many aspects of UK environmental contaminants monitoring policy. Other current PBMS priority chemicals include lead, mercury and Persistent Organic Pollutants (POPs) such as brominated flame-retardants. PBMS data is utilised by policy makers and regulators, such as the Health & Safety Executive, Defra family, European Chemicals Agency, and by industry and non-government agencies. Examples include: in 2015 PBMS data fed in to Defra's Lead Ammunition Group review [25] which made policy recommendations; mercury monitoring provides the UK evidence of the effectiveness of the UNEP Minimata Convention on mercury [26]; PBMS works with government agency partners (e.g. the Animal Plant Health Agency) to screen for zoonotic diseases e.g. West Nile Virus [27].

This essential environmental monitoring will continue into the future. The PBMS sample archive provides the means for both current analyses and retrospective trend analysis of, as yet, unmonitored chemicals. The PBMS work and archive will be essential to the 25 Year Environment Plan indicators of chemical exposure and to post-Brexit pesticide monitoring. Natural England have said '*There is a specific request from government to involve data and the [PBMS] exposures will be invaluable at the table for the monitoring in the 25 year plan*' [22].

5. Sources to corroborate the impact

[10] Minutes of ACP 302, held on 4 September 2003

[11] **'**Potential Risks of Nine Rodenticides to Birds and Nontarget Mammals: a Comparative Approach', July 2004, US Environmental Protection Agency

[12] Chairman of CRRU, personal communication, July 2019

[13] Rodenticides Final Risk Mitigation Decision; Notice of Availability, EPA–HQ–OPP–2006–0955; FRL–8367–8, EPA Federal Register / Vol. 73, No. 108 / Wednesday, June 4, 2008

[14] e.g. Directive 98/8/EC concerning the placing of biocidal products on the market, Assessment Report, Difenacoum Product-type 14 (Rodenticides),Sept 2009

[15] Guidelines to Prevent the Risk of Poisoning to Migatory Birds, UNEP, UNEP, CMS, COP11, Doc.23.1.2, Annex 2, 2013

[16] https://www.hse.gov.uk/biocides/eu-bpr/rodenticides.htm accessed Dec 2019 and 'Consideration of the environmental risk from Rodenticides', HSE, 2012

[17] Shore, R.F., Henrys, P.A. & Walker, L.A. 2014.CEH contract report to the Health & Safety Executive. 45 pp.

[18] 'Risk Mitigation Measures for Anticoagulant Rodenticides', Berny P, et.al., Contract n°07-0307/2012/638259/ETU/D3, October 2014 and 'Transitional Guidance on Efficacy Assessment for Product Type 14 Rodenticides', ECHA, Dec. 2016

[19] https://www.thinkwildlife.org/downloads/ for all annual reports, accessed December 2019

[20] Head of Biocides, UK Health and Safety Executive, personal communication, July 2019

[21]'Revised Emission Scenario Document for Product Type 14 Rodenticides', Aug. 2018, ECHA

[22] Principle Specialist, Natural England, personal communication, July 2019

[23] https://www.rentokil-initial.com/investors/annual-reports.aspx

[24] World Pest Control UK Market Research Report, IBISworld, July 2019

[25] Appendix 6, Lead Ammunition Report, June 2015, Lead Ammunition Group, for Defra

[26] 'Global Review of Mercury Monitoring Networks', UNEP, United Nations Environment Economy Division, Chemicals and Waste Branch, Nov 2016

[27] GB Wildlife Disease Surveillance Partnership quarterly report Disease surveillance and emerging threats, p8 Volume 26: Q3 – July-September 2019, GB Wildlife Disease Surveillance Partnership

Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH02_Sustainable development of offshore renewables through minimising impacts on protected wildlife**

Section B

1. Summary of the impact

The UK government is committed to reaching net zero emissions by 2050. In contributing to this goal, the Offshore Wind Sector Deal has set a target of 30GW generation capacity from Offshore Wind Farms (OWFs) by 2030, which is equivalent to a third of UK electricity demand provided by this technology. However, OWFs may have detrimental effects to protected wildlife, notably seabirds and marine mammals, from collisions and displacement. CEH research on the interaction between seabirds and wind farms has increased biological realism, reduced uncertainty, and transformed the environmental assessment framework. CEH tools are embedded in government planning and industry approval processes for OWFs, reshaping how the offshore renewable targets, and ultimately net zero goals, can be met in a sustainable manner.

2. Underpinning research

CEH began monitoring the demography, diet and behaviour of seabirds on the Isle of May in the outer Firth of Forth in 1973. Since 1986, we have been funded for this work through CEH National Capability and by the Joint Nature Conservation Committee (JNCC). This long-term monitoring research underpins focussed field-based and modelling projects on seabird foraging ecology and population dynamics financed by a range of customers in the public and private sectors.

Baseline understanding of drivers of change in seabird populations *(Leads: Francis Daunt, Sarah Burthe, Maria Bogdanova, Kate Searle and Mark Newell)*

CEH's long-term study of seabird populations is the most comprehensive in the UK. As part of CEH's National Capability programme UKSCAPE, and as a Key Site in the UK's Seabird Monitoring Programme administered by the JNCC, our research on the Isle of May provides a unique resource through its ability to track contrasting population responses in different species over decadal timescales [1]. Statutory bodies and conservation organisations use the results from CEH research in their core activities, for example, in the *State of the Nature 2019* report. We quantify the effects on seabirds of multiple factors, including climate change and fisheries to provide key evidence on causes of change in the populations of UK seabirds [2]. This research delivers a robust baseline that is critical in estimating the potential impacts of OWFs, of which four have been consented in the region.

Novel empirical approaches to estimate interactions between seabirds and OWFs *(Leads: Francis Daunt, Maria Bogdanova, Mark Newell and Kate Searle)*

Traditionally, the distribution of seabirds in the marine environment has been estimated by undertaking at-sea surveys using boats or planes. However, the OWF industry are required to quantify the effects of developments specifically on seabirds breeding at colonies that have the highest conservation designation (Special Protections Areas, or SPAs). The best method of demonstrating the connectivity between OWF sites and SPA colonies is GPS tracking of breeding individuals [3]. This approach not only allows us to quantify the spatial distribution of these protected birds in relation to OWFs but also to evaluate the population-level consequences of these developments on SPAs – the ultimate goal of any impact assessment. We have designed and delivered this approach during 2017–2019, funded by the energy companies EDF Renewables, Equinor and Vattenfall [4].

Novel modelling approaches to estimate impacts of OWFs on seabirds *(Leads: Kate Searle, Deena Mobbs, Stephen Freeman, Maria Bogdanova and Francis Daunt)*

Interactions of the type outlined above may involve seabirds colliding with turbine blades or being displaced from their favoured foraging habitats. Collisions cause immediate mortality, whereas

displacement causes changes in behaviour that affect body condition and, ultimately, survival and successful breeding. This so-called sub-lethal effect is challenging to quantify. CEH has developed an individual-based model for estimating the effects of displacement on survival and breeding performance, which is the most comprehensive undertaking of its kind [5]. Assessing how these changes affect future population size is achieved through Population Viability Analysis (PVA). We have been the first to undertake Integrated Population Modelling in this context, a Bayesian approach that forecasts seabird populations under different future OWF scenarios while properly accounting for uncertainty. These models have quantified the potential effect of consented developments on protected populations in our study region [6]. We have also undertaken a nationwide analysis of seabird colonies and have provided recommendations on the most appropriate population modelling method for forecasting population change given the quality of input data [7]. We have developed a new PVA Metric – a measure for summarising population-level impacts that regulators use in decision-making [8]. CEH has undertaken these research activities since 2013 as part of a series of contracts for Scottish and UK government agencies.

3. References to the underpinning work

Baseline understanding of drivers of change in seabird populations

[1]. Howells, R.J. et al. (2017) From days to decades: short- and long-term variation in environmental conditions affect diet composition of a marine top-predator. Marine Ecology Progress Series 583: 227–242.

[2]. Daunt, F. et al. (2017) Marine climate change impacts – a decadal review: Seabirds. MCCIP Science Review 2017: 42–46.

Novel empirical approaches to estimate interactions between seabirds and OWFs

[3]. Bogdanova, M.I. et al. (2014) Among-year and within-population variation in foraging distribution of European shags *Phalacrocorax aristotelis* over two decades: implications for marine spatial planning. Biological Conservation 140:292–299

[4]. Bogdanova, M.I. et al. (2019) GPS tracking of common guillemot, razorbill, Atlantic puffin and black-legged kittiwake on the Isle of May, summer 2018. Contract report to EDF Renewables.

New modelling tools for assessing effects of OWFs on seabirds

[5]. Searle, K. et al. (2014) Population consequences of displacement from proposed offshore wind energy developments for seabirds breeding at Scottish SPAs. https://www2.gov.scot/Resource/0045/00451411.pdf

[6]. Freeman, S. et al. (2014) Population dynamics of Forth & Tay breeding seabirds: review of available models and modelling of key breeding populations. https://www2.gov.scot/Resource/0044/00449072.pdf

[7]. Searle, K. et al. (2019) Scoping Study - Regional Population Viability Analysis for Key Bird Species CR/2016/16. Report to Scottish Government.

[8]. Jitlal, M. et al. (2017) Testing and validating metrics of change produced by Population Viability Analysis (PVA) (Ref CR/2014/16). Scottish Marine and Freshwater Science 8:23. http://data.marine.gov.scot/sites/default/files//SMFS%200823.pdf

4. Details of the impact

The UK government's Offshore Wind Sector Deal aims to increase generation capacity to 30GW by 2030. It has an ambition for the UK to be part of a global market worth £33bn/year by 2030 with UK exports worth £2.6bn/year and to have generated 27,000 jobs – a three-fold increase on today's level [9]. To achieve the targets set out in the Sector Deal, it is critical that OWF development is undertaken in a manner that does not contravene environmental legislation. Seabirds represent a profound consenting risk to OWFs because of the potential negative impact on their populations. The Director of Marine Operations, Joint Nature Conservation Committee has stated: *"Kittiwakes*

were recently [2019] identified at a key strategic meeting attended by JNCC, Natural England, SNH and RSPB as the species currently posing the greatest consenting risk to offshore wind development in the UK. CEH's long-term study of kittiwake ecology provides JNCC with crucial evidence to inform our advice on kittiwake conservation" [10]. The UK has a particular responsibility in this regard because it is home to internationally important seabird populations that have full legal protection under the Birds Directive. The UK has designated all major seabird colonies as Special Protection Areas (SPAs) under this legislation. Developers of OWFs must demonstrate to regulators that they have satisfactorily addressed these two questions:

1) Are OWFs negatively affecting individual birds from SPAs?
2) Are these effects causing declines in populations at SPAs?

Working with government and the wind energy sector, CEH has substantially improved the evidence base with carefully designed empirical and modelling studies to test robustly these questions for the first time, thereby reducing uncertainty in offshore wind development assessments and subsequent consenting [11]. This is a critical contribution to reducing the risk of not gaining consent, which is the greatest current concern among the OWF sector, and could undermine investment and the achievement of net zero targets. The Chief Scientific Adviser, Defra (2012-2019) has stated: "*One of the biggest challenges to the development of sustainable wind power in offshore regions is the potential impact this could have on seabirds. Research done by CEH, which integrates this improving knowledge base in to impact models, could make the difference between authorities granting an operating licence or this being refused. The work by CEH reduces this possibility, reduces the possible effects after construction and makes the offshore wind power sector more viable*" [12].

Shaping empirical studies in OWF assessments

Since the 1980s, CEH have been global pioneers in deploying electronic data loggers on seabirds to obtain location and behaviour at sea [3]. We were the first to deploy GPS devices to seabirds to test the overlap between planned OWF footprints and individual seabirds breeding at SPAs [13]. CEH has engaged with both industry and government to ensure that it is now a standard approach in OWF assessments. For example, it is integral to the Ornithological Monitoring Strategies of the energy companies EDF and SSE that have been agreed with regulators (2018–2020) [4]. These plans dictate the assessments that developers must undertake before, during and after construction: *"Offshore construction of the Neart na Gaoithe offshore wind farm (NnG) commences in 2020 and CEH are undertaking an ongoing programme of seabird monitoring throughout the different phases of the wind farm. CEH are tracking seabirds to understand if the presence of the new wind farm has an effect on this behaviour. The study falls under the NnG ornithology monitoring strategy (a condition of the project's marine consents) and is approved by the Scottish Government. It uses cutting edge technology that provide important information for understanding the sensitivity of seabirds to offshore development. This type of research is essential for EDF Renewables as a responsible developer, so we can understand the impacts of our projects and if found to occur, to mitigate these impacts. Outputs of the CEH work will feed into future development decisions, such as the allocation of new offshore wind farm sites. Ultimately the work will help the UK to work towards meeting its climate change ambitions whilst minimising impacts on the natural environment"* Project Director, EDF Renewables [14].

CEH's research programme is designed to deliver the most robust empirical estimates of OWF effects on seabird populations in the UK, and is therefore benefitting government, industry and conservation NGOs in their shared goal of responding to the climate emergency in an environmentally sustainable way. The Head of RSPB Centre for Conservation Science has supported this by stating: *"The RSPB have invested significant resource engaging with renewable wind farm proposals to try and ensure positive outcomes for both climate and biodiversity. Key to this work is having good science to underpin the decision making process. The work carried out by CEH in collecting empirical data, such as GPS tracking from internationally important seabird colonies, has been invaluable. This work has been notable for its impartiality and scientific rigour, meaning it is not only invaluable to the RSPB, but also to the renewable energy industry, statutory*

decision makers and, most importantly, to the conservation of our marine environment, helping to ensure the urgent action needed to tackle the climate emergency can proceed in harmony with nature" [15].

Shaping modelling approaches in OWF assessments

CEH has developed an online tool for estimating effects of seabird displacement (SeabORD) [16] that has been adopted by government in the assessment of OWFs (2018–2020) [11]. For key species, of which the UK holds internationally important numbers, it replaces the former method ('Displacement Matrix'), which was a tool for eliciting expert judgement rather than a quantification of empirical data. SeabORD has also been used by industry to aid the design of OWFs and minimise interactions with seabirds (2017–2018): *"ICOL, a wholly owned subsidiary of Red Rock Power Limited (RRPL), has worked with CEH over a number of years for ornithological modelling and advice on the Inch Cape Offshore Wind Farm and as part of the wider Forth and Tay cluster. Novel survey and modelling methods implemented by CEH fed into the complex ornithological assessments for the Inch Cape Wind Farm. Further innovative modelling work carried out by CEH, to assess the displacement and barrier effects of the proposed wind farm, helped feed into the wind farm design process – allowing ICOL to consider different design scenarios which could potentially reduce our ornithological impacts"* Head of Engineering, Red Rock Power Ltd. [17].

Effects of OWFs on protected seabird populations

CEH has developed an online Population Viability Analysis (PVA) tool [18] that ensures transparency and consistency of approach and greatly increases the speed by which estimates of population change resulting from OWFs can be undertaken. Accordingly, it is being used by regulators and wind farm developers for estimating predicted seabird population change associated with new OWFs (2019-2020). The Director Specialist Services and Programmes at Natural England has confirmed that *"CEH were commissioned in 2018 to produce an interactive population modelling tool for Natural England. The tool is freely available online. Several offshore windfarm developers are now using the PVA Tool as part of their impact assessments. This has allowed Natural England to sense-check, replicate and explore uncertainty around the predicted impacts in their assessments. Natural England will be in a better position to advise the regulator about the potential impacts of these developments compared to previous offshore development applications. This should reduce the uncertainty in the assessment of impacts and therefore reduce consenting risk for developers and regulators"* [19].

CEH has developed an overarching framework for assessing population-level impacts of OWFs that has been adopted by the Scottish government. The increased biological realism and reduction in uncertainty that this provides will help ensure that regulators make the most robust decisions (2019–2020) [11, 20]. This end-to-end approach combines indirect effects on mortality through changes in behaviour and body condition arising from displacement with direct mortality from collisions to estimate overall impacts on population size. As such, the framework captures all key processes in assessments of the interactions between OWFs and seabirds for the first time.

Marine Spatial Planning to achieve Offshore Wind Sector Deal goals

CEH has also developed a sensitivity mapping tool that is being used by the Scottish government to devise medium-term plans on the optimal location of OWFs that minimise interactions with protected wildlife (2018–2020) [21]. Scotland's Climate Change Bill has set even more ambitious goals than the UK, with net zero emissions by 2045, and a major expansion of the OWF sector is being planned. This tool is being used to shape how and where this expansion takes places in Scottish waters [11]. Plans are being finalised to expand this tool to the whole of the UK, work scheduled for 2020.

5. Sources to corroborate the impact

[9]. Offshore Wind Sector Deal, March 2019: https://www.gov.uk/government/publications/offshore-wind-sector-deal

[10]. Personal communication, Director of Marine Operations, Joint Nature Conservation Committee. 16/12/19.

[11]. Personal communication, Head of Marine Scotland Science (MSS), Scottish Government. 07/01/20: *"MSS, on behalf of Scottish Government, is committed to developing renewable energy in a sustainable manner based on the best available scientific evidence being used to inform the planning and licencing processes. I am delighted that CEH have been able to undertake a number of projects for the Scottish Government to provide a substantial improvement in the evidence base available in Scotland and across the UK more generally. The projects have enabled us to develop an overarching framework for estimating cumulative effects of offshore wind farm development scenarios on seabirds, and to understand the consequences of displacement from wind farms, attributing affected birds to their protected colony of origin, and assessing seabird sensitivities throughout Scottish waters to potential renewable developments. The outputs from these projects have been used to inform Scottish Government policy, planning and licencing relating to offshore wind farms in Scotland. The work had been underpinned by the long-term studies undertaken on the Isle of May and the invaluable data and technical expertise that these studies have resulted in."*

[12]. Personal communication, Chief Scientific Adviser to Defra (2012-2019). 28/11/19

[13]. Daunt, F., et al. (2011) GPS tracking of common guillemot, razorbill and black-legged kittiwake on the Isle of May, summer 2010. Report to Forth & Tay Offshore Wind Developers Group (FTOWDG).

[14]. Personal communication, Project Director, Neart na Gaoithe offshore wind farm, EDF Renewables. 20/12/19.

[15]. Personal communication, Head, Centre for Conservation Science, Royal Society for the Protection of Birds (RSPB). 08/01/2019.

[16]. Searle, K. R., Mobbs, D.C., Butler, A., Furness, R.W., Trinder, M.N., & Daunt, F (2018). Finding out the fate of displaced birds (FCR/2015/19). Scottish Marine and Freshwater Science Vol 9 No 08. DOI: 10.7489/12118–1. SeabORD tool available at: https://www2.gov.scot/Topics/marine/marineenergy/mre/current/SeabORD

[17]. Personal communication, Head of Engineering, Red Rock Power Ltd. 14/01/2019.

[18]. Searle, K.R., Mobbs, D., Daunt, F. & Butler, A. (2019) A Population Viability Analysis Modelling Tool for Seabird Species. Report to Natural England. Tool available at: http://ec2-54-229-75-12.eu-west-1.compute.amazonaws.com/shiny/seabirds/

[19]. Personal communication, Director Specialist Services and Programmes, Natural England. 20/12/19.

[20]. Searle, K. R., Mobbs, D.C., Butler, A., Trinder, M.N., Waggitt, J., Evans, P., & Daunt, F. (2019) Scottish Waters East Region Regional Sectoral Marine Plan Strategic Ornithology Study. Report to Scottish Government

[21]. Searle, K. R., Butler, A., Mobbs, D.C., Bogdanova, M., Waggitt, J., Evans, P., Rehfisch, M., Buisson, R. & Daunt, F. (2019) Seabird Sensitivity Mapping Tool for Scotland. Report to Carbon Trust.

Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH03_Informing decision-making for the management of Invasive Non-Native Species**

Section B

1. Summary of the impact

Invasive non-native species (INNS) are organisms introduced by humans into areas outside their native range where they threaten biodiversity, ecosystems, or the way we live. INNS are regarded as one of the top five threats to biodiversity worldwide and are economically damaging costing the EU an estimated €12bn per annum. CEH has led a number of key INNS initiatives across the UK, EU, and globally focused on the development on INNS information systems, horizon scanning, surveillance, and risk assessment. Our research has led to the development of species alert systems, the avoidance of costs associated with INNS arrival, and the development of policy, regulation, and management strategies for INNS.

2. Underpinning research

Invasive non-native species (INNS; also known invasive alien species (IAS)) are organisms introduced by humans into areas outside their native range where they then threaten biodiversity, ecosystems or the way we live. INNS are regarded as one of the top five threats to biodiversity worldwide (IPBES, 2019), and they are economically damaging, costing Britain and the EU an estimated £1.7bn and €12bn per annum respectively (CABI, 2010). The effects of INNS are mainly felt in the farming and horticultural sectors, but health, transport, construction, recreation, aquaculture, and utilities are also impacted.

CEH, led by Prof Helen Roy, has undertaken a number of collaborative analyses that demonstrate introductions of INNS are increasing globally at unprecedented rates with no sign of slowing or saturation [1]. Her team at CEH has led a number of key non-native species initiatives across the UK, EU, and globally within terrestrial, freshwater, and marine environments, including database development, reporting of annual trends, horizon scanning, surveillance, and risk assessment.

Information systems: *(Leads: Helen Roy, Jodey Peyton, Oli Pescott, Biren Rathod, Stephanie Rorke)*

CEH has led the development of the online GB Non-native Species Information Portal (GB-NNSIP) [2] and its associated alert system since 2011. Through the GB-NNSIP, CEH provides the main source of detailed information on over 300 non-native species (NNS) for Defra, the UK devolved governments, UK Overseas Territories, and the Non-native Species Secretariat with additional information on more than 2000 non-native species. The main aim of GB-NNSIP is to improve the recording and flow of NNS distribution in Britain, and provide a central repository of useful information accessible to all stakeholders. CEH enables a wide range of organisations (e.g. the National Biodiversity Network, recording societies, government agencies and NGOs) to submit NNS data to the portal. CEH has developed new methods to increase the quantity and rate of flow of records including through citizen science (see below). We have also developed a successful alert mechanism, which has elicited a large number of records for priority species. The development of a comprehensive database to collate information on past invasions has been vital for providing the information on which to base policy decisions.

A COST (European Cooperation in Science and Technology) Action, Alien Challenge chaired by Helen Roy (2013–2017) [3] has enabled CEH to facilitate enhanced knowledge gathering and sharing through a network of INNS experts, providing support to the European Commission's INNS

database and information system, the European Alien Species Information Network (EASIN). Information systems for INNS have also been designed at the country level by CEH, an example of which is the Cyprus Database of Alien Species (CyDAS) funded through a UK Government Darwin Initiative project, 'Researching Invasive Species of Kýpros (RIS-Ký)' (2017–2019) [4].

Citizen science *(Leads: David Roy, Helen Roy, Oli Pescott, Tom August)*

Recent developments in citizen science (CS) provide an opportunity to improve the quality, quantity, and rate of data flow and knowledge on INNS. CEH has led advances in technology, particularly online CS recording through the wildlife observation website, iRecord, its associated smartphone app (https://www.brc.ac.uk/irecord/), and species-specific apps (e.g. Asian Hornet Watch: https://www.gov.uk/government/news/new-app-to-report-asian-hornet-sightings). Along with the development of social media, these advances have revolutionized CS, and the ease with which volunteers can report sightings of INNS. Since its launch in 2017, the Asian hornet app has been downloaded >36,000 times and >7000 records have been submitted and collated in the GB-NNSIP.

Horizon scanning *(Leads: Helen Roy, Jodey Peyton)*

Where INNS will pose a threat to native biodiversity and ecosystems in a region, prompt action is vital. CEH has developed an approach to horizon scanning capable of predicting and prioritising action where there is the potential for harmful INNS to arrive and become established within the next 10 years. Though horizon scanning across taxonomically diverse organisms from all environments is an ambitious task, CEH has successfully achieved this at the British (2014) [5], European, [6] and UK Overseas Territory (2018) [7] levels through a dynamic and iterative consensus-driven approach coupling the best available evidence with expert opinion. The list developed for the EU has been used to produce the annex on species of Union concern for EU Regulation 1143/2014 on Invasive Alien Species.

Risk assessment and management *(Leads: Helen Roy)*

Primarily funded at the British and European level, CEH has led research on INNS risk assessments, specifically leading the development of an approach that complies with standards published collaboratively by CEH and project partners across Europe. CEH was commissioned by the Directorate-General for Environment of the European Commission through a series of projects to establish INNS risk assessment frameworks for Member States to follow as part of the EU's implementation of EU Regulation 1143/2014 on Invasive Alien Species [8] (2014–present). This work has stimulated the design of both UK and European policy, and facilitated the implementation of legislation and regulation.

3. References to the underpinning work

1. Seebens, et al. (2017). No saturation in the accumulation of alien species worldwide. Nature Communications 8, 14435. Altmetric = 558
2. GB Non-Native Species Information Portal (GB-NNSIP): http://www.nonnativespecies.org/home/index.cfm.
3. COST Action TD1209 ALIEN Challenge: https://www.cost.eu/actions/TD1209/#tabs|Name:overview; COST Action CA17122 ALIEN CSI: https://www.cost.eu/actions/CA17122/#tabs|Name:overview.
4. Researching Invasive Species of Kýpros (RIS-Ký), Darwin Initiative, 2017–19: https://www.ris-ky.eu/home
5. Roy, H.E., et al. (2014) Horizon Scanning for Invasive Non-Native Species in Britain. Global Change Biology 20, 3859-3871. Altmetric 141

6. Roy, H.E., et al. (2019) Developing a list of invasive alien species likely to threaten biodiversity and ecosystems in the European Union. Global Change Biology 25(3):1032–1048.

7. Roy, H.E. (2018) Predicting the threat from invasive non-native species in British Overseas Territories: https://www.ceh.ac.uk/news-and-media/blogs/predicting-threat-invasive-non-native-species-british-overseas-territories.

8. Since 2014, CEH has led five projects for the European Commission to inform the list of INNS of Union Concern including: horizon scanning, developing a framework for risk assessments to ensure ecological relevance while complying with articles within the EU legislation, and undertaking risk assessments for priority species (see 'Studies underpinning the IAS policy' for more information **-** http://ec.europa.eu/environment/nature/invasivealien/index_en.htm).

4. Details of the impact

CEH has been carrying out research on INNS over the last 15 years, benefiting the management of invasive species, supporting the development and implementation of government policies and regulations, and providing leadership on invasion ecology domestically and internationally.

Ensuring a rapid response to INNS identification and management

The GB-NNSIP online reporting alert system has ensured a rapid response from the British government to sightings of priority species such as the killer shrimp, Asian hornet, and Asian longhorn beetle, all species identified as high priority INNS through CEH-led horizon scanning. The alert system has received thousands of records of species of potential concern and is linked to information to educate and engage the public in INNS surveillance. The combination of horizon scanning work and the GB-NNSIP online reporting system, where important new INNS arrivals are immediately notified to the relevant statutory bodies, provides an early warning system for INNS and allows a rapid response to deal with them.

In 2016, the first record was received of an Asian hornet in Great Britain, and the GB-NNSIP alert system was instrumental in providing spatial information to the National Bee Unit and Defra to underpin its eradication. CEH led the development of the smartphone app – Asian Hornet Watch – within two weeks in response to an escalation in enquiries following the first record. A major benefit of such a rapid response is cost avoidance, here through the prevention of honeybee hive losses. In 2012, as a result of pillaging of honeybee populations, the Asian hornet had a significant socioeconomic impact in honey-producing regions of northern Spain [10]. Honeybee losses reached as high as 30% in some areas. The total value to the UK economy of honey production has been estimated at £220m per annum [11]. If there was an uncontrolled Asian Hornet invasion on the same scale as that in Spain in 2012, the cost to the UK economy would be in excess of £66m per annum in terms of honey bee losses alone plus the costs of eradication and further control measures. The Head of Plant & Bee Health, Animal and Plant Health Agency (APHA, Defra) has stated '*From the initiation of APHA's response to Asian hornet, we quickly realised that call handling and triaging of information from the public was vital. Having a mechanism in place through Defra's Non-Native Species Secretariat with CEH proved to be the perfect solution. This allowed our National Bee Unit technical staff and inspectors to concentrate their skills to deliver our on-the-ground response … Working with CEH proved to be a great partnership generating many synergies*.' [12].

UK and European INNS policy development

CEH research on INNS has directly benefited the development and implementation of UK and European policy, regulation, and practice around INNS. Through the GB-NNSIP, CEH has contributed information and datasets on INNS in support of the update to the GB Invasive Non-native Species Strategy (2015).The GB-NNSIP is fundamental to the implementation of this strategy

and is repeatedly referenced throughout the document [13]. CEH datasets have supported the development of the UK Biodiversity Indicator 'B6. Pressure from invasive species', which was developed by CEH and is used by the UK government for statutory reporting on the status of UK biodiversity (2019) [14]. CEH has also influenced the development of two indicators for the 25 Year Environment Plan (2018), the UK government's strategy and plan to protect and improve the environment. The indicators – '(H1) Abatement of the number of invasive non-native species entering and establishing against a baseline' and '(H2) Distribution of invasive non-native species and plant pests and diseases' – will be used over the next 25 years to identify whether the number and impacts of invasive non-native species are decreasing.

Seven of the top 10 invasive species identified through CEH horizon scanning have now been reported in Great Britain. The CEH-led horizon scanning approach has been replicated to derive the list of INNS of EU concern [15] and has also been adopted by the governments of the US, Ireland, Cyprus, and all the UK Overseas Territories [16]. The Deputy Administrator of the British Indian Ocean Territory (BIOT) stated '*The new list of invasive species at risk of entering BIOT, and suggestions on how to prevent or react to their arrival, will help the BIOT Administration protect the Territory's unique environment and incredible biodiversity. We are grateful for the support provided by the Centre for Ecology & Hydrology, and look forward to working together again in the future*' [17].The Horizon Scanning exercise carried out in Ireland in 2017 was '*vital to informing the country's developing commitment to the EU Regulation on Invasive Species (EU1143/2014)*' [18].

Regulation 1143/2014 of the EU on invasive alien (non-native) species entered into force on 1 January 2015. The regulation imposes restrictions on a list of species known as 'species of Union concern'. These are species whose potential adverse impacts across the European Union are such that concerted action across Europe is required. CEH's standards, risk assessments, scientific evidence, and frameworks have influenced the implementation of EU1143/2014. In particular, the development of risk assessments for the IAS of EU concern has supported both the European Commission and Member States to deliver their obligations under the regulation and has resulted in a standardised basis for a coordinated EU response to INNS [19]. The **Chief Scientist at the GB Non-Native Species Secretariat has stated** '*In the last few years the Centre for Ecology & Hydrology (CEH) has become an important global player in this field, particularly in relation to the development of the EU IAS Regulation, where CEH led on the assessment of the critical risk assessment methodology and the finalisation of the risk assessments that underpin the listing in the Regulation*.' [20]. CEH's work with the European Commission on EU1143/2014 continues, with further work on risk assessment and the implementation of a new project focused on improving communications around INNS (2019-2022). This work aims to engage constructively with a variety of stakeholders with a view to reducing the level of conflict and misunderstanding around INNS, strengthening the prevention of new invasions and reducing their number, thereby protecting biodiversity in Member States.

International leadership on INNS research policy development & practice

Prof Helen Roy has led CEH work for the European Commission around the design and implementation of Regulation 1143/2014. Her leadership of two COST Actions has developed a network of INNS specialists. Her high profile in the UK, across Europe, and internationally resulted in an invitation to jointly chair the IPBES thematic assessment on invasive alien species and their control (2019) [21]. The Executive Secretary of IPBES commented on the setting up of the new assessment panel that *'The overwhelming coverage and impact of the IPBES Global Assessment Report has demonstrated that there is renewed concern, understanding and commitment to action to reduce and reverse the destruction of nature at every level. The three eminent scientists who have been chosen to lead this new [IAS] IPBES assessment will have the opportunity to seize this momentum and to build on it in the context of the new post-2020 framework for biodiversity that will be adopted in China next year by the governments of the world – at the 2020 UN Biodiversity Conference of the Convention on Biological Diversity*' [22]. In 2019, Prof Roy also gave evidence as an expert witness to the House of Commons Environmental Audit Committee inquiry on invasive species. The resulting report was published in October 2019 [23] and calls on the UK government to increase spending on INNS, encourage an enhanced role for citizen scientists, improve

biosecurity, include invasive pathogens in the next Invasive Non-native Species Strategy, which are both under-represented and diverse [24], and support the UK Overseas Territories to tackle INNS. The United States government's National Invasive Species Council (NISC) (https://www.doi.gov/invasivespecies) has also invited Prof Roy to provide advice on risk assessments and prioritisation of INNS (2019), and she is an invited expert within the South African Centre of Excellence for Invasion Biology (http://academic.sun.ac.za/cib/) (2019).

