Sustainable Use of Natural Resources Theme Action Plan 2009

VISION

On a global scale, the key pressures on natural resources come from climate change and population growth, together with societal expectations for quality of life and wealth, which is increasingly resource demanding. The grand challenge for this theme is to understand better the entirety of processes and consequent outcomes of natural resource use on freshwater, terrestrial and marine systems, and on feedbacks to the atmosphere. The overall science goal is to help deliver the fundamental science to ensure informed choices on the equitable use and allocation of natural resources. Although the term 'sustainability science' has existed for some time,[1] it does not yet capture the complex social-ecological interactions that characterise natural resource use.[2] Integrative rather than reductionist approaches can help advance our knowledge of these interactions and systems thinking underpins the theme. The ambition is to build methodologies that help us understand how system properties emerge in a changing environment through quantitative measures of multiple components simultaneously, and by rigorous data integration with predictive models. Recent technological advances in environmental observation, environmental data handling, and numerical and computational techniques make this possible.

SCIENCE GOALS AND ACTION PRIORITIES

Four high-level science goals map onto the broad SUNR theme challenges (C1 to C4, Table 1). The 2009 TAP proposes actions in three of the four challenge areas. Each proposed action was assessed against science quality, fit to strategy (including cross-Council programmes), and timeliness and anticipated economic impact. As no single discipline can address all the goals of each action, the integration of elements of the terrestrial and freshwater, marine, and earth science communities is critical in delivering the science goals for the theme. Integration is also growing with the atmospheric sciences community through work to define common research scales. Delivering the science to meet these goals will provide society with knowledge of how non-renewable and renewable energy resources can contribute to a low carbon economy whilst ensuring that water and soil life support systems are valued and used within the Earth's environmental limits. Meeting the SUNR challenges will make a significant contribution to three cross-Council research programmes: Living with Environmental Change, the