5. Sources to corroborate the impact

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15. List of Invasive Alien Species of Union concern – https://ec.europa.eu/environment/nature/invasivealien/list/index_en.htm, which includes the CEH-led horizon scanning exercise.
16. Personal communication, **Chief Scientist at the GB Non-Native Species Secretariat:** '*Bringing together scientists from around the world to work with experts from the Caribbean UK OTs has been extremely useful in ensuring focus on invasive alien species management prioritises prevention as a key strategy. This forward looking approach is extremely important and the workshop has been an excellent step in informing the biosecurity process*.' November 2018.
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Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH04_Transforming our understanding and management of insect pollinators**

Section B

1. Summary of the impact

Pollination supports 88% of flowering plants and 35% of global crop production, which is worth €14.6bn per annum to Europe. However, the ongoing provision of these ecosystem services is threatened by declines across many insect pollinator groups attributable to drivers such as habitat loss, agriculture, and climate change. CEH-led research has identified trends and drivers in the decline of pollinators, provided critical evidence in support of the EU ban on neonicotinoid pesticides, and supported pollinator protection through the development of new national-scale policies and monitoring initiatives across the UK.

2. Underpinning research

Working with the UK government (Department for Environment, Food and Rural Affairs (Defra), JNCC), research councils (NERC, BBSRC), and industry (Syngenta, Bayer, Agrii), CEH has had a leading role in insect pollinator research ranging from the analysis and interpretation of biological records data, survey and monitoring, field- and landscape-scale experiments to evidence reviews for key national and international policymakers. Key activities include:

Analysis of biological records data (*Leads: Isaac, Powney, Harrower, Mancini, Carvell, and Woodcock*)

CEH is a world leader in the interpretation of non-structured biological records representing data collected by citizen scientists that documents, in a spatially explicit way, observations of the occurrence of different species [1]. CEH research has pioneered analytical methods to interpret national datasets describing 30 years (1980–2013) of biological records for wild bee and hoverfly communities. This data revealed that a third of wild pollinator species have decreased over this period, identifying how biodiversity underpinning pollination services is changing in the UK [1, 2, 3]. Note: Similar long-term trend analyses are also undertaken at CEH as part of the UK Butterfly Monitoring Scheme, but are distinct from this work. CEH has contributed to the development of robust metrics of both the status (e.g. Red Data Book) and change in trends (species being lost from a specific location) of insect pollinator communities used by key UK government agencies (see Section 4).

Pollinator survey and monitoring (*Leads: Carvell, Roy*)

Building on the pollinator biological records work, CEH established the Pollinator Monitoring and Research Partnership (PMRP) in 2015. The partnership aims to determine how insect pollinator populations are changing across Great Britain. CEH has established two new large-scale pollinator surveys under the UK Pollinator Monitoring Scheme banner (PoMS) that build on and enhance existing recording schemes for pollinating insects [4]. PoMS is currently the only scheme in the world generating systematic data on the abundance of bees, hoverflies, and other flower-visiting insects at a national scale.

Impacts of neonicotinoid pesticides on honeybees and wild bees (*Leads: Woodcock, Isaac, Pywell, Shore, Periera, Bullock, Heard*)

Neonicotinoids represented an economically significant pesticide used on flowering crops that were thought to have a negative impact on bees. Concern about this effect led to an EU moratorium on their use. In 2016, CEH provided the first analysis to identify how long-term exposure to these pesticides (1994–2010) led to national-scale trends in the loss of wild bee populations that fed on treated crops [5]. CEH also undertook the first multi-country farm-scale

evaluation under commercial agricultural conditions to identify the impacts of these pesticides on honeybees, bumblebees, and solitary bees [3]. This work revealed that neonicotinoid pesticides reduce overwintering success and colony reproduction in both honeybees and wild bees, evidence that contributed to a subsequent ban on their use in the EU (see Section 4).

International evidence reviews (*Lead: Vanbergen*)

During 2014–2018, CEH contributed to the development of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as a working-group member developing 'Deliverable 3(a): Thematic assessment of pollinators, pollination and food production' [6, 7, 8]. The assessment covers changes in pollination as a regulating ecosystem service that underpins food production and the restoration of ecosystems. It addresses the status of and trends in pollinators, drivers of change, impacts on human well-being, food production, and the effectiveness of responses to pollination declines and deficits.

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7. The thematic assessment on pollinators, pollination and food production (2014-2016) http://www.ipbes.net/work-programme/pollination.
8. The regional assessment on Assessment Report on Biodiversity and Ecosystem Services for Europe and Central Asia (2015–2018) https://www.ipbes.net/assessment-reports/eca.

4. Details of the impact

Insect pollinators are vital for the maintenance of ecosystem health and for global food security, with 75% of crop species, 35% of global crop production, and up to 88% of flowering plant species being dependent on insect pollinators. However, substantial concern exists over their current and future conservation status. CEH research on pollinating insects has made a significant contribution to UK, EU and international environmental legislation, policy initiatives and their implementation.

UK and EU ban on use of neonicotinoid pesticides

In 2018, widely used neonicotinoid pesticides that had been established to have negative effects on pollinators and shown to contribute to their decline at national scales were removed from use in the UK and the EU [9]. CEH's unique multi-national field-scale evaluation [3] directly informed

the recommendation by the European Food Safety Authority (EFSA) to withdraw these pesticides from use [10]. Coupled with our long-term research on the impacts of neonicotinoids [5], CEH's evidence went on to frame public opinion and inform policy decisions concerning the ban in both the UK and the EU. Defra's Chief Scientific Adviser stated at the time '*Recent field-based experiments have suggested these effects [on pollinators] could exist. In combination with the observation of widespread and increasing use of these chemicals, the available evidence justifies taking further steps to restrict the use of neonicotinoids*' [11]. CEH's key role in '*oversee[ing] the integrity of the work'* funded by industry (Syngenta and Bayer) was recognised by the House of Commons Environmental Audit Select committee [12].

National policy development and implementation

Defra's 25-year environment plan indicators and targets

The UK government's 25-year environment plan (25 YEP) identifies comprehensive and long-term targets for a cleaner, greener country; a component of the plan is the protection and enhancement of native plants and animals. Development of the 25 YEP was dependent on the *State of Nature* report co-authored by CEH [13,14]. Underpinning data for the report is the UK Biodiversity pollinator trend indicator ('D1c Status indicators of pollinating insects') developed by CEH [15]. CEH is currently supporting Defra to develop indicators for the 25 YEP (2018–present), including 'D4 Relative abundance and/or distribution of widespread species'. Defra has confirmed that '*The work by CEH in developing and contributing to the production of the Status of Pollinating Insects Indicator has allowed Defra (through JNCC) to publish the trend in distribution of 365 species of pollinating bees and hoverflies from 1980 to 2016. Defra can now demonstrate long-term and short-term trends in pollinators to the public, and to government ministers. This information forms a baseline to monitor future changes to the pollinator population*' [16].

National Pollinator Strategy (NPS)

This strategy sets out the UK government's commitments to enhancing and maintaining populations of pollinating insects to protect food production and the biodiversity of the country. The development of this strategy was heavily influenced by the CEH pollinator trend indicator (D1c) and the *State of Nature* report. CEH scientists support the Pollinator Strategy Advisory Boards for Defra (since 2014), the Welsh government (since 2013), and the Scottish government (since 2018) [17]. In addition, CEH's development of the pollinator trend indicator (D1c) [15] provided evidence underpinning a Private Members Bill, the Protection of Pollinators Bill. This Bill aimed to support and grow the populations of bees and other pollinators by creating a national network of wildflower-rich habitats. The Bill was ultimately discharged following the Environment Secretary's provision of funding to support the Pollinator Pathways initiative, which supports a similar goal and contributes to the NPS.

New national-scale monitoring initiatives

As a fundamental component of the NPS, CEH has designed and delivered the UK Pollinator Monitoring Scheme (PoMS: 2015–2021). PoMS is supported by Defra, the Welsh and Scottish governments and is helping to deliver the National Pollinator Strategies for each country as well as the 25 YEP. Recognising its significance, the House of Commons Environment Audit Committee stated that PoMS provides a '*clear and less disputed "baseline" [that has been needed for the] understanding of the plight of pollinators, what is putting pressure on their numbers … a necessary first step in identifying practical measures to support pollinators'* [12]. CEH is the lead co-ordinating partner on PoMS, providing around 80% of the input and enabling the involvement of different stakeholders, including volunteers. Defra has stated '*The Pollinator Monitoring Scheme is presented by Defra as an exemplary wildlife monitoring scheme which trains and utilises community scientists, and produces a globally unique systematic data set. This scheme fulfils several priority actions in the National Pollinator Strategy under the key area – 'Improving evidence on the status of pollinators and the service they provide*' [16, 18]. CEH is extending this work internationally by developing a monitoring framework for pollinators across Europe [19] and in Latin America [20].

Citizen science is a significant component of CEH work. It has direct benefits to our pollinator research and provides an opportunity for volunteers to support and have an impact in this area [21]. PoMS is actively building scientific expertise in taxonomy whilst raising public awareness around key environmental issues though this direct public participation. Defra has confirmed that '*The public engagement activities carried out by CEH impact Defra's delivery of the 25 YEP. Pollinator monitoring activity [has been] designed for entry level community scientists to engage new people in the wildlife around them. This work contributes to 25 YEP commitments: Connecting people with the environment to improve health and wellbeing, including encouraging children to be close to nature; and Helping children and young people from all backgrounds to engage with nature and improve the environment*' [16]. A PoMS volunteer has stated '*Overall the experience was 100% positive and rewarding for many reasons, not least for the opportunity to be a part of a worthwhile and important piece of ecological research. I'm now keen to get more involved and am very much looking forward to undertaking next year's surveys!*' [22]. In addition, CEH leads the National Honey Monitoring Scheme (NHMS), which is engaging with 750 amateur beekeepers across the UK. This scheme allows beekeepers to provide honey for genetic analysis and provides them data on bee health [23].

International policy development

Dr Adam Vanbergen, CEH, was an expert lead author (nominated by the UK government) for IPBES reports as part of the Thematic assessment of pollinators, pollination, and food (2014–2016 and 2015–2018) and was selected to join the author team that wrote the Summary for Policy Makers (SPM). He represented the author team in negotiating the final text with more than 130 governments in the IPBES-4 Plenary, Kuala Lumpar, February 2016. The assessment was endorsed at the Convention on Biological Diversity (CBD) 13th Conference of the Parties (COP13) in Mexico, December 2016. It has been instrumental in driving international government commitments to pollinator protection through a "Coalition of the Willing" (http://promotepollinators.org/) as well as the establishment of national pollinator strategies and action plans in many countries worldwide (e.g. in France, Brazil, and South Africa).

Economic impact

Reversing insect pollinator declines and ensuring healthy and abundant populations of pollinators are key to maintaining and enhancing crop pollination services worth €14.6bn per annum to Europe. Recent CEH research has shown that globally, pollinator abundance, species richness and functional diversity is directly correlated with increased yield in oilseed rape, an internationally important crop [24]. Continued pollinator decline, therefore, could have serious financial implications for the production of many insect-pollinated crops. There is scope to counter the decline and improve the quality of production using evidence provided by CEH and others, through the removal of harmful pesticides, such as neonicotinoids, and the improvement of habitat for wild pollinators [25,26].

5. Sources to corroborate the impact

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[14]. Ministerial government speeches: i) Prime Minister (May) at the launch of the 25 YEP (https://www.youtube.com/watch?v=0nLVX7PKHKo see from 12m:15s in); ii) The headline figure from the CEH pollinator indicator was one of just three wildlife statistics quoted by the Prime Minister in January 2018 at the launch of the government's 25 Year Environment Plan; iii) Secretary of State for Environment (Gove), Food and Rural Affairs (Kew Gardens, 16 July 2019): https://www.wcl.org.uk/michael-gove-asks-if-not-now-when.asp).

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[20]. Safeguarding Pollination Services in a Changing World: theory into practice (SURPASS2)

http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FS011870%2F1&cookieConsent=A

[21]. PoMS Twitter account has generated >1200 followers in its first year; PoMS has seen 1,307 FIT (Flower-Insect timed Counts) submitted to iRecord by 168 recorders in 2018; PoMS now has more than 60 volunteers committed to sampling across a new network of 75 x 1 km survey squares.

[22]. Personal communication, PoMS Volunteer. Full testimonial available on request.

[23]. National Honey Monitoring Scheme (NHMS) (https://www.ceh.ac.uk/our-science/projects/national-honey-monitoring-scheme). Uptake and participation by >750 amateur beekeepers across the country. Numerous talks to about the science and impact of neonicotinoids on bees and the NHMS to beekeeper associations across the country. Specific dates can be provided.

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Section A		
Centre:	UK Centre for Ecology & Hydrology	
Title of case study:	**CEH05_Mitigating greenhouse gas emissions through CEH-led research on peatlands**	

Section B

1. Summary of the impact

CEH-led research has shown the UK's peatlands emit over 20 Mt CO_2-equivalent of greenhouse gases (GHGs) per annum, mostly from agriculturally drained systems, which equates to ~4% of the UK's entire GHG emissions. Our work on peatlands has benefited national Kyoto Protocol emissions reporting, the development of emissions mitigation strategies embedded in Defra's 25-year Environment Plan, and government net-zero emissions planning. Our work has underpinned £10s of millions of public and private sector investment in peat restoration, both in the UK and internationally, notably in Indonesia where degraded peatlands are major contributors to global climate change.

2. Underpinning research

CEH has had a leading role in UK peatland research for over a decade, with work ranging from basic research to the operation of sensor networks, field-scale mitigation experiments, remote sensing, development and implementation of emissions-reporting methodologies, evidence reviews for key policymakers, and modelling. Key activities include the following:

Development and operation of a UK peatland flux measurement network (*Leads: Pete Levy, Ross Morrison*)

Since 2002, CEH has led the development of a national network of flux tower monitoring sites over peatlands (currently 15, of which CEH operate 10). This network includes one of the world's longest-running monitoring sites (Auchencorth, South East Scotland) and covers a disturbance gradient from near-pristine bogs and fens to deep-drained cropland. Globally unique, the network provides fundamental scientific understanding of the interacting effects of climate and land use on GHG exchange based on over 40 site-years of data.

Quantifying and mitigating GHG emissions from lowland peatlands (*Lead: Chris Evans*)

CEH led a major research programme funded by Defra (2012-2016), which provided the first comprehensive empirical data on UK lowland peat GHG fluxes [1]. Building on the flux tower network, full carbon and GHG budgets were obtained for 15 instrumented sites under conservation, grassland, cropland, horticultural peat extraction, and restoration management. The study showed that cultivated lowland peatlands are by far the most intensive sources of land-derived CO_2 emissions in the UK, and that raising water levels in these areas could make a major contribution to mitigating emissions even if they remained in agricultural use. Follow-on projects for the NERC Soil Security Programme (2017–2019) and Defra (2019–2022) have tested different mitigation measures, and CEH is now establishing a major high-water table field trial on a commercial farm, working with government, NGOs, and farmers to support the development of economically viable solutions to mitigate peatland GHG emissions.

Development of a UK peatland emissions inventory (*Leads: Amanda Thomson, Chris Evans*)

CEH leads the land-use component of the GHG emissions inventory for the UK, which contributes to national emissions reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol (ongoing work since 1999) [2]. In 2014, Chris Evans was a Lead Author of the Intergovernmental Panel on Climate Change (IPCC) Wetland Supplement, which

provided a methodological basis for reporting emissions from drained and re-wetted peatlands globally [3]. CEH subsequently led the implementation of this methodology for the UK, in collaboration with the James Hutton Institute. This work has, for the first time, estimated that UK peatlands generate GHG emissions of ~23 Mt CO_2-eq $year^{-1}$, equivalent to 4% of the UK's total emissions in 2018 [4]. Over half of these emissions are from cultivated lowland peat. Further research by CEH has contributed to emissions mitigation assessments for the UK, Welsh, and Scottish governments, the UK Peatland Code, the development of novel satellite-based methods for peatland condition mapping to support inventory reporting, and an assessment of land-use options for climate change mitigation for the UK Committee on Climate Change (see Section 3 for examples [5,6]).

Peatland research in South East Asia (*Lead: Chris Evans*)

CEH has translated the knowledge and experience gained in the UK into research and policy impact in South East Asia, where around 70% of peat-swamp forest has been cleared and drained for agriculture since 1990, leading to globally significant GHG emissions in the region. Active projects include: the CEH National Capability programme SUNRISE (2017–2020); a Global Challenge Research Fund (GCRF) project on mitigating GHG emissions and enhancing crop yields in smallholder and plantation areas (SUSTAINPEAT); and satellite-based peatland monitoring (UK Space Agency PASSES project). Since 2016, Chris Evans has also been on the peatland advisory group of Asia Pacific Resources International Ltd (APRIL), one of Indonesia's largest natural resources companies with operations on over a million hectares of pulpwood plantation and conservation forest, mostly on peat. This has included support for APRIL's multi-million pound in-house research programme, and analysis and publication of their long-term, large-scale data. A recent CEH-led publication based on APRIL's subsidence monitoring data (the world's largest such data set) showed that plantation drainage is causing subsidence of 4 cm yr^{-1}, contributing to CO_2 emissions and flooding risks, but also demonstrating significant mitigation potential from raising plantation water levels [7]. CEH are now working with APRIL to trial high water level management as part of their 2030 sustainability commitments.

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4. Details of the impact

UK agriculture, land use, and climate change policy development and practice

CEH peatland research has led to fundamental changes in UK and devolved government policies on agriculture and land-use, highlighting the significance of drained and degraded peatlands as nationally important GHG emission hotspots. Within Defra, our research has led directly to the evolution of policy on peatland emissions mitigation from a focus mainly on upland bog restoration towards recognising and developing policies to reduce emissions from agricultural lowland peatlands. The Senior Science Advisor, Land Use, Natural Environment Directorate at Defra has stated '*Successive research projects undertaken by CEH in the past decade have provided us with essential information on fluvial carbon cycling in peatlands, and on the carbon and greenhouse gas budgets of lowland peatlands. Their work has also been instrumental in identifying agricultural peatlands as the most intense source of GHG emissions from UK peatlands. An on-going research project led by CEH is now developing management options to mitigate GHG emissions from these highly valuable agricultural lands. The outcomes of these research projects are actively used in our policy development on peatland restoration and management, while the ongoing project will support our efforts to achieve sustainable management of lowland agricultural peatlands to meet the UK's Net Zero 2050 target while maintaining food security*' [8].

Lowland peat was identified as a depleting resource and emissions hotspot in the 2016 House of Commons Environmental Audit Committee report on Soil Health (for which CEH's Prof Bridget Emmett was the specialist advisor). It has been highlighted as a priority area for mitigation in the Defra 25 Year Environment Plan (25 YEP) (pp. 45–46) based in part on our research reports [1,2]. This has led to the establishment of the East Anglian Fens as a priority pilot area for the developing England Peat Strategy, and the announcement of the formation of a Lowland Agricultural Peatland Task Force to '*generate new solutions for repairing lowland peat and build consensus among farmers, conservationists, and academics'* [9]. The UK parliamentary Environment, Food and Rural Affairs Committee recently initiated inquiries into both peatlands and net zero agriculture, to which CEH has submitted evidence [10].

The UK government has committed to include CEH-led peatland emissions estimates in the UK GHG inventory within the next three years. They are not currently accounted for in the inventory following CEH-led research that showed that the UK has been underestimating GHG emissions from this source [4]. These estimates have been included in a CEH assessment of land-use options for climate change mitigation [6], which underpins two recent reports by the Committee on Climate Change that identify reducing emissions from peatlands as a priority for reducing land-use emissions and achieving net-zero. The Head of Land Use and Bioenergy Science at BEIS stated '*By improving the accuracy of the assessment of peatland emissions, the research conducted by CEH, supports the Department commitment to ensure its policies and its contributions to wider Government issues are evidence-based and underpinned by the best science advice available. In formulating the Government's view on response setting of the 6th Carbon Budget to the forthcoming recommendations from the Committee on Climate Change, CEH's report has enabled a realistic perspective on peatland emissions and their mitigation potential on the pathway to net zero'* [11]. A Senior Analyst from the Committeee on Climate Change has confirmed '*The CEH work for BEIS on estimating GHG emissions from UK peatlands was used by the CCC in our 2018 Land Use report, and the 2019 Net Zero advice. It was used to calculate current peat emissions (by country and type of peat) and the abatement savings by 2050 from restoration and management of the water table. We will continue to use the CEH work for a third report (Land use: Policies for net zero in the UK) which we will publish in January 2020; while further CCC work will consider the outputs from the on-going CEH work for Defra's lowland sustainable peatland project when that is completed*' [12].

The Office for National Statistics used CEH data for the recent Peatland Natural Capital Assessment, which estimated that returning 55% of peatlands to good status would deliver net benefits of £45–50 billion over the next century. The Head of Natural Capital at the ONS has stated '*The ONS Natural Capital work relies almost entirely on external bodies for the primary data and no organisation has been more influential or important than CEH in this respect. In particular, CEH's peatland research provided the foundation for our 2019 Peatland accounts, making it possible to present a thorough assessment of the state of the UK's peatlands*' [13]. This finding was widely reported in the media, with CEH scientists providing several interviews (e.g. https://www.bbc.co.uk/news/uk-49074872; https://www.thetimes.co.uk/article/uk-failed-to-include-co2-emissions-from-marshes-in-its-greenhouse-gas-accounts-cjh2lsqxz).

On a practical level, CEH peat 'emission factors' (estimates of average GHG emissions for different land-use and condition categories) are now embedded in a range of policy tools and initiatives. These include: Defra's £10m English peat restoration fund (part of the UK 25 year Environment Plan); the Scottish Government's Peatland ACTION programme (~£20m to date); prioritisation of climate mitigation measures in the Welsh Glastir agri-environment programme [14]; the Scottish Government TIMES model for optimising emissions reductions across all sectors to achieve climate change targets [15]; and the UK Peatland Code. The latter is a payment for ecosystem services scheme developed by the International Union for Conservation of Nature (IUCN) Peatland Programme with government support to facilitate private sector investment in peat restoration. The private sector trading of voluntary carbon offsets first took off in the late 2000s. Voluntary carbon projects have helped to reduce, sequester, or avoid over 435 $MtCO_2e$ (Forest Trends, 2018). The UK Peatland Code provides a means to invest in peatland restoration through carbon offsetting. CEH has contributed to a review of offsetting by peatland restoration for the aviation sector, which has already invested in a pilot peatland restoration project in Lancashire and is a potential buyer of verified Peatland Carbon Units via the Peatland Code [16]. In addition, CEH research on developing mitigation measures for peatlands has had a practical impact on the farming sector. Working with G's Growers Ltd, the UK's largest farming company operating on organic soils, CEH has trialled a range of mitigation measures to reduce peat loss, and we are working with the National Farmers' Union (NFU) to build awareness of and implement solutions to lowland peat loss. The Climate Change Adviser at the NFU has confirmed that '*The CEH team have engaged positively and proactively with the NFU and the agricultural community to try to find socially, economically and environmentally viable solutions to emissions from lowland peat. The work has helped to highlight the challenges in reducing GHGs emissions from cultivated peatlands*' [17].

International policy development and practice

CEH staff Chris Evans and Amanda Thomson have made contributions at international level as IPCC Lead Author and expert advisor to the UK government respectively for the IPCC Wetland Supplement (published in 2014) and the Agriculture, Forestry and Other Land-Use volume of the 2019 IPCC Inventory Refinement [3,18]. These highly influential reports form the basis for all international reporting of GHG emissions from wetland soils and underpin global efforts to protect and restore degraded peatlands. CEH has also directly translated our experience and expertise in order to support responsible peatland management in South East Asia, the world's largest peatland GHG emission hotspot. Our work has included advising the Indonesian Peat Restoration Agency (BRG) and Ministry of Environment and Forestry (MoEF); working with the Malaysian Palm Oil Board in Sarawak; and fulfilling a direct science advisory role with one of Indonesia's largest plantation companies (APRIL). This has led to the first publication of previously confidential company data on peat subsidence [7], which has demonstrated the potential to mitigate both subsidence and GHG emissions through raised water levels in *Acacia* plantations. These results have led to a major (~$1m) investment by APRIL in field-scale high water table field trials intended to optimise emissions mitigation in parallel with crop yields. FiberOne Director, Asia Pacific Resources International Ltd (APRIL) has stated *'CEH has helped APRIL strengthen its peatland science programme and develop a Roadmap for peatland management composed of three components: science-based understanding and minimizing impact; responsible peatland operations; and a vision for its peatland landscapes. This pioneering work contributes directly to*

global science-based discussions on responsible resource management' [19]. New instrumentation developed by CEH for peat subsidence monitoring has been deployed by the Malaysian Palm Oil Board, World Resources International Indonesia, and the Borneo Nature Foundation. CEH has also contributed to an FAO-led initiative to support improved global peatland monitoring, who have confirmed that '*CEH have provided the FAO with valuable technical guidance and support on peatland ecology, state-of-the-art monitoring approaches and greenhouse gas emission accounting. Prof Chris Evans was one of the two key persons steering the preparation of a joint overview report on peatland mapping and monitoring (to be published in Q1 of 2020), and also contributed to the publication with an important case study covering the mapping and monitoring advances of the UK. FAO Peatlands unit is looking forward to further collaboration with CEH as part of its commitment to improved global peatland monitoring*' [20].

The international work of CEH is of particular significance. While UK peatlands emit 23 Mt CO_2eq/year, global peatland emissions have been estimated at 1.91Gt CO_2eq/year [21]. The work of CEH scientists, in collaboration with our international partners, forms an important part of continuing efforts to find science-based solutions to this global challenge.

5. Sources to corroborate the impact

8. Personal communication, Senior Science Advisor, Land Use, Natural Environment Directorate, Defra. December 2019.
9. Michael Gove, Speech on UK Climate Change Projections, November 2018: https://www.gov.uk/government/speeches/michael-gove-speech-on-uk-climate-change-projections
10. CEH evidence to the House of Commons Environment, Food and Rural Affairs Committee, October 2019. An analysis of the written evidence shows that half of the submissions to the inquiry cited work from CEH peatland publications either directly, or indirectly via Committeee on Climate Change or ONS reports.

    http://data.parliament.uk/writtenevidence/committeeevidence.svc/evidencedocument/environment-food-and-rural-affairs-committee/peatland/written/105007.html.
11. Personal communication, Head of Land Use and Bioenergy Science, Science & Innovation for Climate & Energy Directorate, UK Department for Business, Energy and Industrial Strategy (BEIS). January 2020.
12. Personal Communication, Senior Analyst, Committeee on Climate Change. December 2019.
13. Office for National Statistics (ONS) (2019). UK Natural Capital: Peatlands. Section 12. Methodology: Food. Personal communication,Head of Natural Capital, ONS. Dec. 2019.
14. Personal communication, Head of Environmental Modelling and Monitoring, EU Exit & Strategy Unit, Environment and Rural Affairs Department, Welsh Government: '*The European Commission Evaluation Help Desk has used the Glastir Monitoring and Evaluation Programme (GMEP) as an example of best practice of how monitoring of GHG emissions and sequestration can be undertaken alongside and integrated with other components of managed ecosystems. This is an area many Member States had struggled to meaningfully integrate within their monitoring programmes; GMEP provided valuable learning*'. Jan. 2020.
15. Scottish Government (2018). Climate Change Plan: The Third Report on Proposals and Policies 2018-2032, Technical Annex, e.g. page 6: https://www.gov.scot/publications/climate-change-plan-third-report-proposals-policies-2018-2032-technical-9781788516761/pages/2/
16. Environment, Food and Rural Affairs Committee. Peatlands Inquiry, October 2019: http://data.parliament.uk/writtenevidence/committeeevidence.svc/evidencedocument/environment-food-and-rural-affairs-committee/peatland/written/105743.pdf
17. Personal communication, Climate Change Adviser, National Farmers Union, December 2019. The NFU also stated in its evidence to the EFRA Committee inquiry on peatlands (see 11 and 17) that '*on very productive lowland peat soils we want to see continued research and*

demonstration of a continuum of practical conservation measures which could lead to lower emissions whilst enabling the UK to sustain production of high quality and value horticulture'.

18. IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Agriculture, Forestry and Other Land-Use. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.
19. Personal communication, Director, FiberOne, Asia Pacific Resources International Ltd. December 2019.
20. Personal communication, Peatlands Unit, Mitigation of Climate Change in Agriculture (MICCA) Programme, Food and Agriculture Organisation of the United Nations. Dec. 2019.
21. Leifeld, J., Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. Nat Commun 9, 1071 doi:10.1038/s41467-018-03406-6.

Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH06_Supporting Policy, Business and Infrastructure through the UK Land Cover Maps**

Section B

1. Summary of the impact

Land Cover Map (LCM) is a land cover map for the UK. It has been produced periodically since 1990 with the latest fully quality assured version being for 2015. The LCM family includes a number of products incorporating other data sets including crops and pesticides. They have a wide range of applications across business, policy and infrastructure. Users have said LCM is '*essential*', '*underpins all the Natural Capital accounting in the UK*' and '*is the best product available'*. Specific case studies across the sectors show that LCM has been used to save millions of pounds in costs as well as helping to protect protected species habitats.

2. Underpinning activities

A land cover map is a map of the physical coverage (e.g. forests, grasslands) of the earth surface. Derived from satellite data, CEH has produced four UK Land Cover Maps (LCM), beginning with LCM Great Britain (LCMGB) in 1990, through to the current LCM2015.

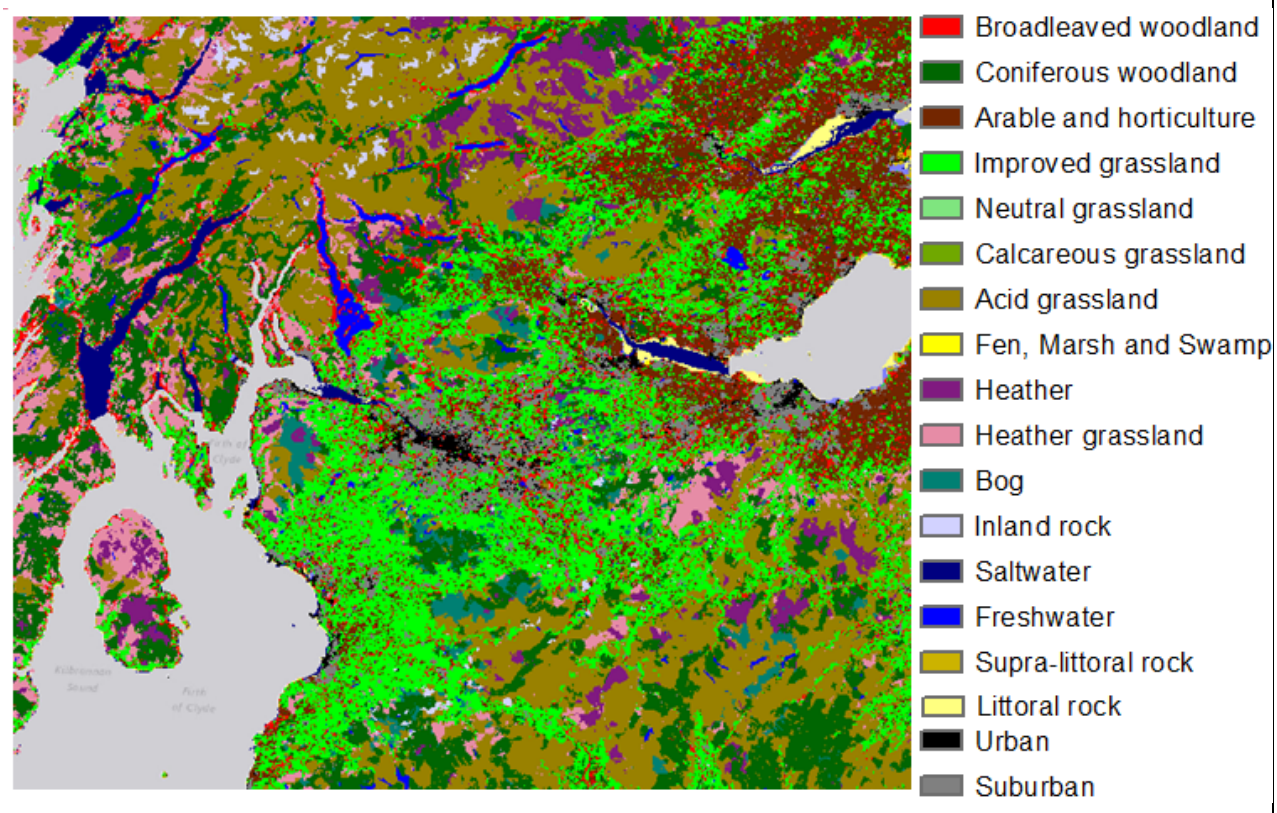

Figure 1 Sample of LCM2015 showing land cover of central Scotland

LCM GB - LCM GB was the first ever digital land cover map for GB [1]. In the late 1980s, satellite data was becoming more readily available. Work at the Institute of Terrestrial Ecology (a precursor to CEH) led by Professor Robin Fuller demonstrated that it was possible to create a map of UK Land Cover types from satellite data. A British National Space Centre demonstrator project, supported by Natural Environment Research Council (NERC) and the Department of the Environment, was commissioned and the first all-digital, satellite GB LCM was produced in 1991.

LCM2000 – was led by Professor Fuller. LCM2000 was funded by a partnership of government-funded bodies led by the NERC and the Department for Environment, Food and Rural Affairs (Defra). It mapped Northern Ireland for the first time to become the UK Land Cover Map. Noise in Earth Observation data at the pixel level meant in LCM1990 identification of real world features was unreliable. LCM2000 improved this by applying spectral segmentation of images to generate vector land parcels. Land cover was identified by the spectral classification of the image data in these parcels. Applying this method of using image-derived segments provided the spatial structure of the map. This resulted in a map which represented real world features down to 0.5 hectares with greater reliability than before. This was the first national-scale land cover map to be produced using image segmentation [2].

LCM2007 – was led initially by CEH's Dr Geoff Smith and then by Dr Daniel Morton supported by Dr Clare Rowland. LCM2007's major innovation was the use of simplified national cartography (Ordnance Survey MasterMap) to create the spatial structure of the product. Real-life landscape features were captured from a generalised version of OS MasterMap. This made it easier for users to interpret and any system which used OS MasterMap could link to it. [3,4].

LCM2015 [5] – was led by Dr Clare Rowland. LCM2015 was funded by NERC National Capability funding. LCM2015's major development was the use of a set of core training areas, selected from the previous LCMs, which enabled quicker, more consistent production. In addition CEH created added value maps by combining LCM with other data sets. Led by CEH's Professor Richard Pywell these are:

a) CEH Land Cover® plus: Crop Map – an annual product since 2015. This is **the first detailed, interactive, digital map of agricultural cropping in Great Britain. Two million land parcels are categorised providing information on annual crop types for every field in Great Britain. Method development was funded via an InnovateUK grant where CEH collaborated with industry through an SME - Remote Sensing Application Consultants Ltd and** Anglian Water.
b) CEH Land Cover® plus Fertilisers and Pesticides (2018-2019) – released in 2019, provides aggregated average fertiliser and pesticide application rates.

LCM2019 – Development of land cover map creation is continuing. Cloud-computing will be used to automate the image pre-processing stages of LCM and to combine different types of satellite data which should result in faster, annual, updates of the LCM[6].

3. References to the underpinning work

[1] Fuller, RM., Groom, G. & Jones, AR., 'The Land Cover Map of Great Britain: An Automated Classification of Landsat Thematic Mapper Data' *Photogrammetric Eng. & Remote Sensing.* 1994*,* 60(5). pp.553-562

[2] Fuller, RM., Smith, GM., et al., 'The UK Land Cover Map 2000: construction of a parcel-based vector map from satellite images' *The Cartographic Journal.,* 2002*,* 39(1) pp.15-25

[3] Smith, G., Beare, M., Boyd, M., Downs, T., Gregory, M., Morton, D., Brown, N. & Thomson, A., 'UK Land Cover Map Production Through the Generalisation of OS MasterMap®' *The Cartographic Journal.,* 2007*,* 44(3), pp. 276-283

[4] Morton, D., C.S. Rowland, et al., 'Final Report for LCM2007 - the new UK land cover map.' CS Technical Report No 11/07, 2011, CEH 112pp.

[5] Rowland, C., et al., Land Cover Map 2015

[6] Carrasco, L., O'Neil, A.W., Morton, R.D. and Rowland, C.S., Evaluating Combinations of Temporally Aggregated Sentinel-1, Sentinel-2, And Landsat 8 For Land Cover Mapping with Google Earth Engine, *Remote Sensing*, 2019, 11(3), 288

4. Details of the impact

In 2019, an independent consultant carried out a survey of users of the LCM products [7]. The results confirmed that there is a very wide and significant range of applications for the datasets. These included assessing land cover and ecosystem services, mapping ecological networks, classifying and assessing wildlife habitat and detecting land cover change. The applications monitor and protect habitats, support biodiversity and prevent its loss, support natural resource management, and climate change mitigation and adaptation. The datasets are of clear benefit to businesses, not-for-profit organisations and the public sector. Many users consider the LCM products to be fundamental tools that underpin their work. Although it can be difficult to have a consistent method to quantify the value and contribution across all users it is clear from the survey there are a wide range of impacts with a value to the UK of tens of millions of pounds. To illustrate the wide range of reach, the case study examines specific examples from the consultant's report for three areas: Business, UK Infrastructure and Policy

1. Business: Water industry and catchment management

Severn Trent - Land Cover Plus: Crops is an essential element of Severn Trent Water's catchment management approach. Severn Trent describes '*LCM plus Crop Map dataset is essential in our catchment management actives – it is crucial in our planning, identifying target areas, forecasting of future trends and pollutant issues'* [7]. It has supported catchment management planning, identifying target areas for pollutants and as a result has negated the need to build new, or upgrade existing, water treatment plants. In general, Severn Trent estimate that for every pound spent on catchment management, they save between £2-20 on water treatment costs and provide another £4 in wider ecosystem service benefits. In one particular catchment, activities underpinned by the LCM-Crops data have saved a significant amount of costs. This is described by a Catchment Scientist, Severn Trent Water: '*In the Tittesworth catchment (Staffordshire), a pesticide treatment upgrade to the water treatment works was planned for Asset management Plan, period 7 (AMP7, 2020-2025), however our catchment activities underpinned by the crop dataset have meant that we are controlling the pesticide issue at source, and as such, the planned upgrade is now not necessary and not going ahead. This has saved £4.1 million is construction costs and an additional £53,000 per year in operational costs, which would have been added to our customers' bills if it had gone ahead*' [7].

Another use of LCM plus Crops dataset has been to identify target areas for metaldehyde (used in slug pellets) catchment activities, specifically where risks are the highest owing to crop rotation, and forecasting of future crop trends. Severn Trent have combined this with other data sets to predict what metaldehyde concentrations are likely at their water treatment works. This has allowed more efficient use of particular treatments at several sites. Severn Trent estimate that there is a *'maximum cost saving of £150,000 per year'* [7].

United Utilities - United Utilities' Sustainable Catchment Management Programme protects and improves the quality of water in rivers and aquifers across the North West of England and cross-border Wales to reduce water treatment costs. LCM and Land Cover Plus: Crops are key datasets to support this approach, as evidenced in the 2017 review [8] of the River Dee catchment where the amount of agricultural pesticides had been increasing. Following the review, action to improve water quality resulted the development of farm water and nutrient management plans, Agri-Environment Scheme grant applications, and a pesticide amnesty across 26 farms resulting in the removal of 1,833 kg of pesticides.

Rivers Trust: As part of Defra's catchment management approach, the Rivers Trust have used Durham University's SCIMAP model to classify diffuse pollution risk based on land cover - LCM2015 is one of the key inputs to the model. The result is a map of diffuse pollution risk across catchments allowing identification of changes in farm land management to help target catchment wide mitigation measures. '*LCM is hugely important for the Catchment Based Approach and Rivers Trust. It's probably the best quality land use map that we have of the UK. And it does get used a lot so for things like the SCIMAP modelling but it's used for other purposes as well… LCM is more accurate than CORINE*', GIS specialist, Rivers Trust [7]. A 2017 study looked at the economic benefits of diffuse pollution mitigation targeting. It found that a spatially micro-targeted approach (as shown with LCM/SCIMAP) reduced the cost of complying with environmental standards - thus benefiting regulators, farmers and the environment [9].

2. Infrastructure planning and development

Nature Space Partnership (NSP) [10] was created to design, manage and deliver the Great Crested Newt District Licencing scheme. They have developed a model/ offset metric with Natural England based on LCM. The LCM 2015 dataset is combined with other datasets and used to assess land habitat suitability for great crested newts around developments. NSP then use their metric to assess impact, and calculate a payment into an offset scheme allowing the creation of conservation habitats elsewhere. LCM is estimated to save multiple days of planning time and hundreds of thousands of pounds in costs. '*Most of what I do now is desk-based modelling rather than lots of surveys and site visits. This saves a lot of time, effort and money for developers, reducing risk for the developer, but more importantly, supporting long-term conservation efforts for great crested newts'*. Ecologist, Nature Space Partnership [7].

Perth and Kinross Council – LCM is used by Perth and Kinross Council to provide land cover information in support of local planning and development decisions. The Council aims to balance the benefits of allowing development while protecting both sensitive habitats and places that are valued for their beauty, biodiversity and value to tourism. Over the last few years, use of LCM has generated cost savings, enabled informed policy-making on renewable energy, supported strategic environmental assessments for local development plans, and enabled clear, visual communication with councillors and members of the public about local development. '*Our strategy for wind farms is to try and identify those areas where development should or could take place - having more information at an early stage means that you're going to minimise potential problems for the future. [LCM] saves us money in some respects, particularly where we have been involved in public enquiries into windfarm proposals. The potential here is where the council's had costs awarded against it because it had an incomplete understanding of the area where the wind farms were going to take place*.' Planner, Perth and Kinross Council [7].

Highways England - As part of a project for Highways England and Kier Highways, CEH used LCM and species data to identify gaps between habitats and species populations near the A30 and A38 in Devon and Cornwall. Highways England then began an extensive planting scheme to improve connectivity between habitats to support wildlife in the area. Ten thousand native trees and shrubs were planted connecting over 105 miles of habitat on the verges and land adjacent to the two roads. In addition, almost 27,000 m^2 of new heathland - a 60% increase – was created along the verge on key sites on Dartmoor, Bodmin and Goss Moor [11].

3. UK Government Policy and practice

Natural Capital Accounting - In December 2012, the Office for National Statistics (ONS) published a roadmap, '*Accounting for the value of nature in the UK*', which set out a strategy to incorporate natural capital into UK Environmental Accounts by 2020. Gross domestic product (GDP) hides and excludes services provided by natural capital, and it focuses only on flows of income and output, not stocks of capital, including natural capital, that underpin them. The Natural Capital Committee and the UK National Ecosystem Assessment flagged the development of natural

capital accounts as a fundamental activity, necessary if natural capital is to be mainstreamed in decision-making. It sends a strong signal to businesses and local decision makers of the importance of monitoring and valuing natural assets. In order to develop a set of natural capital accounts, land cover data is fundamental to describing ecosystem assets and their extent. LCM is deemed essential by the ONS as an underpinning dataset in the methodological development of the UK Natural Capital Accounts. The 2017 background paper published by ONS to develop the framework for ecosystem accounting stated '*The rich spatial detail expected from the Land Cover Map is seen as an essential element of the natural capital accounts. It will form the basis of subnational accounts, and it can be used in modelling the provision of certain ecosystem services such as air pollutant absorption and flood protection. It also provides the opportunity to report the accounts in the form of maps as well as in the form of accounting tables*.' [12]. In October 2019, the Head of Natural Capital at the ONS said '*In general, LCM is underpins all the Natural Capital accounting in the UK – not just by ONS, but for all organisations – because it gives universal, standard coverage across the UK at the appropriate scale. All this allows the UK to make better, more informed decisions for our long term management of environment. It's difficult to put a direct value on this because it is underpinning. If LCM did not exist then you'd have to create a way of doing it – and that would probably by ad-hoc by project or specific small area so you would lose the interoperability at national level, and the standard method that LCM brings'* [13].

Environmental monitoring In England, environmental indicators are produced in order to track progress against the ambitions of Natural Environment White Paper (NEWP) (2011). When compiling these statistics for England, Natural England use LCM2015 and LC plus Crops specifically for the land use indicator and the value of ecosystem services indicator [14]. A Senior Specialist, Specialists Services Programme, Natural England commented '*LCM has complete coverage of England, with a past time series and statistical assessments of uncertainty. For our natural capital mapping and accounts work, it is the best product currently available for assessing the extent of broad habitats*' [15].

In Wales, the State of Natural Resources Report (SoNaRR) (2016) assesses how pressures on Wales' natural resources are resulting in risks and threats to long-term social, cultural, environmental and economic well-being, as set out in the Well-Being of Future Generations (Wales) Act 2015. LCM data was used within the Glastir Monitoring and Evaluation Programme (GMEP), which provides key environmental data to the Welsh Government. LCM data is used to provide statistics on Mountains, moors and heaths, Enclosed farmland and Woodland [16].

General Impact Information

The total value of satellite-derived Earth Observation products for UK government applications is forecast to reach £1.2 billion per year by 2020 [17]. LCM2015 has not been separated out from this value so it is not possible to give an estimate of the total value of LCM. However together the LCM products they have raised over £880k* through licensing agreements. LCM2015 has been licensed to 38 government organisations, 26 businesses and NGOs and is subscribed to by 112 higher and further education establishments through EDINA/DIGIMAP. On average (over the last four years), it (including the free 1km raster version) was been loaded over 5500 times per annum for academic use, and 510 per annum by other users.

5. **Sources to corroborate the impact**

[7] '*Findings from qualitative and online research with current and previous users of LCM*' J Bacon, independent consultant, Prepared for CEH, July 2019

[8] United Utilities River Dee Catchment Report, Sept 2017, (accessed 10th Jan 2020)

https://issuu.com/westcountryriverstrust/docs/uu_dee_catchment_report_11-09-17_we

[9] Transferability of Policies to Control Agricultural Nonpoint Pollution in Relatively Similar Catchments, Ashar Aftab et al., Ecological Economics Vol. 134, April 2017, Pages 11-21

[10] https://naturespaceuk.com/scheme-facts/ (accessed 10th Jan 2020)

[11] Highways Habitat Connectivity in Devon and Cornwall, Kier Highways and Highways England, Shortlisted BIG Biodiversity Challenge Awards, 2018,: https://b1ea6716-8f69-460b-859a-5217029db8ff.filesusr.com/ugd/18479d_41011d50d01e490da3c1f27c718ce93d.pdf accessed Jan 2020

[12] The Principles of Natural Capital Accounting, ONS, 2017

[13] The Head of Natural Capital, ONS, personal communication, Dec 2019

[14] England Natural Environment Indicators, Nov 2017, Defra

[15] Senior Specialist, Natural England, personal communication, Dec 2019

[16] Glastir Monitoring and Evaluation Annual reports, 2nd year report, 2015, B Emmett, 2015

[17] '*Value of satellite-derived Earth Observation capabilities to the UK Government today and by 2020'*, London Economics, Innovate UK, 2018

Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH07_Supporting agricultural and environmental policy in Wales**

Section B

1. Summary of the impact (indicative maximum 100 words)

The Welsh Government (WG) has enshrined the UN Sustainable Development Goals into policies to support a more sustainable, resilient and ethical future for Wales. To support the evaluation of these policies, WG commissioned CEH to implement a series of environmental monitoring and modelling research activities. The outputs of this work have led to policy developments including support for EU Exit preparations and improvements to the Welsh land management payment scheme, Glastir. Welsh Government have described CEH work as supporting *'the most significant transition in agricultural policy over the last half century'.*

2. Underpinning research

Wales' natural resources support significant economic sectors including agriculture and forestry, tourism, health and well-being. In order to develop policies that build social, economic and environmental resilience and to evaluate policy implementation, the Welsh Government (WG) commissioned CEH, after a competitive bidding process, to implement a series of environmental monitoring and modelling research activities from 2012 to 2022 in two separate programmes – the Glastir Monitoring and Evaluation Programme (GMEP) (2012-2016) and the Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP) (2018-2022). A key ambition of this work is to generate high quality evidence, including novel methods, to ensure Wales is at the forefront of an evidence-based approach to delivering its highly innovative policy legislation - the Well Being of Future Generations Act 2015 and Environment Act (Wales) 2016 - and the £250m per annum Wales agri-environment land management scheme, Glastir, funded through the EU Rural Development Programme as part of the Common Agricultural Policy (CAP).

CEH, with its partners, has provided robust, independent evidence to WG (see Section 4). The independent aspect of the work was considered critical by WG to gain the confidence of stakeholders such as the farming unions, forestry industry and conservation NGOs. The work, led and coordinated by CEH, involves over 20 research organisations including: ADAS (agriculture pollutant modelling); Forest Research (woodland modelling for climate mitigation and other ecosystem services); eftec (environmental accounts); Public Health Wales (access to unique public health data); and biodiversity specialists such as the British Trust for Ornithology. CEH has jointly commissioned these organisations to provide contributions to the work programmes; CEH monitors and integrates the findings, and quality assures the outputs prior to delivery to WG.

Within GMEP and ERAMMP, a wide variety of activities have been delivered including;

- A national environmental monitoring programme building on CEH expertise in delivering integrated national monitoring programmes of the wider countryside. Note: GMEP and ERAMMP compliments but does not duplicate the monitoring of designated land (i.e. National Parks, Areas of Outstanding Natural Beauty, conservation areas, etc.), which is the responsibility of Natural Resources Wales (NRW). The approach combines robust statistical design and analysis and enables a high degree of re-use of data for multiple purposes, ensuring both continuity of evidence streams and cost efficiency. Building on CEH's Countryside Survey (CS) methodology, surveyors capture multiple metrics at permanent, co-located positions in carefully stratified random 1km squares across the country, which also minimises disruption to landowners. The co-location of measurements ensures the interactions at a landscape scale between soil, water, vegetation, birds and pollinators can be directly explored;

- The development of novel, robust indices and metrics for biodiversity, High Nature Value Farmland, soil biodiversity, and landscape aesthetics;
- The application and integration of a series of industry standard models to explore impacts of a range of possible futures post-EU Exit resulting from different potential trade deals;
- These same models were also used to explore the potential delivery of public goods and their economic value within a new Welsh CAP replacement scheme, the Sustainable Farming Scheme (SFS); and
- Production of the first Natural Capital Account for Wales.

The novel and high quality nature of the work can be demonstrated from the series of over 20 peer-reviewed papers in the international literature including an initial description of the integrated nature of the work [1]. Highlights include: a novel repeatable approach for assessing Landscape Aesthetic Values using the field survey data and validated with ca. 2500 citizens [2]; insights into the 'hidden' biodiversity in soil and the contrasting underlying factors which influence the spatial distribution of different biological taxa (i.e. bacteria, fungi and mesofauna) [3]; novel integration of field survey and EO data to map net primary production at a national scale [4]; and new approaches to the identification of High Nature Value Farmland - a required reportable metric to the EU for agri-environment/land management payments [5]. Evidence for the outcome of past land management payment schemes [6] and long term trends for a range of natural resources and ecosystem services have also been published [7].

Lead researchers: Bridget Emmett, David Robinson, Jack Cosby, Paula Harrison, Simon Smart, Laurence Jones and Lindsay Maskell.

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4. Details of the impact

Responsibility for agricultural and environmental policies have been devolved from central government resulting in increasingly divergent agricultural and environmental policies across the UK in recent years. The Welsh Government was the first to enshrine the UN Sustainable Development Goals regulations into major new policies to support a more sustainable, resilient and ethical future including the Well-Being of Future Generations Act 2015 and Environment Act (Wales)

Act 2016. Both Acts have key reporting requirements to which GMEP and ERAMMP contribute official national statistics [8,9]. The Well-Being of Future Generations Act has seven goals and 46 clear measurable social, economic and environmental 'National Indicators' to track Welsh progress in meeting the SDGs. CEH developed and is responsible for the metric 'Concentration of carbon and organic matter in soil' and a new metric being considered for tracking the 'Status of biological diversity in Wales' [9]. The Head of Environmental Modelling and Monitoring, EU Exit and Strategy division, Department of Environment and Rural Affairs (ERA), WG has stated '*The CEH-led GMEP and ERAMMP represents a significant and central evidence programme for WG. The return on this investment is a rich and highly valued evidence base. It is robust, wide reaching and insightful. GMEP and ERAMMP national trend data is used for a number of Common Context Indicators in the WG's Annual Implement Reports to the European Commission on the impact of the Common Agricultural Policy (CAP). GMEP and ERAMMP data is used for statutory reporting in relation to domestic legislation including the Wellbeing of Future Generations Act National Indicators, and the Environment Act (Wales) State of Natural Resources Report*' [10].

The UK governments, including WG, have relatively few mechanisms to influence farmers and foresters, and thus the productivity and environmental impacts of over 80% of the UK land area. Regulations and financial incentives are two main policy levers but these are now under major review due to the potential wide-ranging effects the UK's exit from the EU may have on: the profitability and thus sustainability of farming and forestry industries; and the climate emergency. To date, the large programmes of work described in this case study have resided within several WG departments due to changing political situations, most recently sitting within the WG EU Exit Policy Planning team. Through close engagement with WG on GMEP and ERAMMP, CEH has produced a range of rapidly commissioned reviews and reports to help inform fast-moving political developments. This is in addition to the more long term strategic monitoring and modelling work delivered by the programmes.

Examples of these impacts include:

Land management payment scheme development including decarbonisation

CEH-led modelling activity led to the modification of the £250m per annum Glastir scheme to better target payments to increase cost-benefit outcomes (2014). The Head of Environmental Modelling and Monitoring, WG has stated '*In year 1 of Glastir, the CEH-led GMEP undertook a series of model simulations to explore and estimate scheme impact. These outputs were used in year 2 of the programme to modify the scheme in an attempt to increase the impact of the scheme. Modification of a pillar II scheme so early in its programme period based on modelled evaluations was totally novel as traditionally evaluation takes place post programme period and schemes are modified between programme periods'*. [10]. The Deputy Minister for Farming and Food, WG has said '*GMEP is regarded as an exemplar of good practice. This programme has been identified at the UK, European and International level as being at the forefront of the ecosystem approach to evidence capture and [land management] scheme evaluation*' [11]. This view has also been endorsed by the National Farmers Union (NFU) of Wales: *'The reliable, robust scientific evidence gathered by GMEP allows the effectiveness and the value for money of Glastir to be monitored which is extremely important, especially for farmers and land managers to see what is being achieved through being in the Glastir scheme'* [12].

CEH has led the development of the only external-derived evidence base for the new circa £300m per annum Welsh Sustainable Farm Scheme (SFS), the environmental land management payments scheme that will replace Glastir [13]. Critically, this included an integrated assessment across management interventions showing their many co-benefits, trade-offs and spatial constraints and the potential limitations of economic valuation of environmental outcomes. The 'Evidence Pack' was the only document alongside the official consultation document on the public consultation website for the new SFS scheme [14]. The Head of Environmental Modelling and Monitoring, WG has stated '*The distribution of public goods resulting from land management change and the estimated value of these public goods modelled by the CEH-led ERAMMP provided the first and a highly influential piece of evidence to support the most significant transition in agricultural policy over the last half century, namely a shift from money forgone based schemes to payments for public goods based*

schemes. *The shape, form and nature of the CAP replacement programme in Wales will be informed by the high quality evidence generated by the CEH-led ERAMMP'* [10]. In addition, the WG has confirmed its intention to use evidence from ERAMMP to monitor outcomes from the new Sustainable Farm Scheme [15].

CEH-led modelling work has also demonstrated options for the decarbonisation of the agriculture sector and a move towards net zero greenhouse emissions, which are now being considered as part of the new SFS scheme. The WG has recognised through its new climate change policy 'Prosperity for all - a climate conscious Wales' (2019), the critical role of ERAMMP in developing the evidence and models to aid policy delivery on sustainable farming and climate change [16].

EU Exit scenario planning

CEH undertook modelling scenario work that identified up to 7000 Welsh jobs at risk and up to 15% of current land dropping out of agriculture as a result of the UK's exit from the EU [17]. This resulted in the recognition at the quadrilateral meetings of the four UK National Environment Ministers of the need for a 'safety net' in the form of transition support for areas dominated by sheep farming post-EU exit due to the potential for job losses, negative impacts on farmer mental health, and the lack of opportunity and infrastructure in those areas (2019). The Head of Strategic Analysis, EU Exit and Strategy division, ERA, WG has stated '*The scenario planning outputs delivered by the CEH-led ERAMMP team has been the cornerstone evidence for WG to understanding the potential impacts of the changing trade environment as a result of leaving the EU. WG has used this work to influence the UK Government; the outputs were presented at a Ministerial Quadrilateral meeting. At this particular meeting, the UKG were considering the proposed UK WTO schedule of tariffs to be applied to goods imported to the UK. The evidence Wales was able to present persuaded the Defra Minister at the time to lobby the DiT for some tariff protection for UK agriculture. The subsequent announcement included tariff protections for lamb, beef and some dairy products*' [18]. In addition '*The same evidence base has [articulated] the challenges for upland sheep farmers, in all scenarios; this led to the ERA department bidding for funds for some research into how to tackle mental health issues in the farming sector*' [19].

Woodland expansion

The First Minister of Wales has a commitment to a new Welsh National Forest for which £4m for an initial pilot fund has been allocated. Following CEH-led modelling work [17], the WG is now reviewing its policy and guidelines on new woodland planting in Wales. CEH models demonstrated that a focus on the benefits of current land assets as opposed to including opportunities for delivering zero-carbon, restoring native biodiversity and increasing domestic timber supply, limited the potential for new woodland planting. The CEH-led ERAMMP has now been commissioned with new work to support the pilot phase and quantify the full range of potential benefits of a new National Forest. The Head of Environmental Modelling and Monitoring, WG has confirmed that '*The First Minister for Wales is bound by a commitment to establish a National Forest. This is a response to the Climate Emergency, which the Welsh Government recently announced and a recognition of the wellbeing and societal benefits forests deliver. With a highly regarded track record for delivering robust evidence at pace, the CEH-led ERAMMP is tasked with developing an evidence pack to support the development of a new National Forest Policy. A key objective of this evidence pack is to directly contribute to the business case for the National Forest, evidence to draw down significant domestic funding*' [10].

Wales National Natural Capital Account

CEH collaborated with the Office of Natural Statistics (ONS) to create the first ever Wales National Natural Capital Account [20]. The value of the stock of Welsh Natural Capital in woodland, farmland and freshwater was estimated to be approximately £30.5 billion in 2014. This is a partial value - as only seven of the benefits received from natural capital in Wales are currently measured - and the true value is expected to be significantly higher than this figure. Of the services measured, 76% of

this value was attributable to intangible or non-market services not traditionally captured in GDP (e.g. recreation, pollution removal and carbon sequestration) illustrating how we have traditionally undervalued the importance natural assets and cost of their degradation. GMEP and ERAMMP data in combination with other CEH data e.g. from the Land Cover Map (LCM) '*allows the UK to make better, more informed decisions for our long term management of environment'* [ONS, 21].

5. Sources to corroborate the impact

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Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH08_Establishing and underpinning the International Nitrogen Management System**

Section B

1. Summary of the impact

Using nitrogen costs the world billions of dollars through inefficient fertiliser use, associated environmental damage and contributes to climate change. CEH work in nitrogen emissions and effects has underpinned United Nations conventions and resulted in the adoption of national emission level ceilings. The CEH-led European Nitrogen Assessment has inspired other countries by providing an exemplar assessment framework. CEH leads the establishment of the International Nitrogen Management System. The resulting insights have formed the basis for the UN Environment Assembly Resolution (UNEP/EA4/Res14) and for 14 countries to agree the Colombo Declaration, which aims to halve nitrogen waste by 2030 offering a saving of US$100 billion per annum globally.

2. Underpinning Activities

CEH's research into reactive nitrogen has provided a world-leading hub for integrated research on the nitrogen cycle and its interaction with other biogeochemical cycles. Over the last thirty years CEH has developed leading measurement and model programmes of biosphere–atmosphere nitrogen flows, especially ammonia (NH_3), nitrous oxide (N_2O) and nitric oxide (NO) to address the interactions between nitrogen forms, including atmospheric particulate matter; between nitrogen and other greenhouse gases; and between air, land and water flows. This is crucial to understanding the adverse effects of the resultant pollution e.g. eutrophication (excess nutrients in water) and algal blooms. In terms of climate change, N_2O constitutes 8% of global Greenhouse Gas emissions with a Global Warming Potential of 300 (compared with 1 for CO_2).

CEH work integrates mechanistic studies of impacts with long-term measurements to support the development of model chains that feed into cost–benefit analysis and optimisation strategies [1]. One aspect of this has concerned the measurement of ammonia biosphere–atmosphere exchange with terrestrial ecosystems, resulting in new conceptual and quantitative models [2] which have been used to develop mitigation strategies. CEH scientists, particularly Professor Mark Sutton and the Edinburgh team, have developed a suite of tools to quantify the impacts of nitrogen compounds over the UK including FRAME (led by Dr A. Dore) [3] and EMEP4UK [4] (led by Dr M. Vieno). CEH established the National Ammonia Monitoring Network [5] which quantifies temporal and spatial changes in air concentrations and deposition in NH_3 and NH_4^+ (ammonium) at 85 sites across the UK. It uses the Delta system, which was developed at CEH [6] as a uniquely low cost approach for multi-site deployment allowing assessment of long term patterns. The measurements underpin understanding of changes in rural air quality over time and help validation of models. This research underpins understanding of UK air quality interactions and transport, which inform Defra, the UN Environment Programme (UNEP), and the UK's obligations to the United Nations Economic Commission for Europe (UNECE) Convention on Long Range Transboundary Air Pollution (CLRTAP) and the Gothenburg Protocol on atmospheric emissions control. This work to support CLRTAP has been formalised through the UNECE Task Force on Reactive Nitrogen (TFRN) (with Professor Sutton being a founding co-chair) which has delivered options to support the revision of the Protocol.

The work expanded into Europe with projects including NitroEurope (an EC project with 64 institutes, 2007–2011, €28 million, led by Professor Sutton), investigating how nitrogen affects Europe's greenhouse gas balance, and ÉCLAIRE (38 institutes, 2011–2015, led by Professor

Sutton), researching how climate change may alter air pollution impacts on terrestrial ecosystems. NitroEurope showed that nitrogen impacts assessments on greenhouse gas balance need to account for uncertainty in modelled atmospheric nitrogen deposition [7] and quantified how the warming effects of N_2O are offset by cooling effects of nitrogen deposition and formation of particulate matter [8]. A major finding of ÉCLAIRE was that future climate change [2] is expected to worsen the threat of air pollutants on Europe's ecosystems. It will increase the emissions of many trace gases, such as agricultural ammonia, as well as the vulnerability of ecosystems towards air pollutant exposure or atmospheric deposition.

The scope of NitroEurope was extended through the Nitrogen in Europe programme of the European Science Foundation, allowing Professor Sutton to lead the European Nitrogen Assessment (ENA), [8] the first comprehensive continental analysis of nitrogen benefits, threats, and policy opportunities. The ENA provided the evidence base and analysis for European governments and other stakeholders to relate the benefits of nitrogen to society as opposed to the adverse effects of excess nitrogen in the environment. For example, the ENA showed that societal costs of nitrogen pollution amount to an estimated €70-320 billion annually [9] and that halving meat and dairy intake in the EU would reduce nitrogen pollution by 40% [10].

CEH's pioneering of the ENA led to an invitation from UNEP to lead the Global Overview on Nutrient Management (GONM), resulting in the report *Our Nutrient World* (ONW) [11]. This report, led by Professor Sutton, highlighted how nitrogen affects water quality, air quality, the greenhouse gas balance, ecosystems and soil quality, pointing to multiple benefits of more efficient nitrogen use.

From 2012 to 2018, Professor Sutton held the chair of the International Nitrogen Initiative (INI), a joint project of Future Earth and the Scientific Committee on Problems of the Environment (SCOPE). This activity allowed CEH to work with UNEP and the Global Environment Facility (GEF) to develop the International Nitrogen Management System (INMS) through projects with US$6M from GEF backed by US$60M in partner contributions. INMS is a mechanism of science support by providing tools, approaches, and demonstrations that can mobilise policy change on a global scale. This CEH-led partnership involves stakeholders across the world with demonstration activities in Asia, Latin America, East Africa, Europe and North America.

The work in South Asia is being further developed by the CEH-led Global Challenges Research Fund South Asia Nitrogen Hub (SANH, £17m from UKRI, 2019-2024). The hub integrates policy, solutions, awareness and quantification of nitrogen flows through air, land, freshwater and marine systems in a region where nitrogen issues are acute. The hub brings the UK together with all South Asian countries, UNEP and the South Asian Cooperative Environment Programme.

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4. Details of the impact

Updating the Gothenburg Protocol and National Emissions Directives

CEH has provided a significant part of the evidence to the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP) and the Gothenburg Protocol for atmospheric emissions control (which entered into force in 2005). In 2012/13 the UNECE revised the emissions commitments for nitrogen oxides and for ammonia, basing its decision in part on the evidence from NitroEurope, ENA and the Task Force for Reactive Nitrogen (TFRN). Key outputs prepared under CEH leadership included establishing a new Critical Level for ammonia [12], the drafting of the Ammonia Guidance Document [13] and Ammonia Framework Code [14]. The impact of each of these contributions has been amplified through their incorporation into the revised National Emissions Ceiling Directive (NECD, Directive/EC/2016/2284) of December 2016. It commits the UK to achieving nitrogen oxides levels at 73% below 2005 levels by 2030. Ratified by 18 countries, the revised Gothenburg Protocol came into force on 7th October 2019.

UK response

The National Emissions Inventory is the UK's report on emissions for its obligations under the Gothenburg Protocol and NECD. CEH contributes the UK maps on agriculture emissions. After 1990, England's agricultural ammonia emissions have declined by 22%, but since 2005 they have increased by 4% [15] a pattern which is reflected across UK, France and Germany, with the result that these countries are expected to exceed their legally binding limits for 2020 [16]. The English (and overall UK) increase is largely due to an increase in the numbers of cattle kept in slurry-based systems. In 2018, using the CEH led UNECE Ammonia Framework Code [14] as its basis, Defra issued a UK National Ammonia Code and launched a £3 million scheme to support farmers in achieving reductions. If measures in the code are widely adopted then by 2030 the UK will meet its obligations to reduce ammonia by 16% compared to 2005 levels. Based on TFRN findings, it is estimated that it is possible to achieve savings of €1 per 1 kg of nitrogen [13]. A 16% reduction across the UK will correspond to savings to UK farmers by 2030 of £130 million per annum [17], in addition to the benefits to health and the countryside.

The reduction in ammonia emission from agriculture forms a significant part of the UK response to meeting the Gothenburg requirements through the 2019 UK Clean Air Strategy, where it is one of the four main targeted areas for cleaner air. As an indication of the involvement of CEH, the Clean Air Strategy was launched by the then Secretaries of State for Environment (Michael Gove) and Health (Matthew Hancock) at the BT Tower hosted by Dr Eiko Nemitiz of CEH.

Country responses to the European Nitrogen Assessment

Based on the European Nitrogen Assessment (ENA) approach developed by CEH, a number of countries or regions have developed their own nitrogen assessments, including Germany, Denmark, and Portugal. The Portuguese Nitrogen Assessment lead stated that it was '*previously inspired by NitroEurope and the ENA that resulted into a high performance project that has delivered much more than initially promised'* [18]. Outside Europe other national and sub-national

territories such as India [19] and California have done the same. These assessments have provided evidence to inform national nitrogen abatement policies.

Global and World Regional response

Through the International Nitrogen Initiative (INI) and TFRN, the leadership of CEH is being widely recognized by numerous international bodies. These include the UN Environment Programme (UNEP), and the Organisation for Economic Co-operation and Development (OECD), which have acknowledged that nitrogen has been a neglected issue that needs to be considered in order to meet the Sustainable Development Goals (SDGs). Working with CEH, the OECD included nitrogen among the themes of its ministerial Environment Policy Committee (EPOC).

UNEP has recently recognized nitrogen as 'an emerging issue of environmental concern' in its 18/19 *Frontiers* report [20]. This builds on the impact of *Our Nutrient World* [11], which showed how a 20% improvement in nitrogen use efficiency could deliver global savings of US$170 billion per annum, taking account of the societal benefits for health, ecosystems and climate, the implementation costs and the financial benefits. ONW has been complemented by the UNEP report *Drawing Down N_2O*, co-led by Professor Sutton [21]. In the report foreword the UN Under-Secretary-General wrote: '*[nitrous oxide is] the third most important gas in terms of climate change… reducing nitrous oxide emissions also comes with other added benefits – nitrous oxide emissions are connected to many different economic sectors… greater ambition is needed by nations across a suite of challenges*.' Together, these scientific syntheses, prepared under CEH leadership, have demonstrated to UNEP that there is a need for a coherent global approach to manage the nitrogen cycle, maximize benefits and minimize the negative effects.

As a result of these initiatives, CEH was able to win major funding from the Global Environment Facility (GEF) through UNEP (a first within NERC) to establish the 'International Nitrogen Management System' (INMS), directed by Professor Sutton. It aims to '*improve the understanding of the global nitrogen cycle and investigate/test practices and management policies … with a view to reducing negative impacts'*. INMS is already providing indicators of success as it mobilizes country action. For example, engagement with India (as part of the CEH-led Newton-Bhabha 'NEWS India-UK' Virtual Joint Centre on Agricultural Nitrogen) has valued nitrogen pollution impacts on health, ecosystems and climate at between US$40 billion and US$150 billion per annum, while India spends cash costs of US$7 billion annually on its nitrogen fertiliser subsidy [19]. INMS, with the INI, has committed to support a global goal to 'halve nitrogen waste' from all sources by 2030, saving a potential US$100 billion per annum across the planet, and more in terms benefits to health and ecosystems [22].

UN Environment Assembly Resolution and Colombo Declaration

The goal is ambitious and requires a significant effort from policymakers and politicians. CEH's role has been and continues to be catalytic, through initiating, co-chairing or co-directing the various projects. CEH is thereby co-ordinating the global scientific effort to provide the best evidence to decision makers. To this end, INMS, SANH and INI, under the lead of CEH, provided research evidence to the South Asia Cooperative Environment Programme (SACEP) and organised the drafting of a UN Environment Assembly resolution on nitrogen, officially submitted by the Government of India. The resolution, UNEP/EA.4/Res.14 [23] was passed in March 2019 by 173 nations at the Fourth United Nations Environment Assembly where the ONW report [11] was the only cited evidence. The Director General of South Asian Cooperative Environment Programme (SECAP) commented on the South Asia Nitrogen Hub achievements in bringing the South Asian nations together: *'Under the SANH, SACEP has been able to get connected to tackle the problem of nitrogen pollution through a framework policy that is based on scientific research and findings. The UNEA-4 Resolution on Sustainable Nitrogen Management is a unique example. The SANH gives multiple benefits and will help SACEP members to implement multiple SDGs'* [24].

The INMS and SANH have followed up the UNEA resolution by organising a meeting with UNEP and the Government of Sri Lanka in October 2019. Led by Professor Sutton, INMS/SANH provided the latest evidence and analysis, preparing the 'UN Roadmap for Sustainable Nitrogen Management, 2020-2022' and the first draft of the Colombo Declaration, as a foundation for negotiation and ultimate adoption by 14 countries [25]. The process was conducted under the leadership of H.E. the President of Sri Lanka, and simultaneously launched UN Global Campaign on Sustainable Nitrogen Management under the theme of 'Nitrogen for Life' [26].

At the Colombo Declaration meeting, the UK Deputy High Commissioner to Sri Lanka stated that '*INMS [led by CEH] is providing core science support system for UN environment illustrating the UK's continued leadership on science'*. UNEP agreed it would work with the INMS, through the INI and individual nations and with regional bodies, to develop specific actions that will have a global impact. The Deputy Executive Director of UN Environment said, '*the whole campaign is informed by science. [Professor Sutton, CEH] you have managed to mobilise through your networks not only the scientific data but the scientists as a network to support the Global launch … I did not foresee this happening so very, very fast … happening 8 months after the resolution is not common … I've been impressed by the mobilisation of the scientific community that you [Professor Sutton, CEH] have led. So I really want to appreciate your leadership'* [21].

In addition to the work of governments and global institutions, a programme of outreach has been established, particularly through SANH. As part of this programme, Ricky Kej, a Grammy Award winning songwriter and UNESCO Ambassador promotes greater awareness of nitrogen in his concerts. He commented '*Dr Sutton's endeavours to raise awareness come with fresh perspective…Music is a great way to create positive and meaningful impact. Professor Sutton and I [thought it essential to have a song on nitrogen to reach out to more people*' [27].

Through this world-leading programme of science-policy-public engagement, CEH nitrogen research is underpinning UK, EU and international strategies to reduce nitrogen pollution. It is inspiring countries globally to consider the role of nitrogen in climate change, water quality and stratospheric ozone depletion, and to develop approaches that link nitrogen's multiple threats and benefits. Building on the agreements at UNEA-4 and Colombo, CEH is now working with UNEP and its member states to go the next step in catalysing establishment of the *'Inter-convention Nitrogen Coordination Mechanism'* (INCOM) [22], embedding INMS and providing the basis for better nitrogen management to help meet multiple SDGs in the run-up to 2030.

5. Sources to corroborate the impact

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Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH09_Protecting communities and businesses from present and future flooding**

Section B

1. Summary of the impact

CEH's floods research has led to significant improvements in estimating and forecasting floods leading to quantifiable benefits to UK communities and businesses. Across four areas of flood risk estimation; provision of data for flood risk mapping and assessment; real-time flood forecasting; and climate change impacts, CEH's floods research is estimated to generate economic benefits in excess of £150M per annum for the UK. CEH methods underpin many of the industry standard flood risk assessment approaches for infrastructure and are recognised and adopted by national governments. CEH models are used operationally for national flood forecasting. Our data enable SMEs in the flood risk consultancy sector to develop products that in turn generate income and support jobs.

2. Underpinning research

Floods research is a core area of CEH expertise and includes flood risk estimation; provision of data for flood risk mapping and assessment; real-time flood forecasting; and future flood risk due to climate change.

a. Development of the Flood Estimation Handbook (Key staff: Lisa Stewart, Thomas Kjeldsen (left in 2013), James Miller). CEH's Flood Estimation Handbook (FEH) is the UK standard method for estimating flood risk, based on statistical analysis of historic hydro-meteorological records. The CEH spin out company, Wallingford Hydro-Solutions Ltd provide licensing, training and support for the FEH. CEH has continued to develop and refine the key statistical methods for Flood Frequency Estimation [1,2].
CEH has developed a new statistical model of point rainfall depth-duration-frequency (FEH13) for the UK to replace the original FEH DDF model [3]. The new model was constructed for estimating rainfall depths falling over durations ranging from 1 hour to 192 hours (8 days) for return periods ranging from 2 years to 10,000 years. The project was commissioned in response to concerns, expressed by reservoir engineers, about the apparently high estimates produced by the FEH DDF model when it was applied to return periods in excess of its recommended upper limit of 1,000 years. Such high return period estimates are used to calculate the probable maximum flood as a statutory part of the spillway design procedure for major reservoirs. In this project, the framework of the FEH approach to rainfall modelling has been retained, but a number of key elements have been substantially revised. The new model shows that, generally, estimates for the longer return periods are lower, especially in comparison with FEH. However, in Scotland estimates for the shortest durations have increased. These changes are due, respectively, to the improved spatial dependence model and improvements to the hourly rainfall dataset.

In 2015, CEH and Wallingford HydroSolutions launched the FEH Web Service, providing online access to the catchment descriptors and rainfall model outputs used in the FEH methods.

b. Provision of data for flood risk assessment and mapping (Key staff: Cath Sefton, Sean Harrigan (Jan 2016 to Dec 2017). CEH provide up to date river network-wide FEH flood peak estimates for selected return periods as well as FEH13 Rainfall Frequency Grids for a range of durations and return periods. These data are licenced to

Ambiental Risk Analytics, a company of Royal Haskoning DHV, and used in production of their UK FloodMap4™ product.

In April 2014, CEH took over responsibility for the maintenance and public provision of the UK's national peak flow database from JBA Consulting. Since taking over stewardship of this dataset, CEH staff have carried out substantial updates, including addition of 6000 station.years of data and review of the data and metadata at over 500 stations [4]. These data are made available through the National River Flow Archive web portal.

c. Development of real-time flood forecasting (Key staff: Vicky Bell, Steve Cole, Bob Moore). The Flood Forecasting Centre (FFC) is a partnership between the Environment Agency and the Met Office, combining the meteorology and hydrology expertise into a specialised hydrometeorology service. The centre forecasts for all natural forms of flooding - river, surface water, tidal/coastal and groundwater. CEH's grid-to-grid model sits at the heart of the Flood Forecasting Centre, translating rainfall into river flows to predict potential river flooding.

CEH has developed a new methodology for providing real-time forecasts of surface water flood impact [5]. The approach was initially applied to Glasgow for the 2014 Commonwealth Games with funding by the Scottish Government and work carried out by SEPA in collaboration with CEH, the James Hutton Institute, and the Met Office. It has subsequently been incorporated in the Flood Forecasting Centre systems. CEH provided its Grid-to-Grid (G2G) hydrological model to forecast surface runoff on a 1km grid for a 10km square area over Glasgow, and coupled this with the G2G model with Scotland-wide coverage. Surface runoff generation within G2G accommodates the effects on the receiving rainfall of land-cover, slope, soil/geology, and the evolving soil moisture conditions. CEH developed a novel methodology for accumulating surface runoff over different durations and linking these to SEPA's pluvial (rainfall-related) flood risk maps. CEH and SEPA scientists worked closely together to develop practical ways of visualising the spatial risk (on a 1km grid over Glasgow) of heavy rainfall, surface water flooding and its impact on people, property and transport. These digital maps give the extent and depth of surface water flooding for design storms of differing rarity/severity and associated impacts. They were calculated using a detailed flood inundation model and receptor datasets on people, properties and transport. The design storms use CEH's Flood Estimation Handbook assessments of return period for rainfalls of given depth and duration, and proposed rainfall profiles before allowance for storm drainage. The Glasgow Pilot system builds on complementary CEH research on surface water flooding under the Natural Hazards Partnership (involving the Health and Safety Executive and Met Office), with co-funding from the Environment Agency and Flood Forecasting Centre (FFC) [6].

d. Assesment of climate change impacts on the hydrological response across the UK (Key staff: Alison Kay, Nick Reynard). The science to underpin policy relating to the impacts of climate change on flood risk has been developing since the mid 1990s [7]. Work commissioned by the joint Defra/EA Flood and Coastal Erosion Risk Management R&D programme investigated how improvements in climate science and catchment modelling could be incorporated into climate change allowances for peak river flows. In particular, the national applicability of the 20% sensitivity allowance was assessed by modelling the impacts on peak flows for more catchments. This allowed consideration of the potential for regional variation and the risk that applying a single national allowance could lead to over-/under-adaptation. CEH applied a new methodology to address this question. 50-year return period flood peaks were modelled for three time-slices (2020s, 2050s and 2080s) and for each of the eleven regions covering England [8], Wales and Scotland. The approach explores the sensitivity of a system to climatic changes by overlaying climate projections on response surfaces produced by a sensitivity study. This

has the advantage of more readily being able to deal with large ensemble model outputs. The new web-interface enables users to find out changes to peak river flows any point on the river network over the next 50 years.

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4. Details of the impact

a. Development of the Flood Estimation Handbook

In 2006 PwC assessed the annual average economic benefits arising from the FEH [9], and were able to show:

i. time savings from use of FEH (£0.3 million to £1.3 million per annum at 2006 prices);
ii. reduced construction costs and flood damages (£8 million to £30 million per annum);

The FEH Web Service has over 5500 registered users across industry, environmental consultancy, regional and central government, and academia [10]. The new online system allows users to purchase credits (currently £2.50 each) to allow downloads for individual catchments and points. Previously, users had to buy a CD-ROM of FEH datasets covering the whole country even if they only wanted information for a small number of catchments. For some this was prohibitively expensive. In addition, online delivery means that updates can be released quickly and easily to users.

FEH methods have also influenced guidance, improving safety and efficiency across the construction and water management sectors. The FEH methods are recommended by the Construction Industry Research and Information Association (CIRIA) SuDS Manual. This states that *'FEH methods should be the preferred approach for developing runoff estimates for use in surface water management design'* [11]. FEH13 has been formally adopted by OFWAT as the method for assessing the severity of rainfall events. The OFWAT (2018) guidance states that *'Individual rainfall events with a storm return period greater than 1 in 20 years shall be classed as severe weather. The Flood Estimation Handbook, FEH13*

model shall be used to estimate the return periods of individual events, using radar or rain gauge data' [12]. FEH13 methods are also recognised in the fourth edition of Floods and Reservoir Safety [13]. This provides updated guidance to reservoir engineers and hydrologists on the estimation of reservoir flood inflows for the assessment of dam safety. This guidance proposes that the new FEH13 model should '*eventually replace the two existing rainfall models for UK hydrological analysis and design. The new DDF model has now been refined and generalised to provide rainfall estimates for any location or catchment in the UK, and a new web service to deliver the model results is under development'* [13].

b. Ongoing provision of data for flood risk assessment and mapping

CEH licence some of their hydrological data to the flood specialist consultancy, Ambiental. Of CEH, Ambiental state that '*The Q(t) grids and rainfall grids provided by CEH are a key data input to Ambiental's UK flood data products which are supplied into the UK insurance, utilities and conveyancing markets. For our fluvial flood products, we relate CEH's peak river flows to each river segment we model to understand likely frequency of various flood flows (in some cases we use alternative hydrological information). For our pluvial flood products, we relate CEH's rainfall frequency grids to calculate input rainfall intensity for hundreds of full-catchment pluvial models that we simulate throughout the UK.*

Ambiental's UK flood datasets are used extensively throughout the UK (and beyond), by a range of different end market industries. The flood data and advanced intelligence that Ambiental provide to its' customers enables them to make enhanced decisions, based upon a granular and accurate understanding of the complex risks posed by flooding. The CEH data is integral to our data production and insights that we provide to our customers' [14].

Chubb Insurance are quoted as saying of Ambiental's UK FloodMap4™ that *'This data has provided us with a step-change in the way that we underwrite flood risk in the UK. Visualisation and analysis of flood risk at the individual address level is now a much easier, quicker, and more precise process for us'* [15].

The National River Flow Archive (NRFA) Peak Flow database is the key flood data source used by regulators and environmental consultants across the full spectrum of flood risk strategy and planning activities. Its uses include the development of flood risk maps; formulation of national, strategic and local flood risk strategies; preparation of flood risk assessments for specific planning proposals; and designing flood defence schemes. In order to use the FEH methodology, hydrologists need to download Peak Flow data from the NRFA website. Using conservative assumptions, and considering only its usage in preparing and assessing detailed Flood Risk Assessments, the net economic benefits of the database in terms of costs saved by environmental consultants and regulators are just under £5.4m/year. Over the 5-year term (2014 to 2019) that the NRFA has hosted and significantly upgraded the dataset, this equates to an economic saving of over £25M. However, since the NRFA Peak Flow Database is used for many other purposes, this underestimates its full value [16].

c. Ongoing development of real-time flood forecasting

The CEH grid-to-grid model is used for operational flood forecasting by the Flood Forecasting Centre. An independent assessment of the impacts of NERC research activities states that *'the Met Office estimates that up to 10% of the damage caused by flooding can be avoided through early warnings provided by NERC models such as the grid-to-grid model developed by the CEH. On an average year this could prevent up to £127M in damages to homes, buildings, farmland and infrastructure'* [17].

CEH's Surface Water Flooding Hazard Impact Model (SWFHIM) was successfully used during the Glasgow 2014 Commonwealth Games. Notably, heavy rainfall caused some surface water ponding on the roads during the Men's Cycling Road Race through Glasgow. The Scottish Environment Minister said '*The ground breaking capabilities developed by SEPA to alert for surface water flooding was an essential part of our contingency planning*

during the Commonwealth Games' [18]. This piece of work won the 2018 Royal Meteorological Society Innovation Award, awarded to The Scottish Flood Forecasting Service for the project 'Surface Water Flood Forecasting in Urban Communities'.

CEH's SWFHIM was subsequently trialled across England and Wales by the Flood Forecasting Centre in 2017. Senior Hydrometeorologist at the Flood Forecasting Centre commented that *'The Surface Water Flooding Hazard Impact Model is set to take a central role in our suite of tools to forecast surface water flood risk. We are currently moving towards a full operational implementation of the model developed as a strong collaborative effort between ourselves, the Centre of Ecology and Hydrology, the Health and Safety Executive and others through the Natural Hazard Partnership. The approach marks a significant step forward in our capability to forecast flood risk to help support emergency responders make good decisions on surface water flood events'* [19].

d. Assesment of climate change impacts on the hydrological response across the UK

CEH's work on climate change impacts has enabled the EA, SEPA and NRW all to produce updated guidance on flood management and flood assessment [20]. A Principal Climate Change Scientist at the Environment Agency said that *'CEH research is a key part of the scientific basis of our management and regulatory activities. A good example is the work done by CEH on climate change and flood risk. CEH's research has enabled us to provide regional, rather than national, guidance for flood defence planning and flood risk assessment procedures. This increase in spatial resolution has improved the effectiveness and efficiency with which we achieve UK Government flood protection objectives'* [21].

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Section A	
Centre:	UK Centre for Ecology & Hydrology
Title of case study:	**CEH10_The Joint UK Land Environment Simulator (JULES): Informing global weather and climate forecasting**

Section B

1. Summary of the impact (indicative maximum 100 words)

CEH plays a pivotal role in coordinating and carrying out the research, maintenance and development of the Joint UK Land Environment Simulator (JULES) model. The JULES model simulates interactions between the land and atmosphere. It is the core terrestrial component of the UK Met Office Unified Model, which is used for creating both weather forecasts and long-term climate projections. As such JULES contributes both to the Public Weather Service (with estimated benefits to the UK of up to £1.5bn per annum) and to the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. Globally, JULES is in operational use by organisations including the U.S. Army Corps of Engineers, NASA, Australian Bureau of Meteorology and the New Zealand National Institute of Water and Atmospheric Research.

2. Underpinning research

The JULES model simulates fluxes of energy, water and carbon between the land and the atmosphere, incorporating vegetation dynamics. CEH's underpinning role in the JULES model can be considered in 2 parts:

1. Activities to coordinate Land Surface Modelling in the UK.
2. Development of specific key areas of JULES code.

1. Activities to coordinate Land Surface Modelling in the UK (Key Staff: Eleanor Blyth, Doug Clark)

CEH's co-ownership and management of JULES commenced in 2006, and continues to this day, arising through agreement between NERC and the Met Office to pool resources for research into land surface processes. Critically, JULES has since been the single point of focus for NERC research in this area, enabling massive efficiencies in model development. CEH's position at the heart of JULES development means that it is jointly responsible for leading the identification and implementation of substantial missing process representations of how some land ecosystems function.

The joint NERC-Met Office activity, Joint Land Modelling Programme (JLMP) formed in 2018, is a joint activity to develop, maintain and oversee the major configurations of JULES to consolidate national capability in hydrology, weather, climate, earth system and impact modelling. JLMP sits under the NERC-Met Office Joint Weather and Climate Research Programme (JWCRP) and currently consists of a consortium including CEH, National Centre for Atmospheric Sciences, National Centre for Earth Observation and the Met Office, with links to the Universities of Exeter and Reading.

The Met Office's Director of Science comments that *'CEH have invested significant effort in ensuring that Land Surface Modelling within the UK works as a team (hosting meetings, liaising with the science coordinators, keeping the communications going via websites and newsletters, providing community-wide datasets for model testing, etc.). All of this is not only time consuming and requires high-level scientific and technical knowledge to do, but it is really important for the land-surface modelling community to work cohesively'* [1].

2. Development of specific key areas of JULES code.

a. Plant Physiology (Key Staff: Lina Mercado, Chris Huntingford)

i. Plant responses to temperature vary geographically, both causing or being caused by thermally contrasting habitats, in tandem with long-term species adaptations to their climate of origin. Plants can also acclimate to fast temporal changes in temperature regime to mitigate heat stress. Although plant photosynthetic responses are known to acclimate to temperature, many global models fail to include this process. CEH have implemented adaptation/acclimation in the JULES framework, and then determined the implications for global climate–carbon cycle feedbacks. Our results suggest that inclusion of thermal acclimation of photosynthetic capacity estimates tropical and temperate C as less vulnerable to warming, but reduces the warming-induced C uptake in the boreal region under elevated CO_2 [2].

ii. Land-atmosphere exchanges influence atmospheric CO_2, and are known to mitigate a substantial fraction of emissions. However most emphasis has focussed on describing photosynthetic CO_2 uptake, and less on respiration losses. New global datasets describe upper canopy dark respiration and temperature dependencies. CEH investigated the global implications of these parameterisations by adjusting the JULES parameterisation of leaf and plant respiration. CEH analysis suggests plant respiration could be around 30% higher than existing estimates, suggesting smaller "allowed" emissions to keep climate stable below thresholds such as two degrees of global warming [3].

iii. JULES has been improved to contain an explicit description of light interception for different canopy levels, which consequently leads to a multilayer approach to scaling from leaf to canopy level photosynthesis. CEH validated the improved JULES model at a site in the Amazonian rainforest by comparing against measurements. Overall, the new light interception formulation improves modelled photosynthetic carbon uptake compared to the standard big leaf approach used in the original JULES formulation [4].

b. Runoff Generation (Key Staff: Alberto Martinez-de la Torre, Eleanor Blyth)

CEH improved the hydrological performance in the JULES model. Using river flow observations from gauge stations, CEH studied the capability of JULES to simulate river flow at 1 km^2 spatial resolution within 13 example catchments in Great Britain. These catchments exhibit a variety of climatic and topographic characteristics, which CEH represented with a new parameterisation. This new parameterisation substantially improves JULES' performance across Great Britain. As an example, in the Thames catchment, which has extensive areas of flat terrain, the Nash–Sutcliffe efficiency statistic exceeds 0.8 (very good model performance) using the new parameterisation [5].

c. IMOGEN (Key Staff: Chris Huntingford)

CEH has developed IMOGEN, as a computationally efficient modelling system to undertake global and regional assessment of climate change impacts on the physical and biogeochemical behaviour of the land surface [6]. IMOGEN is coupled to JULES for a grid covering the globe. Hence this structure allows extrapolation of General Circulation Model (GCM) simulations to different future pathways of greenhouse gases, including rapid first-order assessments of how the land surface and associated biogeochemical cycles might change [7].

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4. Details of the impact

CEH's development of the JULES model has resulted in impact through the incorporation of JULES in the Met Office Unified Model and the use of the Unified Model for Numerical Weather Prediction and Global Climate Policy. The Met Office Director of Science supports this commenting that *'CEH scientists are responsible for key areas of JULES code development. Specifically, in areas of plant physiology, run-off generation and multi-model inter-comparison. In each case these code developments have led to measurable improvements in the performance and assessment of JULES. These JULES developments from CEH are included within standard Met Office model configurations and are used for our operational weather and seasonal forecasts and production climate change projections.'* [8]. Met Office Head of the Research to Operations team in Weather Science at the Met Office, adds simply that '*MetUM couldn't work without JULES'* [9].

Impact of JULES in Numerical Weather Prediction

A recent valuation concluded with high confidence that the benefits of the Public Weather Service (PWS) to the UK are very likely to exceed £1bn per annum, and are likely to be close to £1.5bn per annum [10]. This is the sum of: value to the public (estimated benefit of £480m per annum), value to aviation (£400m per annum), added value to other sectors of the economy (£400m per annum), storm damage avoidance (£80m per annum), value to land transport (£100m per annum) and flood damage avoidance (£64m per annum) [10].

JULES developments have aided this financial benefit, having led to measureable increases in weather forecast accuracy by the Met Office UM. For example the new snow scheme, '*will significantly improve our near-surface temperature forecasts*', and '*take 10% off our range of errors in near surface temperature in northern hemisphere in winter*' which, in the context of weather forecasting improvement, '*is huge*' [9]. JULES is also used to provide initial conditions of soil moisture for subsequent use in forecasting systems. This is particularly important in summer months, helping to ensure that forecasting models do not diverge from reality, and support projections of extreme heat events. '*It would measurably degrade the performance of our weather forecasts if you took that away*' [9].

The importance of JULES in global climate policy.

Global climate models underpin and progress our understanding of climate change and provide vital evidence for likely future climate scenarios and effective mitigations. Worldwide, the scientific community develop highly sophisticated climate models and these are subjected to assessment and scrutiny through the Coupled Model Intercomparison Project (CMIP). '*Through JULES-related research and development, CEH scientists have contributed to the core team developing UK Earth System Model contribution to CMIP (Coupled Model Intercomparison Project). CEH are also a key contributor to developing and evaluating regional coupled prediction systems through the UK Environmental Prediction collaboration'* [8].

The 5th phase of CMIP, endorsed by the World Climate Research Programme's Working Group on Coupled Modelling, is extensively referenced in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Tables and figures throughout this report cite CMIP5 as the underpinning evidence base – for example '*Figure SPM.10 | The relationship between risks from climate change, temperature change, cumulative carbon dioxide (CO2) emissions and changes in annual greenhouse gas (GHG) emissions by 2050. They are based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations'* [11].

For the first time, the IPCC report included an assessment of a carbon budget - a finite amount of carbon that can be burnt before it becomes unlikely we can avoid more than two degrees of global warming. The JULES model is an integral part of the UK's contribution to global climate modelling and our quantification of carbon budgets. The setting of such a carbon budget requires a thorough understanding of how carbon is absorbed by the oceans and by the land. These 'carbon sinks' together typically absorb approximately half of anthropogenic emissions, but any change in their efficiency will have significant consequences for accumulation of CO2 in the atmosphere.

The Met Office lead researcher into vegetation and carbon cycle modelling and their interactions with climate, and lead author of the carbon cycle chapter of the latest IPCC report believes that JULES is '*central*' to the preparation of carbon budgets, since *'the land is by far the dominant area of uncertainty'* [9].

The work of the IPCC, and all that has fed into it, has made a significant contribution to the 2015 Paris Agreement - a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future. '*Since science underpins the work of the Climate Change Convention, the IPCC works closely with UNFCCC's Subsidiary Body for Scientific and Technological Advice (SBSTA). With its most recent report, the Fifth Assessment Report (AR5), the IPCC presented its finding to SBSTA. The IPCC also took part in the Structured Expert Dialogue and Research Dialogue initiatives which provided the negotiators with an in-depth understanding of the scientific issues and contributed to their negotiations in the run up to the Paris Agreement.*' [12].

International Impact of JULES

The JULES model is used and developed throughout the world. We provide two examples of this here.

The U.S. Air Force (USAF) supplies the authoritative weather forecast to the U.S. Army. JULES is the primary Land Surface Model (LSM) in the Global Air-Land Weather Exploitation Model (GALWEM) used by the USAF. '*Ongoing development of JULES supports U.S. Army decision processes related to flood forecasting and maneuver support (e.g. wet gap crossings, soil trafficability, etc.). As such, the U.S. Army Engineer Research and Development Center (ERDC) is working to integrate JULES into their Streamflow Prediction Tool (SPT) framework to more closely align hydrologic forecasts by the Army with the authoritative USAF weather forecast system. Meanwhile, researchers at CEH, and others across the U.K., are developing a hydrology package for the next generation JULES*

LSM. The HydroJULES package has the potential to indirectly advance Army hydrologic forecasting capabilities. Thus, the relationship with the U.K. JULES development community is particularly valuable to the U.S. Army and its allies. Interaction with CEH on the HydroJULES package is of particular benefit' [13].

The National Institute of Water and Atmospheric Research in New Zealand (NIWA) says *'NIWA uses the JULES model to perform simulations of soil moisture and snow amount over New Zealand for research into land surface processes and ultimately to improve our regional numerical weather predication systems via its use in the Unified Modelling framework. The ongoing development of JULES and our use of it continues to provide insights into the land surface processes that affect the weather and climate of NZ and we foresee future research use of JULES to also encompass its hydrological capabilities. We very much value our relationship with the UK JULES development community and acknowledge our interaction with CEH as particular beneficial in this regard'* [14].

5. Sources to corroborate the impact

[8] Personal communication. Deputy Director and Director of Science, Met Office. January 2020. Letter.

[9] Research Impact Consulting. 2105. The Impact of JULES. Report prepared for CEH.

[10] Gray, M. 2015. Public Weather Service Value for Money Review. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/about-us/what-we-do/public-weather-service/pws_value_for_money_review_-_march_2015.pdf

[11] Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

[12] Lynn, J. and Zabula, W. 2016. Outcomes of COP21 and the IPCC. Bulletin nº : Vol 65 (2). https://public.wmo.int/en/resources/bulletin/outcomes-of-cop21-and-ipcc

[13] Personal communication. U.S. Corps of Engineers Environmental Research and Development Centre. January 2020. Email communication.

[14] Personal communication. Chief Scientist - Environmental Information, National Institute of Water and Atmospheric Research, New Zealand. January 2020. Email communication.

Centre:	UK Centre for Ecology & Hydrology
Title	**CEH11_Strengthening climate-resilient urban and agricultural planning in West Africa**

Section B

1. Summary of the impact

Over the last thirty years, CEH research has produced fundamental new understanding of land surface atmosphere interactions in West Africa which has strengthened understanding of climate change among policymakers. The work has enabled two African governments to reshape policy on agriculture and flooding. It has improved the evidence base of National Adaptation Plans and built capacity within those countries. Estimates of resulting potential savings are in the hundreds of millions of dollars. One government representative said '[*this work] has managed to achieve more understanding…than I have achieved in 20 years'.*

2. Underpinning activities

The Sahel region of West Africa is a climate zone sandwiched between the African savannah grasslands to the south and the Sahara Desert to the north, which extends across West and Central Africa. The region is home to 90 million people, projected to rise to 220 million in 2050 [1]. Agriculture is the main economic sector in the region - contributing 40% of GDP and involving 60% of the population [2] – but is dependent on the West African monsoon. Research led by CEH has developed understanding of the variability of monsoon rainfall in terms of duration, intensity and its vulnerability to climate change.

Research began in the early 1990s, through the 'Hydrologic Atmospheric Pilot Experiment in the Sahel' an international, multi-agency programme co-led by Dr John Gash (Head of Global Processes, Institute of Hydrology subsequently merged into CEH). The CEH team provided the first measurements of evaporation from the semi-arid tropics [3] and showed that soil moisture could affect rainfall [4]. Subsequent projects (NERC 1999-2003 and EU-FP5 Climate and Land Degradation) led by CEH's Dr Richard Harding highlighted the important role of the land surface in Sahelian climate. This was followed by CEH having a leading role in developing the major international programme - African Monsoon Multidisciplinary Analysis (AMMA, 2004-2009). CEH research was led by Professor Chris Taylor who made a significant contribution to understanding of monsoon processes. For the first time, CEH showed that variations in soil moisture on length scales of tens of kilometres exert strong control on storm initiation and rainfall [5]. CEH extended this to the global scale where observational evidence showed that afternoon storms tend to develop over drier soils [6]. This highlighted an important weakness in global weather and climate models, which in contrast to reality, preferentially simulate rain over wetter surfaces.

In 2014, the NERC/DfID programme Future Climate for Africa (FCFA), funded a follow-on called AMMA2050 to examine how climate change will affect hydroclimatic extremes in this climate-vulnerable region over the next 40 years, with particular reference to floods, droughts and agriculture. Led by Professor Taylor, it is an integrated collaboration across multiple organisations in multiple countries. CEH climate research focused on the storms which produce the region's rainfall. The analysis revealed a remarkable tripling in the frequency of the most intense Sahelian storms since the 1980s, an increase which can be linked to global warming [7]. This suggested that the Sahel will experience particularly marked increases in extreme rain and challenges conventional projections made by climate models. This new science is especially important because climate adaptation actions in the Sahel are based primarily on the models. The models predict increased heavy rainfall frequency by +1% to +75%, but AMMA2050 research indicates that this is likely under-estimated [8]. Work by AMMA2050 partners has demonstrated that climate has already led to a crop reduction of 5-20% for 1°C of warming between 2000 and 2009 [9]. The CEH

research will enable better, more accurate predictions of the effects of climate change and better direct mitigation actions.

African Stakeholder Engagement

Twenty-five years of research has seen the relationship with African stakeholders in the Sahel thoroughly established through co-design and co-delivery. It is key to combining delivery of scientific excellence and developmental benefits. AMMA2050 engages with beneficiaries and stakeholders at multiple levels of governance. This includes both national and sub-state decision makers and projects involved in developing climate resilience plans. It also engages at a regional scale being involved in agriculture and the protection of the environment with organisations such as WASCAL (the West African Science Service Centre on Climate Change and Adapted Land Use).

The AMMA2050 project has two pilot engagements to demonstrate the impact of integrating this new climate science with in-country and regional decision making and to strengthen capacities of those local partners. In Senegal, AMMA2050 has sought to engage with COMRECC (the Fatick Regional Committee on Climate Change) and PAS-PNA (Scientific Support Project for National Adaptation Plan Processes), a project providing scientific support to Senegal's National Action Plan. In Burkina Faso, AMMA2050 has most closely engaged with the Ministry of Urbanism and the Mayor of Ouagadougou's office, as well as other national ministries and city mayors and the counterpart national PAS-PNA.

3. References to the underpinning work

[1] DfID, Sahel country profile, 2018

[2] Climate Risk profile: West Africa, Dec 2018, USAID

[3] Gash, J. H. C., et al. (1997). "The variability of evaporation during the HAPEX-Sahel intensive observation period." Journal Of Hydrology 189: 385-399.

[4] Taylor CM, Lebel T. Observational evidence of persistent convective-scale rainfall patterns. Mon Weather Rev. 1998; 126 (6):1597-607.

[5] Taylor CM, Gounou A, Guichard F, Harris PP, Ellis RJ, Couvreux F, et al. Frequency of Sahelian storm initiation enhanced over mesoscale soil-moisture patterns. Nature Geosci. 2011;4 (7):430-3.

[6] Taylor CM, de Jeu RAM, Guichard F, Harris PP, Dorigo WA. Afternoon rain more likely over drier soils. Nature. 2012; 489 (7416):423-6.

[7] Taylor CM, Belušić D, Guichard F, Parker DJ, Vischel T, Bock O, et al. Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. Nature. 2017; 544 (7651):475-8.

[8] Sultan B., Defrance, D., Iizumi, T., Evidence of crop production losses in West Africa due to historical global warming in two crop models, Nature Scientific Reports, 2019, vol 9, Article: 12834

[9] S. Berthou, E. J. Kendon,D. P. Rowell, M. J. Roberts, S. Tucker R. A. Stratton (2019) Larger Future Intensification of Rainfall in the West African Sahel in a Convection-Permitting Model**, Geophysical Research Letters, 2019,** 46, 22, pp 3299-13307

4. Details of the impact

Co-producing climate information to support specific decision-making processes

The engagement of policy decision makers was fundamental in the AMMA2050 project, which was designed and delivered in collaboration with the West African partners as described in section 2. The involvement of the West African partners meant that climate-related information produced by the project was relevant and credible to the stakeholders. The pilot engagements' aim was to contribute evidence and improve decisions for urban

infrastructural planning in Ouagadougou, agricultural investments in Senegal and National Adaptation Planning in both countries.

Urban infrastructural planning in Ouagadougou, Burkina Faso

In AMMA2050 CEH developed methodologies for mapping inundation across Ouagadougou from intense storms, taking account of changes in land use and climate scenarios. Dr James Miller (CEH) trained the Burkina Faso team to use these models, enabling the authorities in the capital to form better decisions with respect to climate. For example, the Burkina Faso government is revising development of the capital within the Grand Ouaga plan. AMMA2050 outputs have been able to improve previous reliance on historical data. The city is also designing a $309m road improvement programme. CEH developed rainfall Intensity Duration Frequency (IDF) curves and 10- and100-year flood maps (produced by Dr James Miller) for the engineering group Agence d'Etudes d'Ingénierie et de Maîtise d'oeuvre (AEIM) to inform these road construction projects. It is difficult to obtain estimates of specific savings in the road construction design, but to quote Solimane Hamed Ouattara (Ministry of Urbanisation and Habitat, Ouagadougou, Burkina Faso), '*The flooding database AMMA2050 developed is a god-send and we are grateful. It will better guide decision-making of our cities'* [10].

In 2009, floods in Ouagadougou affected more than 150,000 people, entailing a disruption cost that has been estimated at $400m [11]. It is expected that the frequency of future flood events will increase – the frequency of intense storms has tripled since the 1980s and there is a corresponding increase in the number of floods [7]. Employing the methodology used by PwC to estimate savings from flooding in the UK, it can be estimated that $40m would be saved from the cost of a future flooding event by using the CEH flood maps [12]. The Mayor of Ouagadougou has said *'Indeed, the tools developed by [AMMA2050] … reinforce the ability to anticipate and the adaptation of Ouagadougou in the field of prevention of inundations, in addition to completing the City Risk Reduction Plan. [My technical teams] are ready to use, as far as possible, the tools that have been developed in order to strengthen the resilience of Ouagadougou against floods'* [13].

Senegalese National Adaptation Plan and impacts on agriculture

AMMA2050 is recognised as the primary source of climate change information for the work to update PAS-PNA (Scientific Support Project for National Adaptation Plan Processes). Dr Conni Klein (CEH) developed metric atlases that were used to inform the Senegalese PNA process, sectorial (coastal zone, agriculture, water resources) strategies and plans that, at the local level, will inform regional and district development plans [10]. '*It was very challenging for our project to get good data on climate change, specifically high quality of projection and impacts for a local level … now AMMA's output has been used at national level: Senegalese National Adaptation Plan process, climate policies, and sectorial (coastal zone, agriculture, water resources) strategies or plans and at local level, integrated in local development plans'* , Dr Mélinda Noblet, Climate Change Impacts and Adaptation Expert - PAS-PNA – Senegal. The development of the PNS-PNA [14] suggests a cost of $14bn will be required to implement the required adaptations [15]. The research from AMMA2050 will be used to better direct the mitigation actions. There are multiple inputs into the development and implementation of the plan, so it is difficult to distinguish the CEH and AMMA2050 contribution. Even if this is as low as a 1% difference then a potential $140m could be saved in implementation costs. A Key Informant Interviewee stated '*At local level, AMMA outputs will be integrated into local development plans and are being used in the development of a concept note (project proposal) which will be submitted to the Green Climate Fund. AMMA's data (climate projection (CMIP5) and agriculture impact model (SARRA-H) has been used under PAS-PNA to feed our vulnerability analysis related to climate change, specifically exposure for the 3 sectors (coastal zone, agriculture, water*

resources) and sensitivity for the agricultural sector. Those studies will be used to build the Senegalese NAP and the sectoral NAP in Senegal' [16].

Training through workshops and secondments was used to develop capability amongst decision-makers across levels and in-country research institutions. From the Key Informant Interviews (used to measure impact), a local government representative from the Fatick region commented, *'[AMMA2050] has managed to achieve more understanding in one workshop than I have achieved in 20 years*' [16]. African modellers were trained in the use of climate metrics and scenarios developed by CEH and others within AMMA-2050 leading to the development of climate vulnerability assessments. Early Career Researchers in ANACIM (the National Agency of Civil Aviation and Meteorology), Senegal, used AMMA2050 training in IDF curves to '*provide Senegal's climate projections for 2100, contributing to developing the National Determined Contributions'* and also to inform infrastructural investments [17].

In a specific example of how the future scenarios developed by CEH have been used to determine mitigation strategies, AMMA2050 partner, ISRA examined the change in planting patterns of millet in Senegal. If no climate change mitigation actions are taken, millet production will decrease by 30%. As illustrated in figure 1 the projection for 2050 shows that to avoid this productivity loss some farmers will have to change from Sanio millet to Souna millet. This has implications for the timing of the harvest, seed buying, and production processes (since Souna millet is harder to process than Sanio millet). If recommendations derived from the modelling are implemented, the cost savings can be estimated at $60m [18] as the equivalent purchase price of replacement millet. Findings such as these from AMMA2050 were presented to members of the National Assembly at the final project meeting in June 2019, [10] causing representatives to raise the need to review the national policy for self-sufficiency. One representative commented '*AMMA2050 outputs allow us to be armed to influence national public policy'*. AMMA2050 learning will also inform local government planning, for example through the Plan de Developpement Communal 2020–2025 in the Fatick commune.

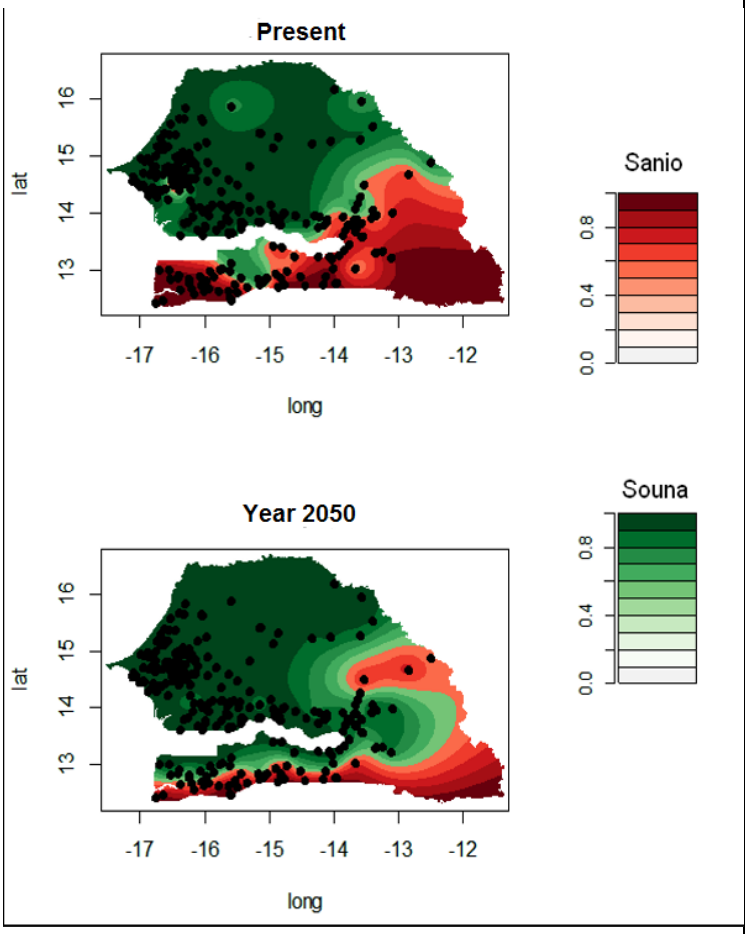

Figure 2 illustrates how the optimum land area for Sanio (red) and Souna (green) millet changes because of AMMA2050 climate change projections over the next 30 years

Wider impact

Examples of AMMA2050's achievements beyond the specific pilots described include

- Supporting regional approaches to building climate resilience. For example a joint workshop with WASCAL was held. Feedback showed all participating decision makers found the workshop either very helpful (64%) or helpful in identifying and acting on opportunities to integrate climate change information into decision-making processes.
- Promoting international investment in strengthening scientific capacity within the West Africa region, facilitating a session bringing together learning from across DFID supported climate research and resilience building initiatives for the region within the UN Office for Disaster Risk Reduction (UNDRR 2019) conference.
- Capacity building by augmenting regional expertise towards building adaptive capacity and resilience to future climate change through secondments, exchanges, and training for early career researchers.

In addition, the framework of science and partnership led by CEH enabled other collaborations to develop, for instance, a practical guide for policymakers communicating climatic uncertainties [19] and a manual on co-producing African weather and climate services at local, national, and regional levels [20].

5. Sources to corroborate the impact

[10] AMMA2050 Final meeting report, Dakar 2019.

[11] 'Start' briefing, Humanitarian funding analysis: Flooding in Burkina Faso, Aug. 2015

[12] 'Economic benefits of environmental sciences', PwC report for NERC, Nov. 2006

[13] Letter from Ouagadougou Mayor's office after workshop.

[14] 'NAP resubmission', Project Identification Form, Global Environment Facility, Dec 2014

[15] National Adaptation Plans in focus: Lessons from the Republic of Senegal, UNDP-UNEP NAP Global Support Programme, Nov 2018.

[16] PAS-PNA Senegal questions for 2019, Key Informant Interviews Scorecard AMMA2050 and 'Evaluation de la vulnérabilité du secteur ressources en eau à la variabilité et aux changements climatiques dans la région de Fatick', Climate Analytics, Jan 2019.

[17] FCFA Impact case study, AMMA2050 Climate metrics impact case study. Dr A. Bamba et al., April 2018.

[18] Senegal produces 570,000 tons of millet per annum of which 500,000 tons are for food within Senegal. The price of pearl millet is $350 per ton, so a value can be estimated from Senegalese crop at $200million from FAO, http://www.fao.org/3/W1808E/w1808e0c.htm.

[19] https://futureclimateafrica.org/wp-content/uploads/2019/09/approaches-to-communicating-climatic-uncertainties-with-decision-makers_final.pdf.

[20] AMMA2050 case study input to and co-authorship of the WISER TRANSFORM/FCFA 'Manual; Coproducing African weather and climate services (available as digibook and pdf) https://futureclimateafrica.org/resource/co-production-in-african-weather-and-climate-services/.

Centre for Ecology & Hydrology (CEH): Environment Document

1 Organisational Context, Mission and Strategy

1.1 Overview: Context and Ambition

The Centre for Ecology & Hydrology (CEH) is the UK's Centre of Excellence for integrated research in terrestrial and freshwater ecosystems, including land-atmosphere interactions. We seek to understand the environment, how it sustains life, and the human impact on it – so that together, people and nature can prosper.

Scientific curiosity, integrity and transparency are at the heart of how we work, investigating, measuring, monitoring and modelling environmental change. Our research extends from molecular biology to global climate modelling. We undertake fieldwork worldwide, from the semi-arid West African Sahel to the rainforests of South East Asia. Our focus is to deliver research, evidence and innovation needed for mitigating and building resilience to climate change, preventing and reducing pollution, and creating sustainable ecosystems.

Our ca. 500 science and infrastructure staff provide the fundamental understanding, data and insights that researchers, governments and businesses rely on for world-class research and to create a productive, resilient and healthy environment. We believe that the best solutions are co-designed and co-delivered through our partnerships, which cross borders, sectors and disciplines.

We are the strategic delivery partner for the Natural Environment Research Council (NERC), part of UK Research and Innovation (UKRI), for Terrestrial & Freshwater Sciences. Through NERC national capability funding, CEH enables the UK to deliver world-leading environmental science, underpins the NERC Delivery Plan 2019, to meet national strategic needs and help the Government respond to emergencies.

1.1.1 Key Highlights (2013-2019 unless stated)

- Published 2,935 ISI Journal articles (54,500 citations) and 627 Contract Reports
    - Highest cited UK institution in Biodiversity & Conservation and Water Resources over the last 20 years (InCites);
    - 95% publications externally co-authored, involving 139 countries;
    - 3 scientists in the 2019 global list of Highly Cited Researchers;
    - 91% Open Access publication rate (2019).
- £117m competitively won income delivered (2013/14-2018/19).
- Partner of choice for UK Government and Devolved Administrations; £35m research contracts (2013/14-2018/19).
- Supervised/co-supervision 336 PhD Students across 63 national and international universities.
- Data Centres supporting 150,000 users and 977,000 online visits (2015/16).
- 50 years of biological recording establishing >250,000,000 records of >40,000 species.
- 40 year UK soils archive; 9,500 samples analysed; 4,500 frozen 'living' samples.
- Database of 21,922,725 days of UK river flow data from 1,529 gauging stations.
- UK Greenhouse Gas Flux network generated >2 million half-hourly observations.
- Delivered across the UK the first, globally, national real-time soil moisture monitoring network (COSMOS) and the UK Hydrological Outlook.
- Developed the world's first field-scale national crop map from satellite radar data.
- Excellent staff retention; ca. 6.5% turnover pa.
- 92 staff promoted including seven NERC Individual Merit Promotions.
- Athena SWAN (Gender equality in HE and Research) and Investors in People accreditations.
- Secured ISO certifications for Quality and Environmental Management and renewed certification for analytical chemistry methodologies and Health & Safety Management.
- 28 MoUs with international research and impact partners.

1.2 Entity, Size and Structure

On 1 December 2019, we became an independent research institute, autonomous from UKRI and NERC, launching as a not-for-profit company limited by guarantee with charitable status. As part of this change the institute was renamed the UK Centre for Ecology & Hydrology (UKCEH).

Our mission, purpose and scientific integrity is preserved. We deliver impartial, world-class environmental science for a wide range of funders, and remain a key strategic delivery partner for NERC.

UKCEH operates from four sites in England, Scotland and Wales, depicted in Figure 1-1, providing access to diverse habitats and supporting university and wider stakeholder engagement.

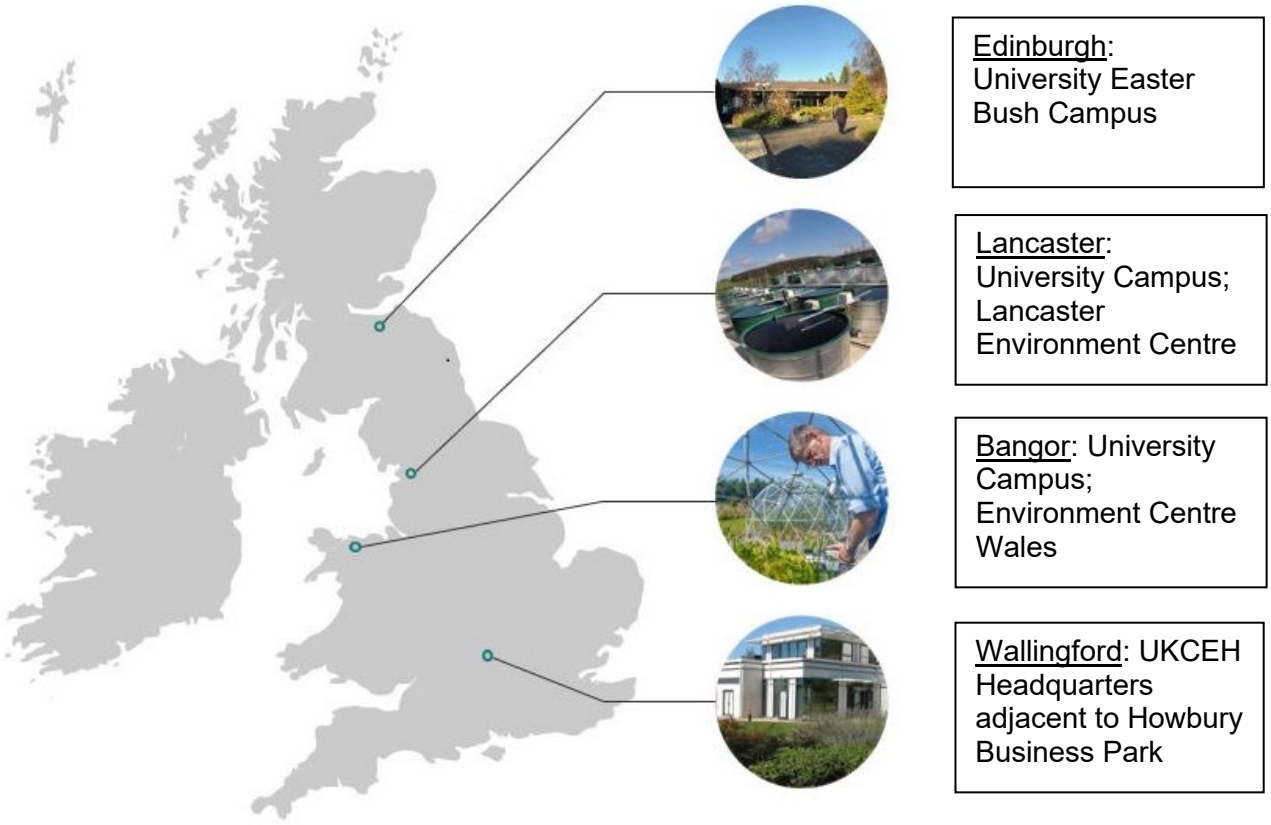

Figure 1-1. UKCEH Sites

Whilst staffing details are provided in Section 2 and associated Data Template, at 1 April 2019, CEH employed 519 staff (490 FTEs), including 351 scientists and an additional 60 PhD students supervised and hosted at CEH sites. The current Management Structure of UKCEH is provided in Figure 1-2, depicting revised Science Areas, implemented in the latter part of the Evaluation period.

1.3 Research Strategy

CEH's Strategy 2014-19, Meeting the Challenges of Environmental Change, had three interdependent, societal and environmental challenges:

- **Securing the Value of Nature,**
- **Building Resilience to Environmental Hazards, and**
- **Managing Environmental Change.**

These aligned with NERC 2013 strategy, *The Business of the Environment*. CEH's Strategy was implemented through 8 Science Areas underpinned by Monitoring and Observation Systems, Environmental Informatics, Business and Policy Innovation, and Public Engagement (Figure 1-3).

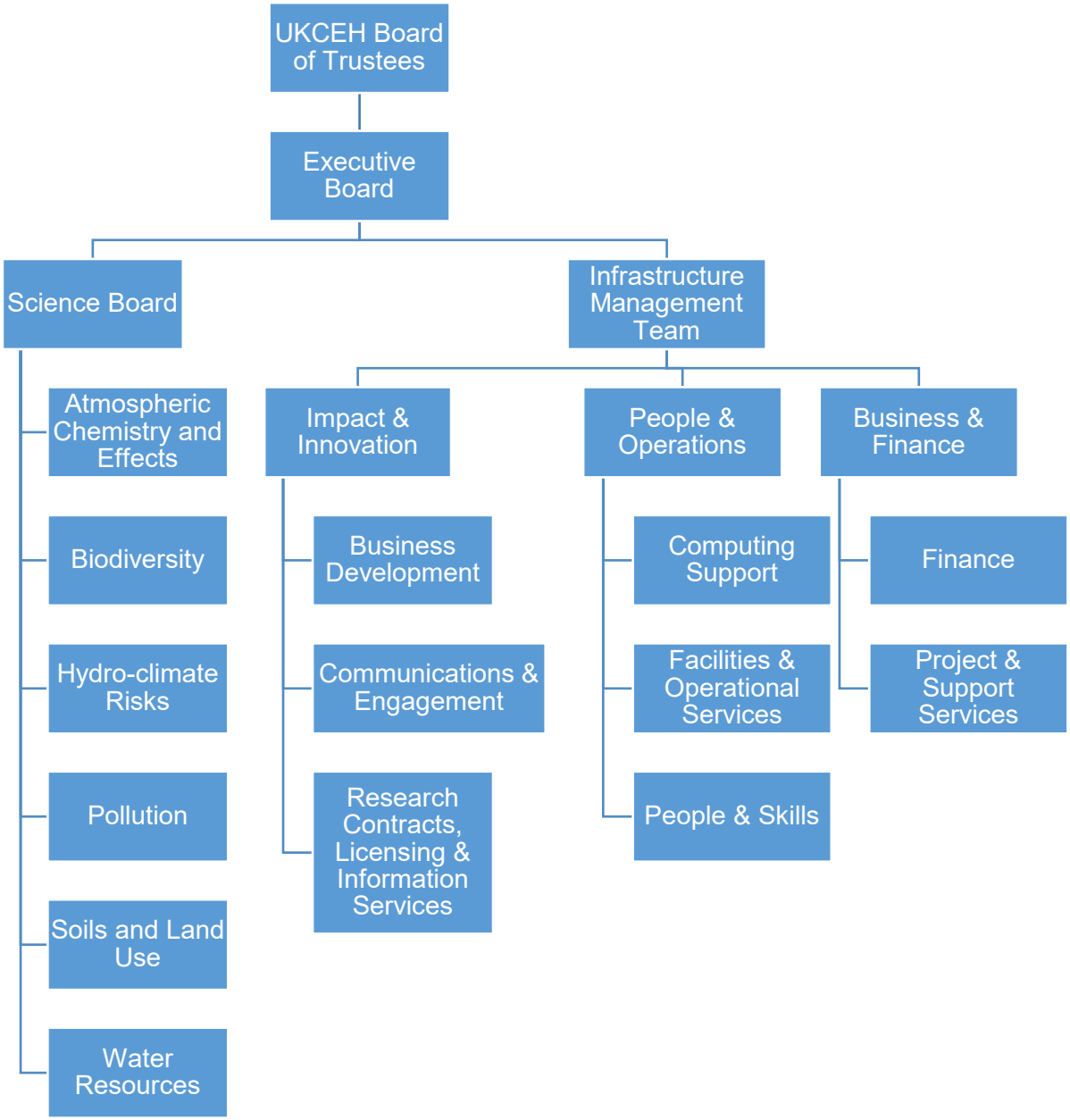

Figure 1-2. Current UKCEH Management Structure (post-Science Area revision)

1.3.1 Achievement of Strategic Aims for Research 2013-19

CEH delivers multi-disciplinary measurement, monitoring and hypothesis-led experimental investigation. Descriptions of CEH's 8 Science Areas and **selected highlights** are provided below. This performance is underpinned by, and drives, successful research collaborations worldwide (Section 4.1).

Natural Hazards: *science to improve the prediction and understanding of the threats and impacts posed by natural hazards and development of management and resilience strategies.* Key highlights included decadal analyses of European river flooding identifying regional patterns of increases, decreases and timing that reflected our changing climate [Bloschl et al. **Nature** 2019, **Science** 2017]. Data led observational studies identified that the frequency of extreme Sahelian storms tripled since 1982 correlating highly with global land temperatures [Taylor et al. **Nature** 2017]. Uniquely demonstrating that variations in soil moisture drive afternoon storms that actually develop over drier soils. Non-native invasive species (NNIS) research estimated 1-16% of all species, depending on taxonomic group, qualify as potential aliens [Seebens et al. **PNAS**, 2018], and 37% of all "first records" over the last 200 years were reported 1970–2014 [Seebens et al. **Nat. Comm.** 2017]. Methodological advances and horizon scanning identified 30 high risk NNIS for GB [Roy et al. **Glob.**

Change Biol. 2014] and improved models for estimating continental-scale plant invasions [Chapman et al. **Glob. Change Biol.** 2016] directed surveillance.

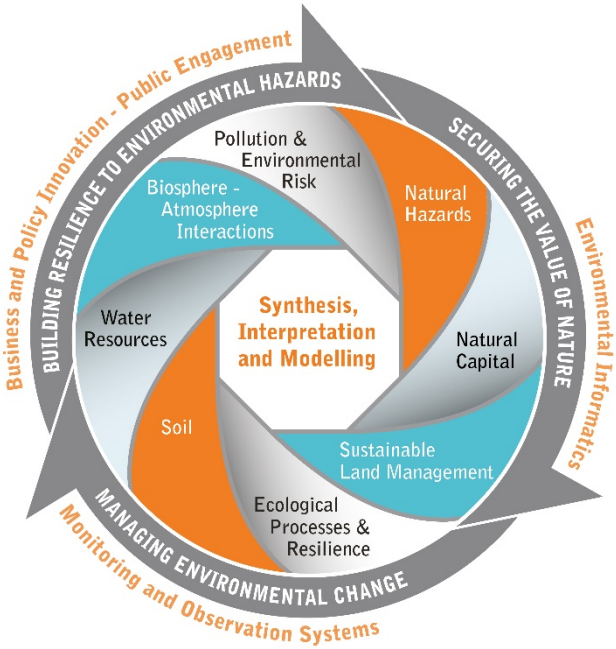

Figure 1-3. Depiction of CEH's Science Strategy 2014-19

Natural Capital: assessing state and change in natural assets and their benefits to people. We developed effective, linked decision-tree systems that overcome individual model constraints for assessing and valuing ecosystem services for practitioners and researchers, [Jakobs et al., Harrison et al. **Ecosyst. Serv.** 2018]. Representation in these systems of cross-sectoral interactions with climate change impact models was shown to be essential to avoid misrepresentation of spatial patterns, and the direction and magnitude of most impacts [Harrison et al. **Nat. Clim. Change** 2016]. Practical, analytical frameworks for enhancing natural capital across large geographic areas and a novel approach to quantify air pollution removal by vegetation were produced [Spake et al. **Nat. Sustainability** 2019, Jones et al. **J. Environ. Economics and Policy** 2019].

Sustainable Land Management: delivering solutions to conserve and restore biodiversity, natural resources and ecosystem functions in semi-natural and intensively managed habitats vital for human wellbeing and livelihoods. CEH provided the first evidence that wildlife-friendly management of temperate farming systems can support ecosystem services that are compatible with, and can even increase, crop yields [Pywell et al. **Proc. R. Soc. B:** 2015]. Field data and meta-analyses revealed that both pollinator and natural predator functional diversity enhanced crop pollination and yield [Greenop et al. **Ecology** 2018; Woodcock et al. **Nat. Comm.** 2019]. We then tested the widely held assumption that non-crop habitats support natural pest control and demonstrated that interactions between local landscape composition and farm management have the greatest influence [Karp et al. **PNAS** 2018].

Ecological Processes & Resilience: advance and apply understanding of ecological and socio-ecological processes and resilience to meet the challenges of environmental change. Substantive advances have been made in the understanding of phenological sensitivity to climate across broad taxa and trophic levels [Thackeray et al **Nature** 2016], identifying phenology as a key determinant of species' range margins [Macgregor et al. **Nat. Comm.** 2019, Chapman et al. **Glob. Change Biol.** 2013]. CEH defined UK-wide biodiversity losses [e.g. State of Nature Report 2019, Natural England] and species specific changes, e.g. pollinator biodiversity deterioration, although we identified that non-crop pollinators may be benefiting from recent agri-ecological management interventions [Powney et al. **Nat. Comm.** 2019]. Research on species resilience to environmental and climate change provided evidence for effective landscape-scale habitat restoration, of the positive impacts of habitat quality, and that microclimatic heterogeneity substantially reduces extinction risk [Oliver et al. **Nat. Clim. Change** 2015, Carvell et al. **Nature** 2017, Suggitt et al. **Nat. Clim. Change** 2018].

Soil: scientific knowledge of soil functioning and relative importance of soil biota, physical and chemical properties, to assure security for food, fuel and water. Global soil carbon quantification confirmed that rising temperatures stimulate soil carbon net loss in carbon-rich soils [Crowther et al. **Nature** 2016]. Since 1990, SE Asian peatland disturbance has increased fluvial organic carbon flux by 32%, more than half the equivalent flux in European peatlands [Moore et al. **Nature** 2013]. To aid soil management we demonstrated that elevated soil-C at high plant diversity is a direct function of the microbial community [Lange et al. **Nat. Comm.** 2015], that rarer bacterial taxa are most important for structuring soil communities [Ramirez et al. **Nat. Microbiol.** 2017], and although microbial richness is driven by environmental properties, soil animal richness responds to changes in land use intensity [George et al. **Nature Comm.** 2019].

Water Resources: research into the relationships between natural water resources and their dependent ecosystems, to understand impacts of exploitation. Multi-model assessments of water availability under climate change, project greater exacerbation of current regional and global scarcity problems [Schewe et al. **PNAS** 2014;]. Different representations of terrestrial processes generate larger uncertainties in hydrological drought projections than previously thought [Prudhomme et al. **PNAS** 2014]. Our studies have also revealed substantive impacts of climate change on freshwater ecosystems [Thackeray et al. **Nature** 2016; Leger et al. **Adv. in Ecol. Res.** 2013]. Our novel assessment of 100 years of GB droughts identified that groundwater-dependent areas experience more severe events, despite no consistent change in drought characteristics [Rudd et al. **J. Hydrol.** 2017]. CEH-led the collaborative development and now produces a regular Hydrological Outlook service for the UK [Prudhomme et al. **Hydrological Sci. J.** 2017] and is developing one for India.

Biosphere-Atmosphere Interactions: understanding and quantifying interactions between biosphere and atmosphere based on measurements, experiments and modelling of greenhouse gases, reactive air pollutants, water and energy. As part of an international consortium to create future baselines, datasets and methodologies quantified key components of the global carbon budget 1959-2011 [Le Quéré et al. **Earth System Science Data** 2013**].** Further research identified the essential processes required to provide more accurate spatially explicit climate models; these include nutrient limitation [Piao et al. **Glob. Change Biol.** 2013], natural feedback from wetlands and permafrost [Comyn-Platt et al. **Nat. Geoscience** 2018], and dissolved organic carbon processing/emissions from inland waters [Evans et al. **Nat. Geoscience** 2017]. CEH also led the first knowledge synthesis for the global nitrogen cycle [Fowler et al. **Phil. Trans. R. Soc.B**, 2013] and defined a future architecture for NH_3 emission–deposition modelling that integrates spatio-temporal interactions, and assessment of climate change consequences [Sutton et al**. Phil. Trans. R. Soc. B**, 2013] that is now informing approaches of the UNEP International Nitrogen Management System.

Pollution & Environmental Risk: providing scientific knowledge, evidence and risk assessments for sustainable chemicals management. CEH-led studies confirmed that neonicotinoids negatively affect pollinator health under agricultural conditions and that sub-lethal effects of neonicotinoids cause losses of bee biodiversity [Woodcock et al. **Nat. Comm.** 2016, Woodcock et al. **Science** 2017]. European scale exposure monitoring and modelling of pollutants including heavy metals, nanoparticles, oestrogen pharmaceuticals and freshwater acidification informed regulation [Harmens et al. **Environ. Pollution** 2015, Dumont et al. **Environ. Pollution** 2015, Johnson et al. **Env. Sci. Technol.** 2013]. Restoration research revealed that phosphorus in river basins mobilize long after inputs decline that led to changes in management [Powers et al. **Nat. Geoscience** 2016, Sharpley et al. **J.Environ. Quality** 2013]. Our long term studies have led to important human health benefits based on four decades of UK air pollution control policies [Carnell et al. **Env. Res. Let.** 2019].

In summary, CEH delivers integrated research activities to determine the fundamental components that underpin productive ecosystems, and the drivers that make them vulnerable or resilient to a broad range of biological and physical stressors. In advancing our science, we have progressed from the study of individual species, chemical or physical factors to understanding how they interact at the systems level. Our curiosity-led, observations-led solutions-led, and fundamental research enables us over decadal scales to provide the information and science needed for the informed management of whole interconnected landscapes.

1.4 Future Research and Innovation Strategy

Our future strategy is to further advance an integrated, systems approach to addressing the world's environmental challenges. This is supported by the breadth of CEH expertise, our underpinning and enduring capabilities in Measuring, Monitoring & Observation, Analytics, Forecasting & Projection, the provision of Facilities & Experimental Platforms, together with our partnerships worldwide.

'Strategy 2025', UKCEH's research & innovation strategy for 2020-2025, focuses on the organisation's role in addressing three grand societal challenges:

- Creating and enhancing sustainable ecosystems
- Reducing and preventing pollution
- Mitigating and building resilience to climate change

Our specific contribution to these challenges is defined in 10 integrated issues (Table 1-1).

Table 1-1. CEH Strategy 2025 Issues

Clean Air: The evidence-base for reducing air pollutants
Water Quality & Resources: Balancing water demand with a healthy and productive environment
Sustainable Agriculture: Understanding and enhancing ecosystems functions that underpin productive and regenerative agricultural systems
Net-Zero Greenhouse Gas Emissions: Improving land-use planning and land management practices
Soil Health: Enabling integrated management for healthy soils
Mitigating Flood and Drought Impacts: Increasing societal and environmental resilience to hydro-climate risks
Chemical risks: Sustainable use of chemicals to protect the environment and people
Land Surface Modelling: Land surface science for climate change prediction, adaptation and mitigation
Biodiversity: How biodiversity drives ecosystem function to safeguard and enhance the health and resilience of the environment
Ecosystem Restoration and Resilience: Restoration for long-term recovery and resilience to deliver sustainable landscapes

1.5 Optimising Impact

CEH stimulates, leads and participates in trans-disciplinary partnerships involving academia, public, private and third sectors and the public themselves, at national and international scales. The strategic context for CEH Impact and Knowledge Exchange (KE) is represented as *use inspired* and *applied research and development*.

Through co-design and co-delivery, our research partnerships are directed to have the greatest impact by ensuring outcomes are relevant for societal needs, make a material difference and achieve science excellence. We train our staff and provide support from our Business Development and Communication & Engagement teams to meet these objectives.

Within each programme and project, we seek to develop a blend of relevant pathways to impact: e.g. science to policy, commercial innovation, capacity and capability development, development of environmental practices, forecasting and decision support tools, and public engagement with research. Impact optimisation is supported by CEH's '*Innovation to Impact Strategic Framework',* (Table 1-2), wherein CEH's approach to optimising impact is illustrated through reference to submitted Impact Case Studies.

Table 1-2. CEH Innovation to Impact Strategic Framework with links to Impact Case Studies (CS)

World-class, Relevant Research: science is directed and delivered with ***intent*** of socio-economic change, where Knowledge Exchange (KE) is an integral component

- Substantial scientific advances and impact are delivered through citizen science, not least through recording environmental quality, creating datasets of a scope and scale not otherwise affordable for fundamental research, informing policy development and review, and national and international reporting. For example, the Predatory Bird Monitoring Scheme works with the public to collect up to 650 bird carcasses pa, facilitating a national-scale surveillance mechanism critical for researchers, policy-makers, regulators and industry.
- Impact CS: *Control of rat poisons by underpinning policy and UK Stewardship scheme*

Embed Innovation & Impact Best Practices: deliver researcher training and retain CEH innovation professionals

- CEH supports KE professionals to optimise two-way stakeholder engagement, e.g. Business Development and Innovation Managers lead and facilitate researcher-led user-inspired research and development, and partnership building. This professional expertise has been successfully extended through focussed NERC KE Fellowships – CEH held six from 2013-19.
- Relevant to all Impact Case Studies.

Objective-based Investment & Evaluation: develop Innovation to Impact Plans enabling CEH to prioritise, evaluate and improve performance

- CEH ODA projects develop a Theory of Change with relevant stakeholders, shaping objectives and ensuring projects optimise work plans to achieve intended impacts and outcomes. In addition CEH staff have received MEAL training (Measurement, Evaluation, Accountability and Learning) to improve project management and outcomes of impact-oriented studies.
- Impact CS: *Strengthening climate-resilient urban and agricultural planning in West Africa*

Partnership: partner with researchers, policymakers, businesses and international organisations to co-design and co-deliver research and innovation

- Enduring strategic partnerships are critical to optimise impact, exemplified by the Natural Hazards Partnership (NHP), providing information, research and analysis on natural hazards to develop more effective policies, communications and services. Through the NHP, CEH led the development of a new Surface Water Flooding Hazard Impact Model.
- Impact CS: *Protecting communities and businesses from flooding*

Commercial Innovation: deliver an open innovation process and culture, stimulating the development and commercialisation of products and services

- The development of CEH Land Cover plus: Crops Map, the first national-scale crops map developed using Sentinel 1 data, was the result of industrial collaboration with Remote Sensing Applications Consultants and Anglian Water. We invest in the development of commercial innovation opportunities, e.g. novel ammonia sensors, natural flood management planning tools, environmental DNA methodologies. These are managed through to commercial partnership under CEH's Commercial Innovation Protocol.
- Impact CS: *Supporting Policy, Business & Infrastructure through UK Land Cover Map*

Engagement: stakeholder engagement to accelerate and extend the impacts of CEH research

- CEH supports international science-policy initiatives, including the Intergovernmental Panel on Climate Change, e.g. updating methodologies for estimating greenhouse gas levels, and lead authors of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report on pollinators, pollination and food production, and the UNEP Global environment Outlook 6 Chapter 'Air'. Indeed, CEH initiated and coordinates the World Meteorological Organization's Global Hydrological Summary and Outlook System to support sustainable development of water resources and increase resilience to hydro-meteorological hazards.
- Impact CS: *Nitrogen management* and *Peatlands*.

1.5.1 Future Impact Perspectives

Strategy 2025 is issues based, explicitly identifying those critical socio-economic environmental challenges our researchers will address to advance knowledge and provide solutions to the environmental crisis. Building on our world-class scientific excellence, our research will have socio-economic impact and deliver environmental benefits. We will refine our organisational framework for each pathway to impact, e.g. science to policy, and in doing so, consider partnership as a central theme.

1.6 Interdisciplinary Research

CEH's strength is its breadth of excellence in a wide range of environmental science disciplines, e.g. atmospheric, soil and land system scientists, ecotoxicologists, ecologists and hydrologists, underpinning our high quality inter- and trans-disciplinary research.

We work in teams across projects with individuals providing their expertise. A retained workforce who are directed, flexible and delivery-orientated makes us distinct. We hold regular cross-site seminars and project and Science Area meetings for training, information exchange and planning. These are further supported by a Science Co-ordinator network that reports to Science Area Heads and Directors.

Our experience of interdisciplinary working provides the capability to bridge to other disciplines: firstly by routine engagement with other disciplines, exemplified by economists and expertise related to human, animal and plant health, and secondly, by the employment of specialists from other disciplines, e.g. statisticians, data scientists and social scientists, for effective engagement with leading researchers beyond CEH. Interdisciplinary collaborations enable integrated and systems-based approaches to be developed and are essential to address real world challenges, a pervading theme across CEH's portfolio.

Examples of interdisciplinary projects include:

- EKLIPSE: a €3m Horizon 2020 CEH-led project in which 10 partners including political, natural and social scientists, established a mechanism for evidence-informed decision-making at the science-policy-society interface, affecting biodiversity and ecosystem services. The project responds directly to policy and other societal knowledge needs.
- Environment & Rural Affairs Monitoring and Modelling Programme: a £5m Welsh Government initiative, coordinated by CEH, linking >20 public, private and third sector partners and disciplines including environmental sciences, agronomy, health-related disciplines and economists, to deliver monitoring and modelling across the Welsh landscape and inform policy for social, economic and environmental resilience.

In practice, many of CEH's interdisciplinary research projects and partnerships, are transdisciplinary, engaging non-research stakeholders from the outset in defining the challenge, co-designing and delivery of the research and innovation.

1.7 Open Research Environment

CEH research is independent, objective and transparent, thus CEH is committed to making our scientific data, models and publications accessible, and thereby also optimising CEH's reach and impact. This is supported through mentoring, training, our core expectations and the requirement for all projects to implement a data, sample and model management plan.

CEH follows UKRI and other funder open access policies. Peer reviewed journal publications are made available through publishers or through post-prints in the NERC Open Research Archive (NORA). In 2019 CEH achieved an open access publication rate of 91%. This Repository now catalogues 6,446 ISI Journal articles with 2,935 added in 2013-19. Reports and contract reports are also made available through NORA, totalling 3,976, with 627 added in 2013-19.

CEH applies UKRI's Concordat on Open Research Data, NERC data policy and the FAIR Data Principles (Findable, Accessible, Interoperable and Reusable), across its Data and Records Centres (see Section 3.3.3).

- Findable: of 999 datasets in CEH's Environmental Information Data Centre, 896 have digital object identifiers. Data is discoverable through web search engines given our focus on open metadata.
- Accessible: The CEH Environmental Information Platform (EIP) provides bespoke portals for data visualisation and evaluation in a user-oriented manner.
- Interoperable: the EIP facilitates CEH and 3rd party data Interoperability, e.g. UK Lakes Portal, providing integrated typology, chemistry, land cover, and connectivity data of >40,000 freshwater bodies, from CEH, UK measuring authorities and National Biodiversity Network.
- Reusable: contextual metadata optimises discovery, is reinforced through peer reviewed data publications and professionally curated.

CEH extends the FAIR Data Principles to other research outputs. Our model and data catalogues are integrated, alongside a model repository. This facilitates reusability and importantly reproducibility, supported through NERC national capability awards to deliver virtual data labs, and augmented by external funding, such as the £3.1m EPSRC project, DSNE, with Lancaster University. These facilities provide an open science and innovation environment enabling users to analyse and apply CEH and third party data and models. Model interoperability is supported through open standards, e.g. CEH co-developed a Hazard Impact Framework through the Natural Hazards Partnership to facilitate multi-hazard warnings. This Framework underpinned CEH's development of a new Hazard Impact Model for Surface Water Flooding.

CEH's approach to open research extends to wider activities including project design and operation, exemplified by a CEH-led pan-European study, funded by Syngenta and Bayer, to quantify impact on honeybees of neonicotinoid seed treatments. Expecting substantive public, commercial and regulatory interests an independent Scientific Advisory Committee was established. To meet our exacting standards of independence, CEH designed the methodology and led the experiments, released design details and analytical study protocols, and all experimental data. All findings were peer reviewed.

1.8 Research Integrity

1.8.1 Organisational Values and Core Expectations

CEH recently defined three organisational Values (Section 2.1.2), involving substantive staff input and brought to life through workshops. These form part of the staff induction programme, are an integral part of the annual appraisals process and reinforced through Director's staff updates.

- Excellence - delivering world-class science supporting global environmental challenges; valued by stakeholders and meeting customer requirements.
- Integrity - maintaining the highest standards of research and professional ethics and impartiality.
- Teamwork - working together effectively with colleagues, partners and customers to achieve long-term success.

CEH Values are underpinned by core expectations. 'Integrity' core expectations are to:

- Reach conclusions based on robust and ethical scientific and professional practice.
- Follow CEH policies and procedures and lead colleagues to do so.
- Seek good value for money, complying with financial policies and procedures.
- Be open and transparent about reasons for decisions and in undertaking activities.
- Recognise appropriately the contributions of others.
- Develop and maintain professional relationships with stakeholders and customers representing CEH appropriately and respecting diversity and cultural difference.
- Disclose and actively manage any conflicts of interest, maintaining ethical standards.

1.8.2 Working to International Standards

CEH operates a Quality Management System, BSI certified to ISO9001 and meets the requirements of the Joint Code of Practice for Research. This encompasses CEH's Project Management System, including guidance and mandatory project documentation, research contract report reviews and customer feedback. Other certification to international standards, includes UKAS accredited ISO17025 analytical chemistry methodologies, Environmental Management ISO14001 and Health

& Safety Management ISO18001. CEH maintains a culture of continual improvement though internal and external audits.

1.8.3 Governance and Reporting

CEH operates to UKRI's Policy and Guidelines on the Governance of Good Research Conduct and as part of UKRI, a signatory of the Concordat to Support Research Integrity. As an independent organisation, CEH has affirmed commitment to this Concordat, and has a Code of Ethics, extending to all aspects of governance, policy, operations and administration. CEH has sought independent ethics advice for studies involving human subjects, e.g. Liverpool School of Tropical Medicine. From 2013-19 a single claim of scientific misconduct was investigated, found unsubstantiated and withdrawn. In addition, a single University partner-led co-authored publication was retracted due to improved interpretation.

2 People

2.1 Staffing Strategy and Development

CEH's People Strategy *'Expertise and Excellence through Teamwork'* defines our approach to recruiting, leading and developing research and support staff to deliver science excellence with impact. Founded upon CEH Strategy, it demonstrates our commitment to the Concordat to Support the Career Development of Researchers.

2.1.1 Expertise and Excellence

Workforce planning, informed by our Research and Innovation Strategy, is embedded in annual science and business planning. Science and support leaders review capabilities and skills needs against planned research and innovation, infrastructure development and longer-term ambitions. Resultant skills needs are prioritised for recruitment or training investment by the Science and Executive Boards, to ensure both longstanding capability and continuous development of new skills to match scientific and technology advances.

Our successful combination of a Research Associate (RA) development scheme (Fixed Term; 14% of scientific staff) with strong performance management and selective open-ended appointment, provides a successful staffing strategy. The RA scheme addresses skill shortages to attract and retain talent; developing researchers to secure ongoing research posts within CEH and beyond. Effective development and career support is demonstrated by 82% RA conversion to open-ended appointment, including scarce skills such as engineering, modelling, web and app developers, supporting strategic investments such as COSMOS and HydroJULES (Sections 3.2.2 and 3.3.5). Seasonal field work is supported by Short Term Appointments.

CEH has developed a market-based reward framework for independence, seeking a competitive position whilst retaining the positive culture which attracted and retained our existing strong talent base. Our demographic profile change to 2019 and current open ended staff turnover (6.5%) evidences a successful balance between skills refreshment and retention despite challenges from Brexit and pay restraint.

Succession planning is supported by Learning & Development (L&D) initiatives, our merit promotion scheme and extension of leadership opportunities and development to a new cohort of science Group Leaders underpinned by our 'People Management Framework'.

2.1.2 Teamwork

Collectively developed CEH Values including Core expectations (Section 1.8.1) are published in our People Strategy and embedded in annual forward job planning (FJP) and appraisal system (100% completion rate). Our effective researcher development and support, and commitment to achieving equality, diversity and inclusivity is demonstrated by maintenance of Investors in People (IiP) and Athena SWAN (AS) accreditations, positive feedback in biennial staff surveys and from our staff consultation group:

> *"We are encouraged to contribute and are listened to"*
>
> *"I do feel valued and the people around me who care about me. We have pride in our work"*

Our 2018 IiP accreditation specifically noted the following good practices:

> *"CEH continues to operate people practices that would be the envy of other employers …"*

- Participation in regular staff surveys, which pinpoint issues that are addressed
- Staff consultation group to shape people practices that suit operations and culture
- High quality management development interventions

- Excellent encouragement of collaboration
- A high-level of pastoral support to staff and students including support from Welfare Officers and Occupational Health.

Our qualified HR expertise supports effective staff recruitment, performance management, career development, learning and development and wellbeing initiatives.

2.2 Equality, Diversity and Inclusivity (EDI)

CEH promotes a strong ethos of equality of opportunity, inclusion and equitable treatment for all employees, students and applicants; working to ensure no discrimination, including grounds of protected characteristics. Employee responsibility (in daily actions, decisions and behaviour internally and externally) to create an inclusive environment where differences and all contributions are valued, is promulgated in CEH's EDI policy and leadership communication. CEH has publicised procedures should staff have concerns that standards set out in the policy have been breached (Grievance, Whistleblowing, and Harassment and Bullying).

CEH's staff gender profiles are provided below (Figure 2-1). Band 5 and above eligible science staff submitted to this Evaluation exercise included 78 (69%) male; 35 (31%) female reflecting the greater proportion of male staff at higher bands, addressed in our Athena SWAN programme.

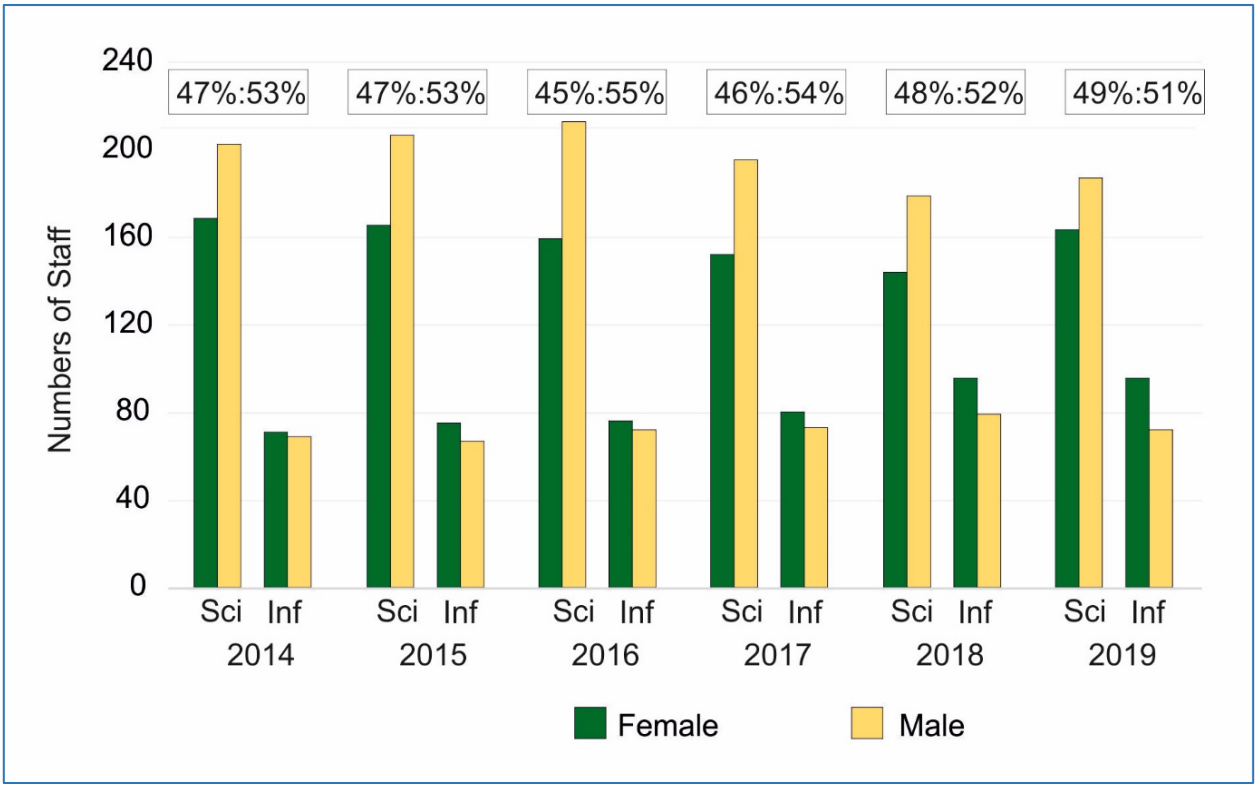

Figure 2-1. CEH Science (Sci) and Infrastructure (Inf) staff gender distribution 2014-2019. Percentages indicate female:male balance for all staff.

Employee age profiles are provided in Figures Figure 2-2 and Figure 2-3. The majority are between ages 30-59, peaking in the 40-49 cohort. Data show steady increases in staff between 20-29, and reductions in staff over 60. The bulk of staff whose outputs contributed to this evaluation exercise were aged 40-60, reflecting higher band status.

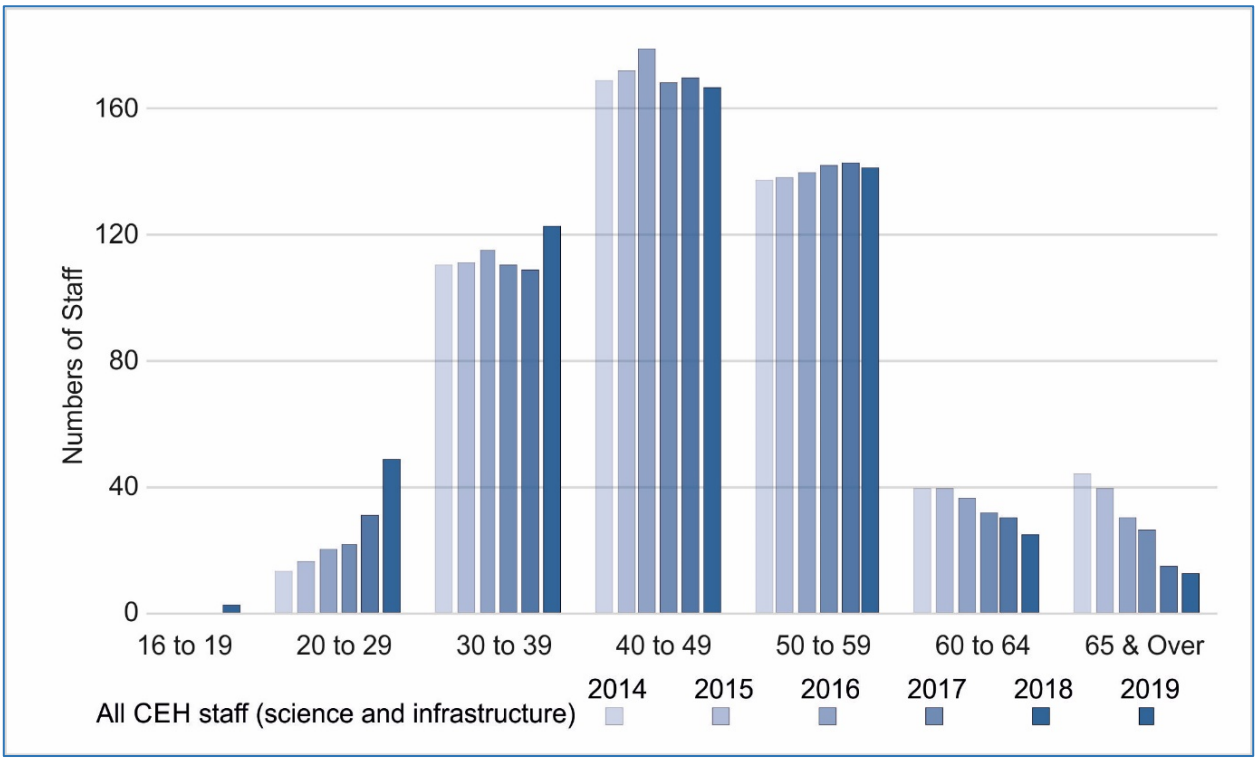

Figure 2-2. Age distribution of all CEH staff 2014-2019

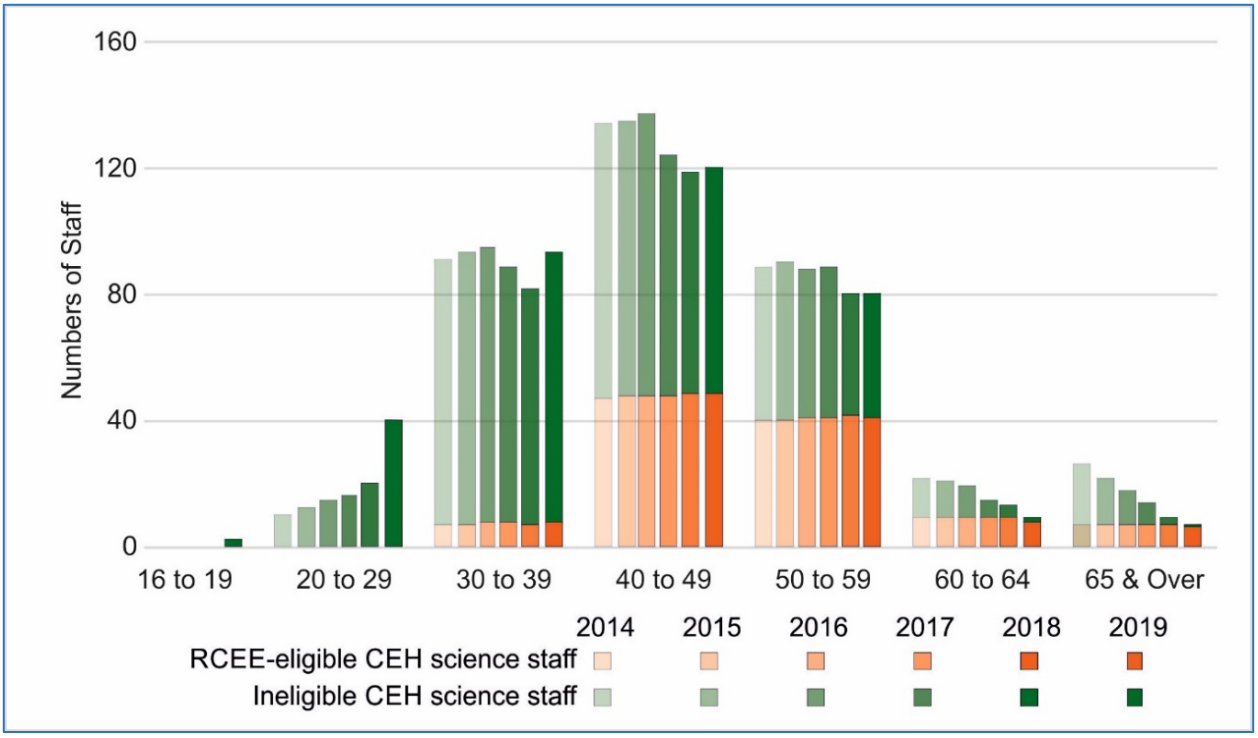

Figure 2-3. Age distribution of CEH science staff (including RCEE-eligible) 2014-2019

2.2.1 EDI Training

EDI considerations regarding decision-making have been addressed by awareness raising and both EDI and Unconscious Bias training undertaken by all Directors, senior managers, Science Area Heads and Group Leaders. Principles are applied to recruitment, career opportunities, promotion, policy development etc. Feedback included:

> "*I have changed procedure for reviewing applications – I go through sets twice with different criteria… I have become more aware of unconscious bias with respect to male/female staff…*"

> "*It challenged my preconceptions regarding staff roles and capabilities… I have taken the training into account when managing staff issues, in particular when dealing with staff who might hold different views*".

2.2.2 Study Leave

Staff may apply for paid time off work for study, e.g. up to 30 days p.a. for part-time courses which involve attendance at university/college. If undertaking a part-time PhD, additional study time can be granted.

2.2.3 Flexible and Remote Working

CEH operates a flexible working environment. Policy reinforces that wherever possible:

- Meetings held during core hours (10.00-12.00 & 14.00-15.30).
- Important meetings avoided during school and religious holidays.
- Training delivered as short/half day sessions at rotating CEH Sites.
- Cross-site meetings use videoconferences, reducing travel and overnight stays.
- Reimbursable Childcare costs due to work outside normal hours.

Mechanisms to enable flexible working include: reduced hours and flexible patterns, flexible working time, flex leave, Time Off in Lieu (TOIL) and informal and formal home working. CEH has supported remote working at collaborators' sites relating to personal domestic pressures to support female career continuation e.g. senior scientist located at INRA (France) for 18 months, senior hydrologist working remotely in France and a meteorologist split time at CEH and Innsbrook University.

2.2.4 Work-related Travel

CEH supports staff with caring responsibilities. Quote provided for Athena SWAN submission:

> "*I have been supported to develop my international profile whilst working part-time. CEH enables me to attend international meetings by paying for over-time and childcare costs".*

2.2.5 Returning to Work

People & Skills Function provides a dedicated family-friendly specialist who offers advice upon pregnancy or intended adoption and supports individuals through their parental/adoption leave and return to work. In 2016 CEH introduced a 'Return to Work' survey to continuously improve the process of returning to work.

Feedback included:

> "*Clear document …. – phased return to work plan*"
> "*Good support for staff on career and maternity breaks. One of the greatest benefits of working for CEH and overall flexibility of time management drives staff loyalty*".

2.2.6 Staff and Protected Characteristics

In our Workplace Wellbeing Policy and EDI policies, and in accordance with the recently updated Researcher Development Concordat, CEH takes responsibility to:

- Promote good mental health and wellbeing, e.g. through effective management of workloads and people, and effective policies and practice for tackling discrimination, bullying and harassment, including providing support for those reporting issues;

- Ensure that managers of researchers are effectively trained in relation to equality, diversity and inclusivity, wellbeing and mental health.

CEH's Work Pressure Review Group includes union representatives, assesses workplace risk factors and manages an action plan which includes awareness raising, training for managers, and is using the Thriving at Work Report framework to implement mental health standards. At recruitment CEH ensures that our application process is accessible, and we make any reasonable adjustments that can help someone start or keep their job. CEH is committed to removing barriers to disabled people and those with long-term health conditions, and to ensuring staff and students are provided with opportunities to fulfil their potential and realise their aspirations. CEH actively supports line managers who manage staff with neurodiversity or mental health issues. All staff have access to CEH Welfare Support and an Employee Assistance Programme.

CEH has held IiP and Athena SWAN accreditation since 2009 and 2014 respectively. Data from independently verified biennial staff surveys and internal pay analysis show no discrimination by gender or pay band. Strong HR and Occupational Health support is provided as standard in cases of disability with flexible working and physical provision to enable new/continued employment and partnership working. The 'Disability Confident scheme' is standard in our recruitment.

2.3 Career Development

2.3.1 Early Career Researchers

CEH is committed to enhancing staff capabilities and training environmental scientists, striving for excellence in a broad range of disciplines (environmental sciences, maths, statistics, computing, data management etc.) as follows:

- Researcher Development Coordinator and Student Liaison Officers support the training, development and welfare of Early Career Researchers.
- Recruitment processes consistently praised by new starters.
- Appointees supported and assessed through formal induction and probation processes, with published checklists, guidance and formal assessments of learning and performance objectives.
- Induction effectiveness evaluated annually with resultant improvements implemented.
- Mentoring new staff and students with 'buddies' formally identified for new starters.
- Individual career development meetings.
- Individual Research Associate 3 year development plans from appointment.
- Scheduled L&D opportunities, developing technological and research skills to meet long-term science needs.
- Tailored workshops and individual interventions for RAs and students designed and delivered in accordance with concordat and Vitae Researcher Development framework.
- Career development workshops for Band 7 (Graduate) and Band 6 (Postgraduate) staff feedback includes:

> *"People around me are already noticing my professional growth … and this will be a continual process as I use the tools and knowledge from this course. … I have watched others on the course develop alongside me and heard feedback from their line managers that they have a new drive in CEH which can only benefit the organisation."*

2.3.2 Career Development at all Stages in Research Careers

We are committed to maintaining excellence through continuing professional development (CPD), evidenced by IiP and AS accreditations, and our comprehensive portfolio of L&D offerings available to staff and students.

Our performance management, development and reward systems are designed to support our strategic priorities and key strengths:

- Individual expertise combining across CEH to deliver integrated science through teamwork;

- Valuing diversity for the performance achievements and variety of perspectives and talents provided;
- Joining in partnership with academic institutions, research institutes, industry and policy-makers.

L&D opportunities enable all staff to achieve their potential to meet CEH needs and those of its funders, customers and end-users, continuously developing knowledge and skills to ensure delivery is based on sound expertise in appropriate specialisms, and is authoritative and credible. Annual L&D plans utilising annual evaluation reporting are prioritised by science leaders and Executive Board with average investment of £250k p.a. non-pay in training courses alone.

Senior staff and potential future leaders continuously develop leadership and management skills, including business and science leadership qualities for a changing environment (NERC *Growing Future Leaders* scheme and *Leadership Programme*). Our tailored e-learning portal on 'Mindtools' is based on our Management Framework and Values.

All staff agree performance and development objectives in FJPs, assessed in annual appraisal cycles and including upwards feedback to managers, supporting appropriate balance of how we work and what we deliver, striving to continue to learn and optimise performance to meet stakeholder needs.

2.3.2.1 Part-time and Fixed-term Staff

Career opportunities are equally available for all. Performance and merit promotion expectations for part-time staff are pro-rata with instructed allowance for timescale impact.

Table 2-1. All CEH staff on full-time or part-time terms 2014-2019 (headcount pa).

	All Staff		Science Staff		Infrastructure Staff	
	2014 - 2018	**2019**	**2014 - 2018**	**2019**	**2014 – 2018**	**2019**
Full Time	429 ± 12 (84%)	431 (83%)	302 ± 21 (84%)	294 (84%)	127 ± 12 (84%)	137 (82%)
Part-time	82 ± 4 (16%)	88 (17%)	55 ± 4 (16%)	57 (16%)	25 ± 3 (16%)	31 (18%)
Total	**511 ± 10**	**519**	**357 ± 22**	**351**	**152 ± 14**	**168**

Evaluation-eligible part-time staff included in this 2019 Evaluation were 19%, compared with 12% in 2014, showing increased adoption of flexible working arrangements for higher band staff embedded within CEH business practice.

2.3.2.2 Research/Sabbatical Leave

CEH supports attendance at international conferences and encourages sabbatical leave, particularly with peer organisations, examples are:

- Career Break & Sabbatical Procedures provide guidance on opportunities to meet individual personal and development needs. Clear defined criteria combine benefits to individuals, their careers and CEH.
- Overseas engagement opportunities e.g. mathematical modeller undertaking 12 months working at Colorado State University.

Current Secondments include:

- Into CEH:
  - Oxford University Professor to lead Hydro-JULES programme
  - Exeter University Land Surface Modeller to work on JULES

- Out of CEH:
  - Biodiversity Website Designer to SAMS
  - Head of National Capability to UKRI NERC Head Office

- Senior scientist to Gothenburg University (Professor, Sustainable Development).

2.3.2.3 Stimulating and Facilitating Exchanges with Business, Public or Third Sector Bodies

Business Development and Tender Support Teams support staff to achieve impact from research via assistance in proposal writing and post-project activities (e.g. technical implementation plans and facilitating exchanges between staff and industry, public/third sector bodies) by:

- Identifying and securing joint funding, innovation and commercialisation opportunities;
- Marketing activities that raise our profile and identify user-needs.

Examples include NERC KE fellowships held by staff and selection of CEH staff to act as key account managers for various UK water companies (Section 4.2.1).

2.3.2.4 Recognition and Reward

CEH operates a legacy bonus and allowance system and offers new terms with performance progression steps, organisational bonus and Exceptional Contribution awards to reward achievements and impact. Distribution of allowances, bonuses and awards is through a process with Director oversight, transparent defined criteria and equality analysis prior to award. Since 2017 there has been a marked increase in team bonuses and an improvement in gender balance: bonuses awarded to 45% female: 38% male eligible population Nov 2017- June 2019. NERC Equal Pay Report 2016 stated CEH had no statistically significant pay difference in Band 5-3 pay with difference in female favour for Bands 7 and 8.

We also recognise success through non-monetary mechanisms e.g. peer/manager feedback, and internal announcements. We encourage publication for all researchers, requiring recognition of all contributors.

Our Merit Promotion scheme recognises development of knowledge and skills to meet organisational need, resulting in 85 promotions (2013-19) with individual feedback reviews for unsuccessful applicants. The external Individual Merit Promotion scheme provides a promotion route for senior scientific researchers who make outstanding personal contributions in their field. Seven staff achieved IMP status in 2013-2019.

2.4 Support, Training and Supervision of Postgraduate Research (PGR) Students

CEH does not award degrees, but partnered with 63 national and international universities to supervise and co-supervise 336 PhD students over the period. A third of these were hosted throughout their PhD, providing an applied, end-user focussed environment with access to national capability. Over the Evaluation period, 85% of CEH-associated students (2013-2019) completed their PhDs, compared to a national average of 73% (seven-year completion rate reported in Times Higher Education, 2013).

CEH is a key partner in NERC Doctoral Training Partnerships and Centres for Doctoral Training, equipping students with skills and experiences to allow them to become world-leaders in their careers (Section 4.4.1).

In PGR student recruitment with HEIs, we promote EDI best practice. Using short-listing matrices and independent moderators on interview panels ensures candidates are selected on fit-to-project basis and ability to undertake PhD research; reducing potential gender or protected characteristic bias.

2.4.1 Monitoring and Support

CEH's Researcher Development Coordinator and Student Liaison Officers provide impartial advice and support to students and supervisors. Supervisors are required to undertake training with refresher courses every 5 years. Mentoring is encouraged, particularly for female students if their supervisory team are all male.

Students are invited to attend an individual annual 'PhD MOT', an opportunity for them to meet staff outside their supervision team, providing objective views on their studies.

All students can access CEH's Welfare Support and Employee Assistance Programme. A Student Handbook outlines support available and offers guidance to help students maximise their time at CEH and prepare for their next career move. L&D resources are available to develop research skills and scientific knowledge. Specific courses are offered to support students at key stages, designed in line with Vitae and Concordat principles:

- PhD Induction (0-6 months): introduction to key people, processes and services.
- Essential Skills for Research Excellence' (6-18 months): based on Vitae programme, provides training on project management, team working and supervisor management.
- Finishing your PhD on Time and Careers: What Next? (2-4 years).

Feedback included:

> "*CEH provides really good learning opportunities – more than I realised that there would be*" and "*There are more opportunities at a research institute than there are at a University*". Our Investors in People assessor commented: "*Students appear to continue to be provided with a good learning environment and work well with their Student Supervisor responsible for identifying training needs, checking work, etc. Processes continually appear to be reviewed and refined*."

3 Income, Infrastructure and Facilities

3.1 Income Strategies

During 2013-2019 CEH established and implemented a 2020 Business Plan Programme to ensure the sustainability of CEH's scientific capability, underpinned by a five-year business plan. The Programme was delivered through the following:

- **Science Restructure:** Science Areas fully represented on the Science Board, with each developing and maintaining three-year business plans that identify key scientific objectives, income generation and workforce plans.
- **Income Consolidation & Diversification**: providing researcher support for proposal development, supporting four industrial sector initiatives (infrastructure development, water, finance, and environmental and engineering consultancies), and the development and implementation of an international strategy and marketing plan.
- **Supporting Improved Project Management:** delivering an enhanced Project Management System, certified to ISO9001 within CEH's Quality Management System.
- **Governance & Ownership:** establishing CEH as a not-for-profit research institute with charitable status.

CEH's Impact & Innovation Directorate was established in the evaluation period in recognition that optimising impact was fundamentally important, and directly related to extending partnerships and diversifying income. This Directorate encompasses and integrates externally focussed activities across business development, communications and engagement, commercialisation, research contracts and quality assurance. It works in partnership with scientists to be competitive in securing research funding, continue to deliver the evidence-base for environmental policy at national and international scales, support informed public debate and public engagement with research, and better engage with industry to secure material innovation. A Tender Support Team was also formed to support opportunity identification, proposal development and submission. The Team facilitates quick-turnaround tenders and promotes equality, diversity and inclusivity in CEH (Section 2.2). Importantly, this Team gathers customer feedback on completed research contracts as part of CEH's commitment to continual improvement.

Research income is dependent on partnerships across academia and public and private sectors (Section 4.1). This includes collaborative research networks such as PEER (Partnership for European Environmental Research), EurAqua and AlterNet, leading to successful research consortia proposals e.g. DANUBIUS-RI (international centre for advanced studies on river-sea systems), NanoFASE (Nanomaterial Fate and Speciation in the Environment) and Historic Droughts. Beyond networks, CEH has research partnerships with other UK organisations, e.g. James Hutton Institute, Rothamsted Research, Met Office and other NERC Centre Surveys, many of which support income generation and delivery. CEH has also supported several successful workshops e.g. *Reflections on the science underpinning the EU Biodiversity Strategy* (Ghent 2013); *Wildlife pathogens: an overlooked bioinvasion threat* (Wallingford, 2015); *Maximising the contribution of long-term experiments to global science* (Bergen, 2017), often stimulating new collaboration and joint proposals.

3.2 Research Funding

3.2.1 Competitively Won Income

CEH delivered £117m competitively won income in 2013/14-2018/19. The breakdown of income by customer group is provided in Figure 3-1 and associated Data Template. In addition to NERC and UKRI, CEH is a key research partner for UK Government and Devolved Administrations (research contracts of £35m 2013/14-2018/19), industry and increasingly, significant international funding (Section 4). Beyond increased international income, CEH has in part reversed the decline of UK Government and Devolved Administrations revenues from 2013/14-2017/18, given increases in 2018/19. Whilst maintaining total income through increased competitively won awards, CEH's NERC national capability has decreased from 47% to 41%, as a proportion of total revenue and capital 2013/14-2018/19.

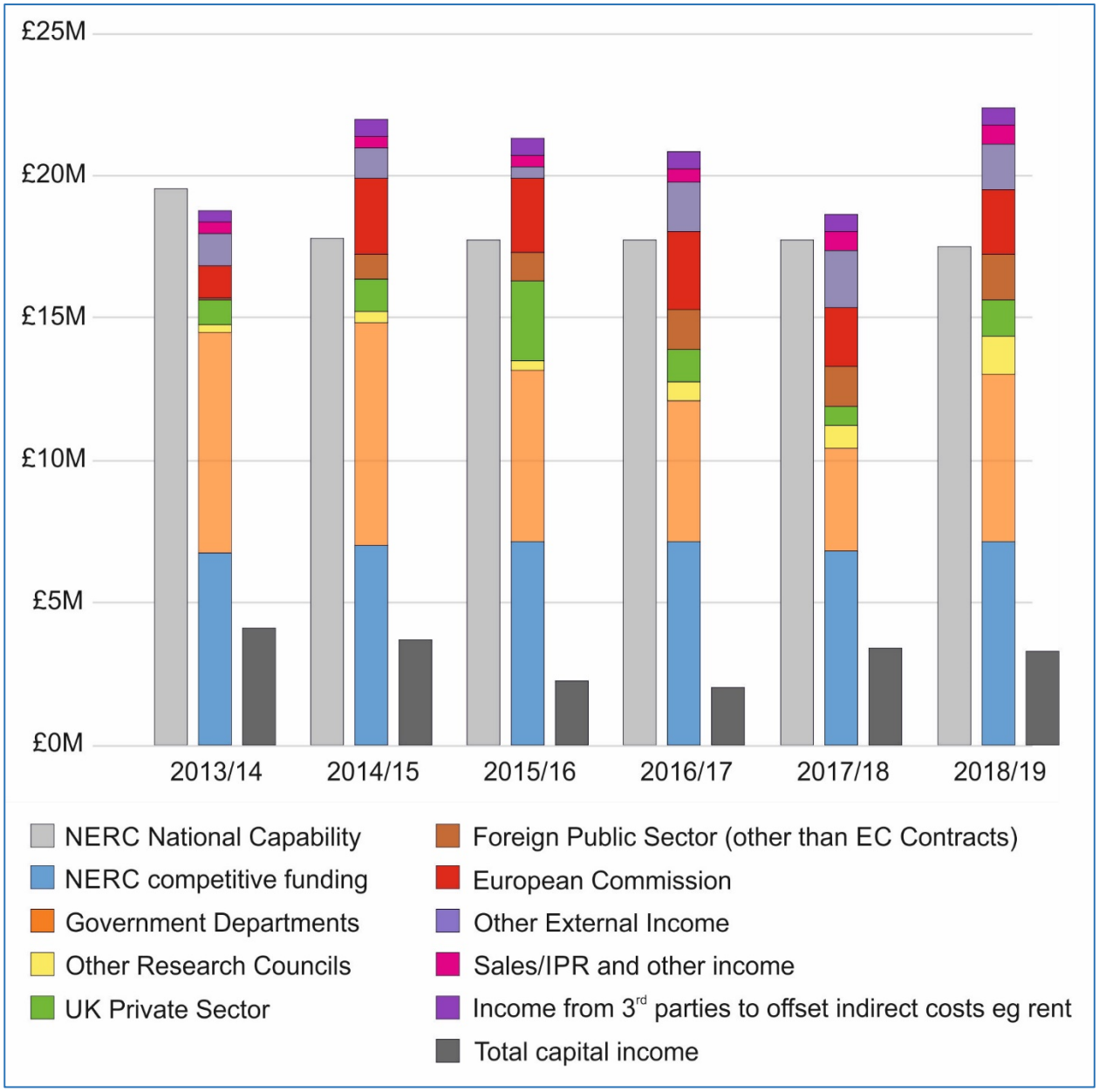

Figure 3-1. Comparative income for CEH 2013-2019. National Capability, capital and competitively won income split by funding source. Note NC is normalised to include overheads at full cash cost.

In 2013/14-2018/19 there were >25 CEH-led competitively won awards in excess of £1m paid to CEH, including Co-investigator and sub-contract funds. These had a cumulative value of £60m. Several of these awards were substantially larger, where funders pay Co-investigators directly, e.g. the EU-funded CEH-led NanoFASE Project award to CEH was €1.7m with a €11.3m total project value.

Prestigious and competitive awards include a CEH-led, major international research programme tackling socio-economic environmental nitrogen pollution in South Asia. The South Asian Nitrogen Hub, established under the Global Challenges Research Fund (GCRF), comprises 50 organisations across the UK and South Asia. This is a five-year (2019-2024) award of £17.1m from UKRI, £2.5m from other UK and international partners, e.g. the South Asia Cooperative Environment Programme (SACEP), and £7m in-kind partner contributions.

Another substantive competitive award, exemplifying the link between excellent research and impact includes a CEH-led Programme, which informs the Welsh Government's Sustainable Farming and our Land consultation through evidence collected by the Environment & Rural Affairs Monitoring and

Modelling Programme (ERAMMP). This £5m Programme involves >20 partners including ADAS, Institute of European Environmental Policy, Forest Research and Ricardo, and delivers the evidence base on links between on-farm actions and delivery of environmental outcomes required by the Welsh Government to develop policy analyses for a post-Brexit landscape.

Other substantive awards are summarised by customer group in Table 3-1.

Table 3-1. Representative examples of CEH-led competitive project and work package awards by customer group, including Co-investigator and sub-contract funding, paid directly to CEH

Source	Title	Value	Years
NERC Discovery Science	GloboLakes: investigating the state of lakes and their response to climatic and other environmental drivers of change at a global scale *(Sterling University-led)*	£380,000	2012-2017
NERC Highlight Topic	Detection and Attribution of Regional greenhouse gas Emissions in the UK	£480,000	2019-2023
NERC Strategic Research Programme	Emerging Risks of Chemicals in the Environment	£2,400,000	2018-2022
Other Councils (MRC)	Zoonotic forest disease (KFD, India): forest management to maximise ecosystem benefits and minimise exposure to zoonotic disease	£610,000	2017-2019
EU	NanoFASE: Nanomaterial Fate and Speciation in the Environment	€1,670,000	2015-2019
Government Departments	UK assessment of Eutrophying and Acidifying Pollutants	£3,530,000	2009-2020
Private Sector (Bayer & Syngenta)	Investigation of impacts of neonicotinoids on honey bees	£2,420,000	2014-2017
International (ECMWF)	Demonstrator for improved decision-making under climatic change in the European water sector	£1,360,000	2015-2019
International (UNEP-GEF)	Global Nitrogen Cycle towards an International Nitrogen management System	£4,800,000	2017-2022

3.2.2 National Capability (NC) Funding

NERC NC enables UK scientists to deliver world-leading environmental science, meet national strategic needs, and help the Government respond to emergencies. CEH delivers this UK capability in terrestrial and freshwater sciences. NERC NC science integrates over at least national and decadal time-scales, and consists of the Long-term Science delivered by:

- NC Science Multi Centre (NC-MC)
- NC Science Single Centre (NC-SC)
- NC Official Development Assistance (NC-ODA)
- NC-Services, Facilities and Data (NC-SFD)

Significant NC funding directed towards cross-Centre/Survey collaboration, supports CEH partnerships with BGS, NOC, NCAS, NCEO and others, which are summarised in Table 3-2.

Table 3-2. Summary of NC-MC research delivered by multiple Centres

ASSIST (Achieving Sustainable Agricultural Systems)	Developing farming systems that contribute towards environmental sustainability	CEH-led, with Rothamsted Research (BBSRC funding), and BGS
Hydro-JULES	Combining hydrological and land surface modelling	CEH-led, with BGS and NOC
LOCATE (Land Ocean Carbon Transfer)	Investigating long-term fate of organic carbon washed from soil into aquatic environments	NOC-led, with CEH, PML and BGS
UK-ESM (UK Earth System Modelling)	Developing a new Earth System Model	NCAS-led, with NOC, CEH, NCEO, BAS and BGS

The remaining NC funded work undertaken by CEH is delivered through our UK-SCAPE and SUNRISE programmes, and via NC-Services, Facilities and Data (NC-SFD) and NC National Public Good (NC-NPG) programmes (Table 3-3).

Table 3-3. UK-SCAPE, SUNRISE, NC-SFD and NC-NPG Programmes

UK-SCAPE (NC-SC) UK Status, Change and Projections of the Environment	• To research and provide national-scale measurements, data and models designed to deliver new integrated understanding of the environment, and of consequences of interventions in the UK landscape
SUNRISE (NC-ODA) (Sustainable Use of Natural Resources to Improve Human Health and Support Economic Development)	• Developing hydro-climate services for water management • Restoration and remediation of degraded resources • Managing land to ensure environmental sustainability
EIDC (NC-SFD) Terrestrial and Freshwater Sciences component of NERC Environmental Data Service (EDS)	• Delivering data services to UKRI/NERC award holders to ensure long-term security and access to environmental data • These services comply with wider goals of NERC EDS and are certified by ICSU World Data System
National Public Good (NC-NPG)	• Providing independent scientific and expert advice to UNESCO and WMO hydrological programmes and supporting broader UK activities through advice to the UK Permanent Delegation to UNESCO (DFID/FCO) • Representing the UK in the governance of the UNESCO Hydrological Programme

3.2.3 Capital Funding

CEH secured £19m capital investment 2013-2019, critical to mainlining and developing world-class facilities for CEH and the wider scientific community. Key investments include:

- COSMOS: Long-term UK monitoring network, delivering near real-time measurements of soil moisture (£2.4m)
- Greenhouse Gas Flux Systems: Network of eddy covariance flux towers observing land-atmosphere fluxes of CO_2 and H_20 (£1m)
- Liquid Chromatography Mass Spectroscopy: high precision organic analysis of biotic and abiotic samples (£800k).

3.2.4 Links Between Research Funding and High-quality Research Output or Impact

CEH has published >2,900 journal articles (2013-2019) with >54,000 citations. 95% of these were co-authored, involving partners in 139 countries. This would have been possible without the support that research funding provides. For example, the South Asian Nitrogen Hub (SANH) builds on years of previous nitrogen research. Furthermore, CEH led the first knowledge synthesis for the global nitrogen cycle [Fowler et al. **Phil. Trans. R. Soc.B**, 2013] associated with >370 citations, and used the output from EU research projects (ACCENT+, PEGASOS and ECLAIRE).

3.3 Provision and Operation of Infrastructure and Facilities

CEH state-of-the-art facilities, sites and platforms afford a high quality research environment for CEH staff, students and members of the research community. Our laboratory facilities, comprised of specialised, purpose-built laboratories, provide a broad range of resources required for experimental techniques, underpin research collaborations. They enable CEH to take the lead in national and international research projects. Several EU funded infrastructure projects and research programmes depend on CEH facilities (Table 3-4).

As part of NERC's national capability, CEH's facilities enable the UK to deliver world-class environmental science, providing the evidence base for European and UK environmental regulations and facilitate national and international reporting against those commitments. These facilities are also used by CEH stakeholders, e.g. SMEs developing novel air quality sensors.

3.3.1 Centralised Research Facilities

CEH's centralised chemistry laboratories at Lancaster with capabilities in organic, nutrient, metal and radionuclide chemistry are UKAS accredited to ISO/IEC 17025:2005 standard. Staff analyse up to 20,000 samples pa, reporting >250,000 determinands. As part of the National Environmental Isotope Facility, CEH also provides a wide range of organic and light stable isotope mass spectrometry analyses for research communities, and is a node of the NERC Life Sciences Mass Spectrometry Facility (LSMSF).

3.3.2 CEH Monitoring Sites, Platforms and Networks

CEH operates a national network of monitoring sites in diverse habitats including lowlands, uplands, wetlands, coasts, lakes, rivers, forests and heaths, accumulating decades of detailed data from wild bird populations on the Isle of May to water quality of freshwater lakes (Table 3-4).

Table 3-4. Examples of monitoring sites and networks

Site	Network	Details
Auchencorth Moss	ACTRIS	Research infrastructure for the observation of aerosols, clouds and trace gases.
Moor House **Whim Bog**	ExpeER	EU Experimentation in Ecosystem project with an open Transnational Access call and invites proposals for small research projects or visits to any of the 31 ExpeER infrastructures.
Plynlimon CZO **Conwy** **Whim Bog** **Auchencorth Moss** **Cairngorm** **Moor House** **Wytham**	eLTER H2020	CEH coordinates the UK's LTER network, the UK Environmental Change Network and operates several field research sites that are included in the eLTER project. CEH disseminates data from these sites and invites researchers to access some sites via the Transnational Access scheme.
Easter Bush	INGOS	Key site of GREENGRASS, a validation site under the CarboEurope IP and a Level-3 site of NitroEurope IP.
ECN Cairngorm	INTERACT	EU-funded research infrastructure project concerning arctic and sub-arctic research stations.

Many of our experimental and monitoring platforms have been in operation for >20 years, and have international standing. We participate in national and international programmes (e.g. Integrated European Long-Term Ecosystem, Critical Zone & Socio-Ecological Research Infrastructure) and our facilities form an integral component of a number of global experimental networks and observatories. These include GHG flux and soil moisture monitoring stations, observatories for air quality and air pollutant deposition impacts (WHIM, Auchencorth Moss), long-term climate change (e.g. Clocaenog), and sustainable farm practice experiments (Hillesden Farm). For example, the Auchencorth site is a Regional Station within the World Meteorological Organization's Global Atmosphere Watch programme. Site data are submitted to global databases, as well as UK-Air and European databases, enhancing worldwide use of the measurement data. CEH maintains facilities for the construction and maintenance of instrumentation, servicing the engineering and electronics needs of these experimental and monitoring platforms.

CEH actively encourages the shared use of our infrastructure and resources – our monitoring sites and environment controlled facilities (Solar-Domes, Gro-Dome, Aquatic Mesocosm Facility) are available for use by the wider environmental research community, with data and sample archives similarly accessible.

3.3.3 Operational and Scholarly Infrastructure Supporting Research and Impact

CEH delivers the Environmental Information Data Centre (EIDC), a NERC Data Centre and certified repository by CoreTrust Seal, managing data for the NERC research community and also curates other CEH data holdings, e.g. Biological Records Centre, National River Flow Archive, Environmental Change Network and Air Pollution Information System. These Record Centres collectively deliver to 150,000 users and in a single year (2015/16) had 977,000 visits. In addition, CEH's Environmental Information Platform provides access to the data catalogue via web-based tools and programming interfaces. Until 2015, CEH also managed the NERC Environmental Bioinformatics Centre.

In addition to delivering the infrastructure that underpins the NERC Data Centre and web portal development, CEH's Applications Development Team create information systems, decision-support tools and smartphone apps, providing a critical capability to secure and deliver research grants and contracts.

The Impact & Innovation Directorate delivers a range of activities to support research and impact (Section 3.1), including income generation, partnership building, funding for proof-of-principle commercial innovation projects, commercialisation, and promotion of CEH impacts and research outputs.

3.3.4 IT Resources and Technical Support Staff

CEH Computer Support (CCS) provide an integrated IT service that is responsive, innovative, secure and cost effective, to deliver excellent science. CCS is responsible for all aspects of IT including desktops, networks, servers, data storage, communications and scientific computing, including high performance computing facilities and support for flagship field site instrumentation.

Library services in CEH are provided through the NERC Library Service (NLS), which aims to provide the best information services and resources to support NERC's Delivery Plan.

3.3.5 Advanced Equipment

Advanced equipment is deployed at many monitoring sites and facilities. In some cases, e.g. diffusion denuder equipment for atmospheric sampling, the equipment has been developed by CEH.

CEH established a UK-wide network of soil moisture monitoring stations (COSMOS), that measure cosmic-rays to determine soil moisture, providing near-real time soil moisture data supporting research and applications including farming, water resources management, flood forecasting and land-surface modelling. This sensor network is the highest density deployment anywhere in the world. CEH is now working with partners to establish an analogous network in India.

Auchencorth Moss is one of the UK's measurement supersites for concentrations and surface/atmosphere exchange fluxes of trace gases and aerosols, including physical and chemical properties. Of particular significance is the continuous operation of a MARGA wet-chemistry analyser for hourly measurement of gas-phase pollutants. The instrument is based on denuder/steam jet

aerosol collector technology, coupled with online ion-chromatography, which provides a range of gas/aerosol measurements.

The CEH centralised analytical chemistry laboratories have a variety of high specification mass spectrometers and dedicated analytical staff. The facility provides the capability to quantify environmental concentrations of polar and non-polar organic contaminants, metals and stable isotopes, and the capability to scan samples for unknown emerging contaminants.

3.3.6 Environmental Sample Archives

CEH maintains a series of long-term, national environmental sample archives, often integrated with other national and international archives, including the development of a UK virtual Environmental Specimen Bank to facilitate rapid discovery of archived biological specimens.

- **Predatory Bird Monitoring Scheme (PBMS):** an archive established in the 1960s to quantify the concentrations of contaminants in species of predatory and fish-eating birds in Britain. It aims to detect and quantity current and emerging chemical threats to the environment. PBMS is integrated with the European Raptor Biomonitoring Facility.
- **UK National Fish Tissue Archive:** samples are collected in partnership with the EA and enables freshwater chemical contamination assessment.
- **National Honey Monitoring Scheme:** working in partnership with UK beekeepers, using advanced analytical techniques to monitor long-term changes in condition and health of the UK countryside.
- **National Soils Archive:** dried and frozen soil samples from the national integrated monitoring programme UKCEH Countryside Survey. CEH is a partner in the UK Soil Observatory, making soils information widely accessible.

3.3.7 Major Benefits In-kind

CEH provides training and information systems, in partnership with JNCC and over 80 UK and Ireland volunteer recording schemes, exemplified by iRECORD and an associated suite of mobile apps (Section 4.2). This infrastructure supports structured and unstructured environmental survey through citizen science. This facilitates environmental survey at a scope and scale beyond CEH's science budget, and an effective mechanism to increase the public's engagement with, and understanding of, nature and environmental challenges. In 2018 JNCC valued volunteer biodiversity recording at £20.5m pa, supporting research, e.g. the first continent scale impact assessment of an invasive species, policy development and statutory reporting, natural capital assessment and land-management decisions.

4 Collaboration and Contribution to Research Base, Economy & Society

4.1 Research Collaborations, Networks and Partnerships

CEH's research and innovation, and indeed its culture, is built on collaboration and partnerships nationally and internationally across academia, business, the third sector, and the public. The importance is evidenced by the fact that CEH research is primarily delivered in concert with, or directly informed by, partners, with 95% of CEH's publications co-authored.

4.1.1 Research Collaborations and Partnerships

Research collaborations are often the outcome of successful relationships with academic colleagues at other institutes and the product of effective support in developing successful proposals. 90% of CEH's research projects are delivered in partnership, 35% in international partnership (2019). Our strategy has led to an increase in international collaboration beyond the EU – in 2013 50% of our international research projects were delivered with partners outside the EU, rising to 70% in 2019.

CEH researchers maintain active research collaborations through science awards. CEH's Tender Support Team (Section 3.1) provide assistance to researchers to develop proposals for a variety of calls. Progress and outcomes of research collaborations are formally monitored by the CEH Executive Board via a quarterly balanced scorecard with quantitative and/or qualitative targets. Researchers are also supported to participate in networks, e.g. conference attendance, in addition to student supervision across 63 national and international universities (Section 4.4.1), and committees and fellowships (Section 4.4.2). The evidence of success is demonstrated by the scale of joint awards (90%) and publications (95%).

The process for identifying, prioritising, developing and supporting partnerships is primarily informed by corporate business planning, developed first at Science Area-levels, then amalgamated at a corporate level. The business planning process uses the Directional Policy Matrix tool (Figure 4-1), led by a Business Development Manager, to identify key opportunities. Outcomes are formalised via the Science Area Management Plans, with actions delivered by Directors, scientists and the Business Development Team, e.g. CEH staff are identified for key relationship management roles.

Science Areas report through the CEH Science Board to share information and ensure organisational awareness on partnerships. More broadly, the growth in cross-sectoral opportunities, including from UKRI, and in pursuit of CEH's international development objectives have resulted in CEH recruiting technical specialists in social and data sciences over the review period to act as the interface to wider complimentary disciplines. Examples of partnerships and networks include:

- CEH is a founding member of the Partnership of European Environmental Research (PEER) a network of eight of the largest European environmental centres, employing >5,000 people. PEER aims to follow a joint strategy in environmental sciences and to enhance research on ecological sustainability.
- The EurAqua network provides a forum for CEH to collaborate, influence, and advise on the development of European freshwater science and technology.
- Defra Strategic Research Partnership that aims to increase sharing of data, models, skills and facilities, identify elements of policy-relevant existing research and make aligned funding available for the development of policy applications.
- Centre of Excellence in Environmental Data Science (CEEDS) is a partnership launched in 2019 between CEH and Lancaster University, building on the strengths of the two institutes, including data science, data infrastructure and environmental sciences.
- ASSIST (Achieving Sustainable Agricultural Systems), a 5-year CEH-led multi-centre national capability programme, to develop farming systems that contribute towards environmental sustainability, in partnership with Rothamsted Research and British Geological Survey (BGS).

Corporate partnerships and collaborations are enhanced by co-location: two CEH laboratories within the campuses of the Universities of Bangor and Lancaster, co-location of the Edinburgh site in the Edinburgh University Easter Bush Campus and the co-location of staff from BGS, Met Office, Wallingford HydroSolutions Ltd., Natural Resources Wales, JNCC and International Association of Hydrological Sciences at CEH's facilities.

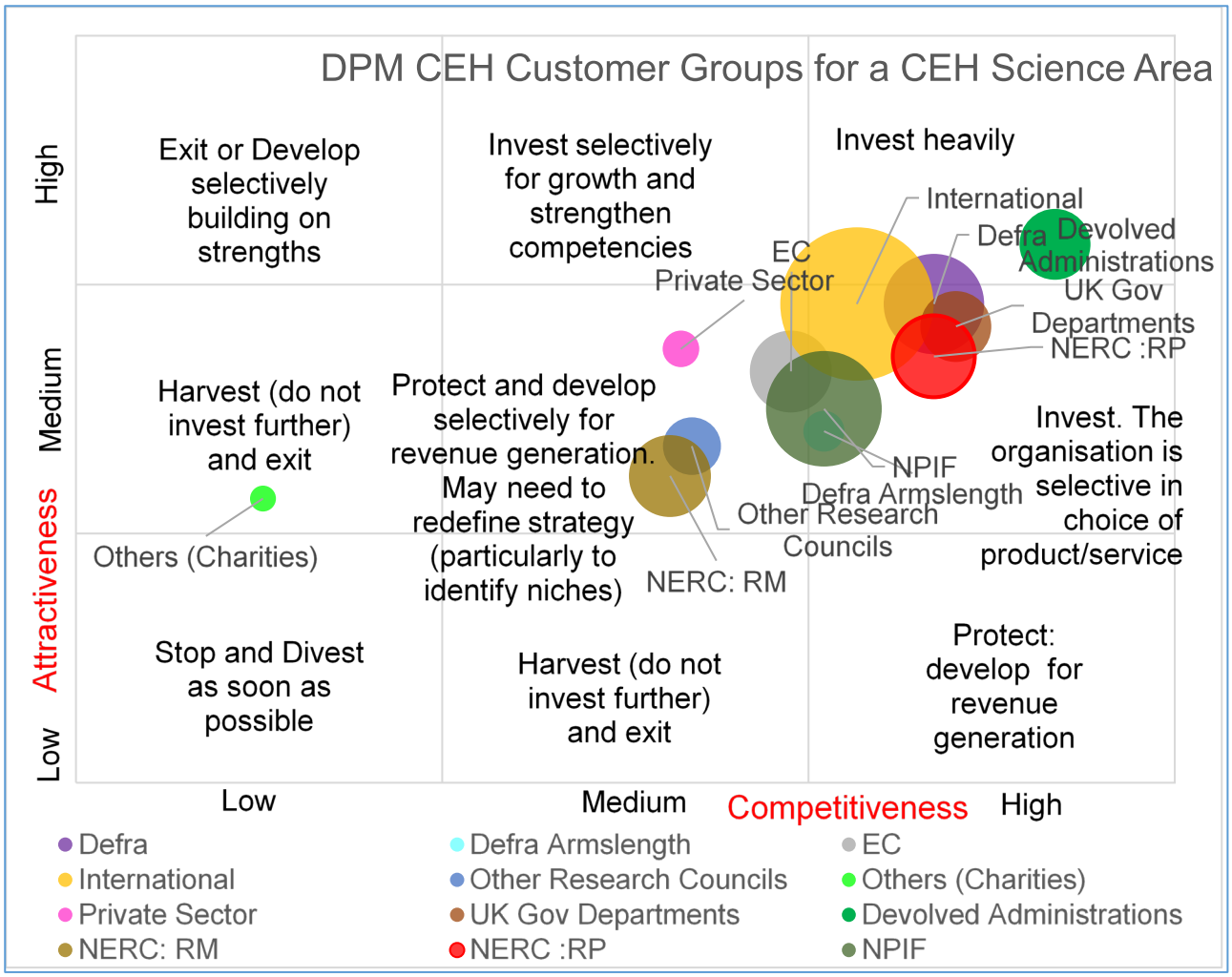

Figure 4-1. Directional Policy Matrix

4.1.2 International Partnerships and Collaborations

CEH makes a significant contribution to international research and evidence provision, underpinned by substantive international partnerships and collaborations. The importance of partnerships for science excellence, delivery, impact, and diversification and growth, resulted in a strategic objective to expand CEH international partnerships in 2013-19.

International engagement and partnerships are managed centrally, informed by CEH's International Strategy, such that support can be provided to staff in the identification and establishment of new partnerships and collaborations. The geographical breadth of CEH's engagement (individuals through to corporate level) has expanded during 2013-2019 (Figure 4-2), with Director-level engagement to strategically identified research institutes and impact partners, resulting in >25 Memoranda of Understandings (MoU) across 7 countries signed since 2013, including: West African Science Service Centre on Climate Change and Adapted Land Use, United States Army Corps of Engineers, National Institute of Hydrology (India) and Chinese Research Academy of Environmental Sciences.

The successful outcomes of our formal and informal international partnerships and collaborations have seen a substantive increase in research project activity and income for projects with international collaboration since 2013 (Figure 4-3), primarily due to increased activity outside the EU (ca. 160 global projects, funded by UKRI and international organisations, e.g. with the Asian Development Bank, World Bank, UN Environment Programme and World Meteorology Organisation). During the review period CEH has been involved in 44 EU Research Framework projects, with particular success by the Ecotoxicology group in the Industrial leadership pillar of Horizon2020; in the latest call (2020) CEH was successful in 75% of proposals in this area.

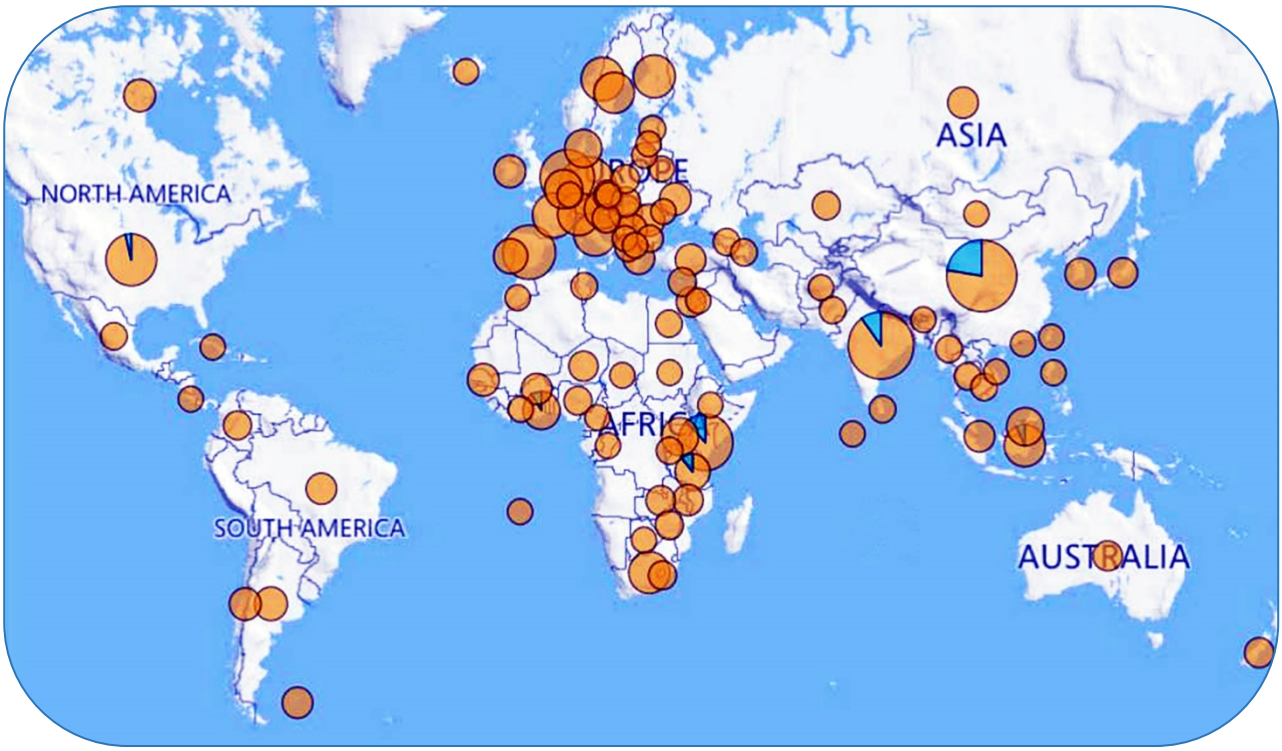

Figure 4-2. 2019 global CEH engagement (Circles are shown centrally on a country. Circle size indicates numbers of engagements in the country. Purple indicates numbers of organisations with MoUs).

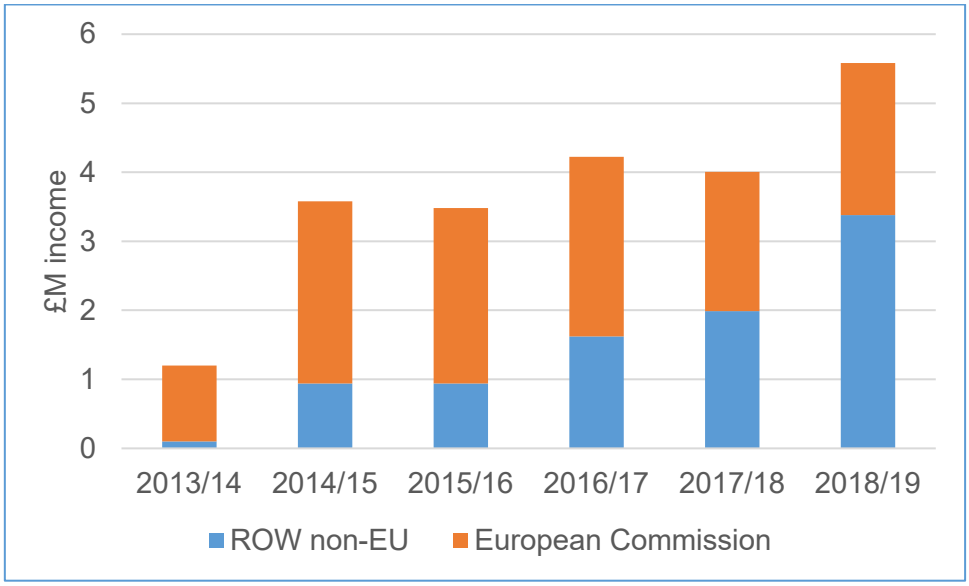

Figure 4-3. International public sector project revenue.

Further indicators of the success of our collaborations which enrich and contribute to the research base is evidenced by an increase in research papers co-authored with international colleagues (Figure 4-4). In 2013, publications included co-authors from 70 countries, including 32 from the Global South, which increased to 98 countries in 2018, including 52 from the Global South. Publications during 2013-19 involved 138 countries beyond the UK.

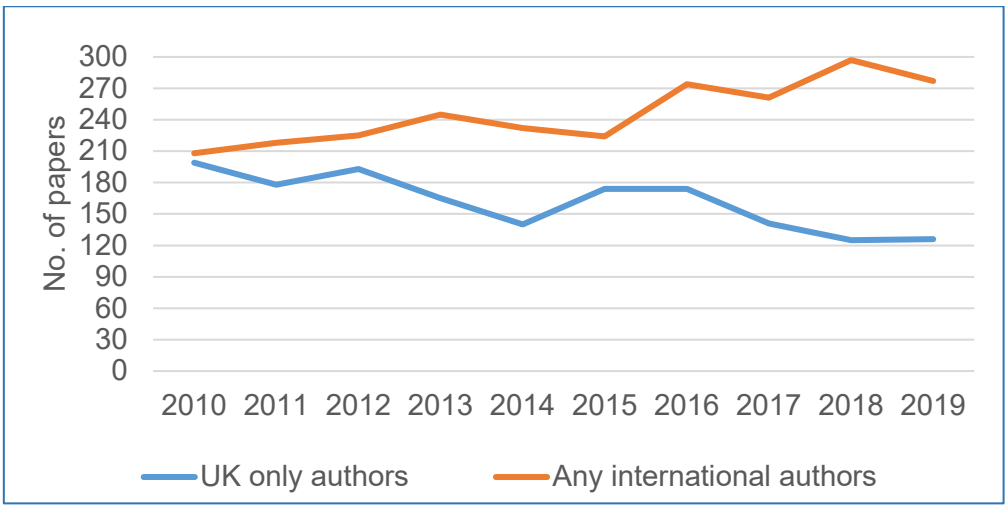

Figure 4-4. CEH authored and co-authored papers where 1 or more co-authors outside of the UK compared to papers with only UK co-authors.

CEH has been involved in 28 Newton and GCRF projects, the most significant of which is the £27m South Asia Nitrogen Hub, bringing together countries in South Asia, UNEP and the South Asian Cooperative Environment Programme. In concert with the CEH-led International Nitrogen Management System, a $60m project of the Global Environment Facility, it provided the evidence for 2019 UN Environment Assembly resolution UNEP/EA.4/Res.14.

Examples of other joint international projects include:

- iCLEAR: alongside Portsmouth and Salford Universities, CEH has worked on Chernobyl Exclusion Zone management with the State Agency for Exclusion Zone Management, Chernobyl ECOCENTRE, Ukrainian Hydrometeorological Institute and Ukrainian Institute for Agricultural Radiology.
- The UN ICP Vegetation Programme, managed by CEH, coordinates research on ozone's harmful effects on European vegetation. Outcomes have been included in UN transboundary air pollution policies, forming part of the UN Economic Commission for Europe Convention (UNECE) on Long-Range Transboundary Air Pollution.
- HydroSOS: the World Meteorology Organization is developing a global capability, led by CEH, to give the current hydrological status across the globe.

4.2 Relationships with Users, Beneficiaries and Audiences

4.2.1 Industry

CEH engages with industry through provision of environmental data, commercialisation, research contracts and research and innovation collaborations. These relationships are often identified, validated and stimulated by CEH's Business Development and Innovation Managers.

Priority areas include water, financial, land management and infrastructure sectors, alongside environmental and engineering consultancies. Significant research programmes include awards from the water sector's research body, UKWIR, for microplastics (£200k) and Anti-microbial Resistance (£1.2m), a strategic Biodiversity Action Plan project with Network Rail, and risk-quantification opportunities with insurance companies. A significant contract with Syngenta and Bayer is detailed in the Impact Case Study, *'Transforming our understanding and management of insect pollinators'*.

CEH's Business Development, Innovation and Licensing Managers, also support commercial exploitation of information products, e.g. Flood Estimation Handbook Web Service (Figure 4-5), to identify and establish joint product development opportunities. The development of CEH Land Cover plus: Crops Map, the first national-scale crops map developed using Sentinel 1 data, was produced with industrial partners, Remote Sensing Applications Consultants and Anglian Water.

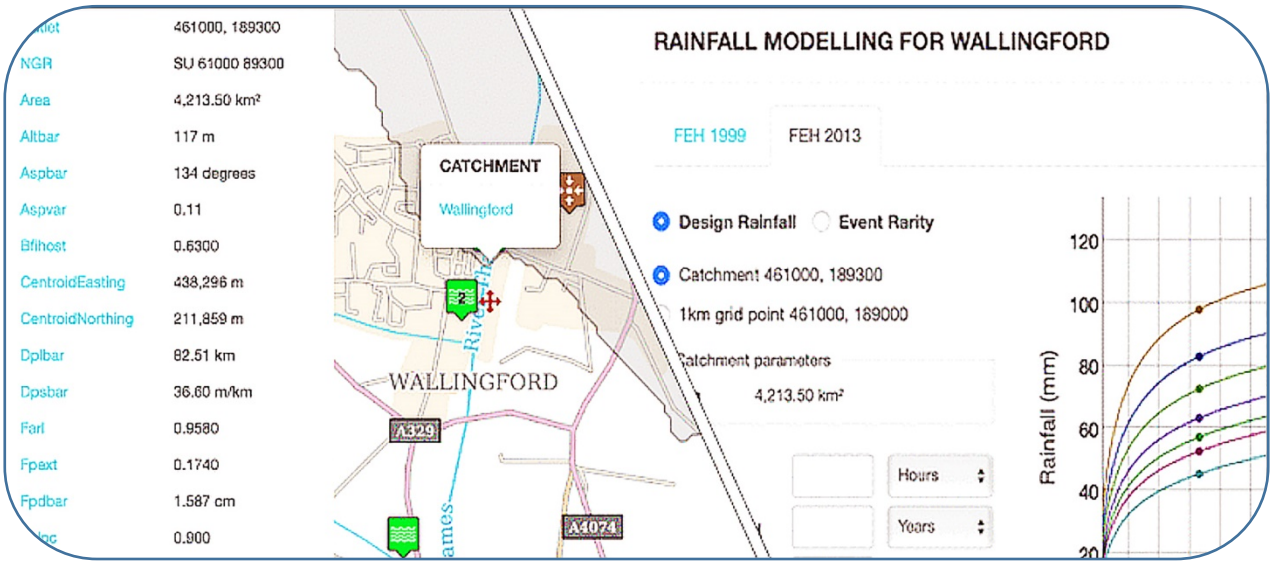

Figure 4-5. Screenshot of FEH Web Service

Whilst, CEH generates and reinvests £725k pa through commercialisation activities, environmental data is freely available, e.g. consultants utilise hydrological data from CEH's National River Flow Archive (71,000 users in 2018) in partnership with UK measuring authorities.

CEH also works with industry in research and innovation collaborations, exemplified by the CEH-led NanoFASE project to maximise synergies across EU nanoparticle research projects addressing ecotoxicology, exposure assessment, risk assessment and standardisation.

4.2.2 Training

CEH's external training portfolio enables stakeholders to access training on environmental topics and techniques. With courses ranging from *'Evidence Synthesis to inform policy and business decision-making'* through to *'Water, land and crop management'*, it extends our relationship with, and disseminates our expertise to, industry, regulators and academia. In 2019, CEH secured World Bank funding to deliver training to the Myanmar and Nepal Hydrometeorological Services.

4.2.3 Public Engagement and Communication

CEH recognises public engagement as integral to science delivery and to optimise impact. CEH interacts and engages with diverse communities through mechanisms ranging from publicly-oriented communications to active participation in the design and delivery of research. CEH aspires to be leaders in specific areas of public engagement, building on existing strengths in citizen science, community engagement and public dialogue. Our strategic approach has been defined within CEH's *Principles for Public Engagement with Research*.

In a typical year, CEH records:

- More than 380,000 website visits and >600,000 unique page views.
- In 2018/19, >2,000 items in UK press, with audience reach in excess of 30 million in print and 190 million online; outlets include BBC Six and Ten o'clock news; Radio 4 Farming Today; Radio 4 Today; The Times, The Guardian; The Daily Telegraph; Daily Mail; BBC Online.
- Social media following > 45,000: Twitter, LinkedIn and Facebook.

4.2.3.1 Citizen Science

CEH is a leader in citizen science, supporting public participation in research, exemplified by partnerships with >80 volunteer recording schemes, and delivery of best practice guides for the UK Environmental Observation Framework and SEPA. Exemplars of public engagement with CEH research include:

- CEH has developed >12 Apps for citizen scientists to record environmental observations including: Asian Hornet Watch (Figure 4-6) and iRecord Butterflies.
- National Plant Monitoring Scheme: a CEH-led consortium enabling trained citizen scientists to collect plant abundance and diversity data.

- UKEAP monitoring: citizen scientists collect ammonia monitors at >70 UK sites, saving £70k pa, and enabling higher resolution air quality assessments.
- An award winning partnership, Big Bumblebee Discovery, led by CEH ecologists with the British Science Association, EDF Energy, and 30,000 school children to examine how environmental changes were affecting bumblebee populations.

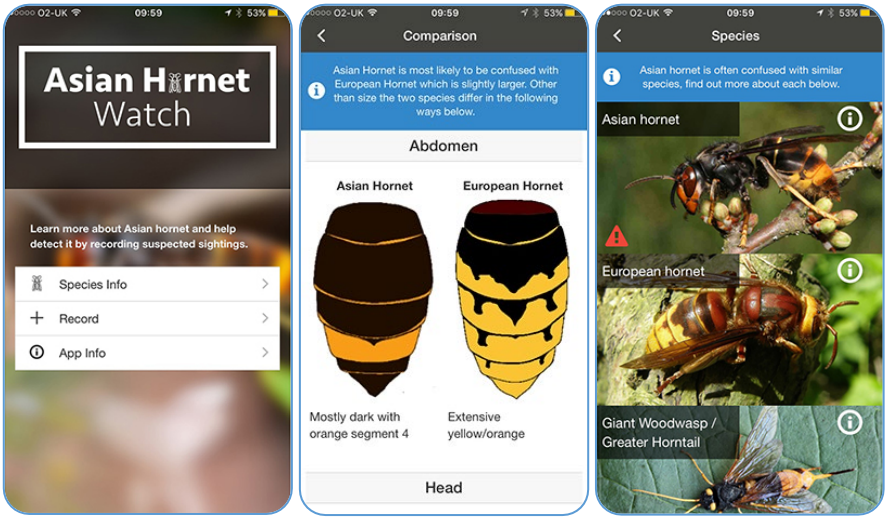

Figure 4-6. Screenshots from Asian Hornet Watch App.

4.3 Contributions to Economy and Society

4.3.1 Policy Engagement

CEH has an enviable record of providing the research and evidence-base for policy, development, implementation and review for the UK Government and Devolved Administrations, and internationally. CEH supports staff in developing and maintaining critical and strategic relationships with governments through membership of advisory and expert panels (Section 4.4.2) and its Business Development Team, who monitor political developments and support responses to government-led consultations. Relevant information is reported to CEH's Science Board to identify a) insights of relevance to CEH's research, and b) opportunities for CEH to optimise impact.

Table 4-1 illustrates 2019/20 UK Government and Devolved Administration engagement through research contract income. Examples of CEH activity contributing to society and the economy through research activities delivering to policy, provision of expert advice to government and intergovernmental bodies are listed below, whilst.

- Supporting UK Government and Devolved Administrations to prevent and respond to emergencies, e.g. floods and droughts, through membership of the Natural Hazards Partnership.
- Hosts the UK National Focal Centre for critical loads mapping and modelling, responsible for co-ordinating the UK activities and data submission to the Coordination Centre for Effects for the Working Group on Effects of the UNECE Convention on Long-Range Transboundary Air Pollution.
- Hosts the Secretariat of the UK Environmental Observation Framework, a coordinating public sector body for the UK's environmental observation community.
- Provision of critical, national-scale datasets and frameworks, supporting the UK National Ecosystem Assessment, Office of National Statistics' UK Natural Capital Accounts and Forestry Commission Natural Capital Accounts.
- Presented evidence on water quality to the House of Commons Science & Technology Committee (2013) and to the Environment Audit Committee (2019) on toxic chemicals in everyday products.
- Specialist adviser to House of Commons Environment Audit Committee Inquiry on Soil Health (2016).

Table 4-1. 2019/20 UK Government and Devolved Administration research contracts.

Direct Government Contracts	Income Budget 2019/20
UK Government Departments	
Defra	REDACTED
Environment Agency	REDACTED
Food and Environment Research Agency	REDACTED
Joint Nature Conservation Committee	REDACTED
Natural England	REDACTED
Committee on Climate Change	REDACTED
Department for International Development	REDACTED
Department of Business, Innovation and Skills	REDACTED
UK Space Agency	REDACTED
Northern Ireland	
Department of Agriculture, Environment & Rural Affairs	REDACTED
Northern Ireland Environment Agency	REDACTED
Scotland	
Marine Scotland	REDACTED
Scottish Government	REDACTED
Scottish Natural Heritage	REDACTED
Scottish Canals	REDACTED
Wales	
Natural Resources Wales	REDACTED
Welsh Government	REDACTED

4.4 Contributions to the Research Base

CEH's contribution to the UK and international research base is detailed below, through research projects and the dissemination of outcomes; training including supervision of PhD and Masters; and providing expertise to committees, journals etc. Evidence of CEH's contribution to the research base through science excellence (InCites data analyses; 2013-19 unless otherwise stated) includes:

- Three CEH scientists are named in the global Highly Cited Researchers 2019 list from the Web of Science Group (Professors Chris Huntingford, James Bullock, and David Roy);
- 2,935 Articles, Reviews, Data Papers and Proceedings Papers 2013-2019 (to 30.11.19), cited 54,508 times;
- Highest publication citations of all UK institutions in Biodiversity & Conservation and Water Resources over the last 20 years (InCites).

4.4.1 Sustainability of the Research Base and Responsiveness to National and International Initiatives

Next generation of scientists PGR training: CEH's contribution to developing the research base through postgraduate training is outlined in Section 2.4. CEH participates in 16 UKRI-funded PhD partnerships (4 Centres for Doctoral Training and 12 Doctoral Training Partnerships). CEH is also involved in PhD partnerships, via industry, European and foundation funding. CEH staff provide postgraduate teaching at a range of universities, including an MSc module on Lake Ecology at Lancaster University. In 2016, CEH partnered with Lancaster University and Rothamsted Research in establishing the Lancaster Graduate School for the Environment.

Responsiveness to initiatives: Response to changes in national and international priorities and initiatives includes both researcher- and strategic-level responses. CEH researchers are encouraged to respond in an agile and flexible manner to the evolution of research questions and wider priorities to enable individuals to develop their personal careers and for CEH to maintain itself at the forefront of current science. Large-scale new initiatives and priorities are identified, developed and responses implemented through the Science Board and Science Area Strategy Teams. Thus external priorities inform research strategy and workforce planning where appropriate.

For example, in 2013 the UK Government committed to delivering an element of its Official Development Assistance (ODA) budget via the UK Research Councils, significantly altering the UK research funding landscape. CEH responded quickly: increasing networking/engagement (Section 4.1.2), instigating relevant training for staff e.g. Theory of Change and MEAL (Monitoring, Evaluation, Accountability & Learning). This has resulted in an increase in income from ODA-funded sources (in 19/20 project income for international activity from ODA-funded sources was 4x that of non-ODA funded international projects), and a near doubling of publications with co-authors from the Global South (Figure 4-7).

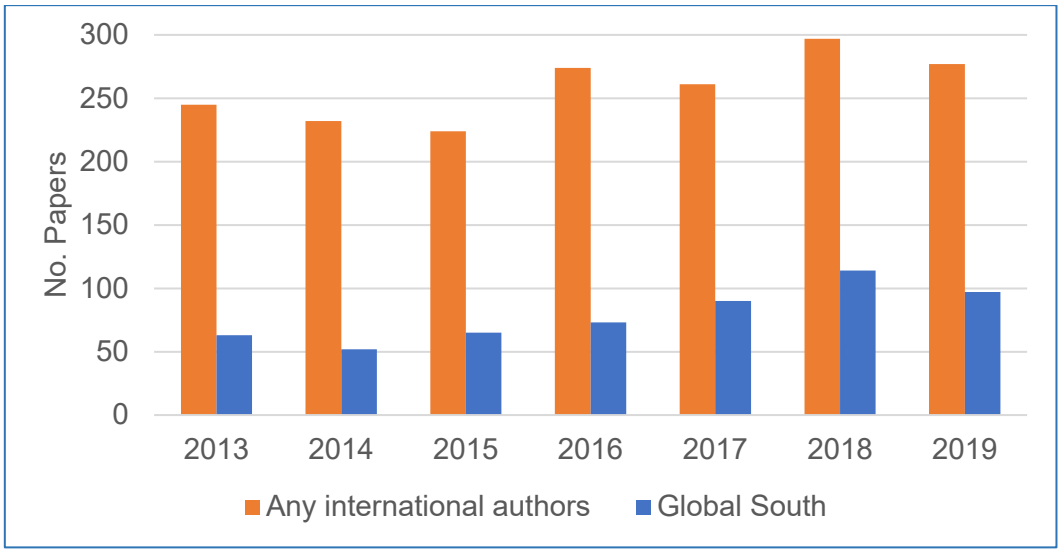

Figure 4-7. Number of CEH papers with international co-authors.

4.4.2 Journals, Committees, Fellowships, Prizes

Indicators of wider influence, contributions to, and recognition by, the research base are outlined below.

Journal editorship: CEH staff have editorial responsibilities in over 20 journals, including subject editor for Global Change Biology and Founding Editor of the International Society of Microbial Ecology Journal (Nature).

Grant committees participation: CEH staff support many NERC advisory groups e.g. NERC Strategic Programme Advisory Group and NERC Knowledge Exchange Advisory Board membership. Thirteen staff are currently on the NERC Peer Review College and associated panels, and attended or chaired >40 panel meetings across UKRI and Academies, and reviewed hundreds of proposals. CEH staff also support UKRI Programme development, e.g. Scoping group for UK forests call and RCUK and Innovate UK Bioenergy Strategic Co-ordination Group.

Membership of national and international committees: CEH encourage staff to participate in national (>40) and international (>50) expert panels and advisory committees. These include: NERC Science Board, Chair of the Advisory Committee on Releases to the Environment, Defra's Science Advisory Council, Horizon Europe Mission Board (sole UK academic member), Hydrological Adviser to UK Government with the World Meteorological Organization and Defra's Expert Committee on Pesticides.

Fellowships and Professorships: over 40 staff have been awarded fellowships and honorary or visiting professorships at distinguished societies and national and international HEIs, including: Royal Statistical and Meteorological Societies, Liverpool School of Tropical Medicine and Chinese Academy of Sciences.

Prizes: CEH staff have won a large number of awards during the review period, including the following few examples:

- Research: Times Higher Education 'Research Project of the Year', British Ecological Society Marsh Awards and RSPB Conservation Science Award.
- Innovation: Royal Meteorological Society Innovation Award.
- Engagement: Third Sector Business Charity Award for Charity Partnership (short-term).

Invited keynotes, lectures and conference chair roles: CEH's researchers have delivered numerous keynotes, lectures and conferences, for example:

- Professor Bridget Emmett was a scientific committee member and invited speaker at the *6th International Symposium on Soil Organic Matter* (2017) and keynote speaker at the 2019 *International Soil Modelling Consortium meeting*, Wageningen, NL.
- Professor David Fowler FRS CBE gave a keynote presentation to the Science for Defra Conference (2017) at the Royal Society, London.
- Professor Mike Acreman convened the Natural Capital Initiative summit, *Valuing our Life Support Systems* (2014), the first summit held by the Initiative in 2009 led to the formation of the Cabinet Office's Natural Capital Committee.

ENVIRONMENT COMPONENT DATA

Total income (funding and capital): £m

2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
41.77	42.77	40.54	39.81	39.10	42.46

Open access data

	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
UKRI open access block grant awarded to the Centre (£k)	32.5	38.2	43.6	61.2	68.0	80.7
% of UKRI open access block grant spent	56%	154%	104%	100%	78%	80%
% **overall** open access compliance for UKRI-funded papers (as reported to UKRI)	65%	81%	83%	85%	89%	91%
% **gold** open access compliance for UKRI-funded papers (as reported to UKRI)	27%	45%	44%	55%	51%	65%
% **green** open access compliance for UKRI-funded papers (as reported to UKRI)	38%	36%	39%	31%	38%	25%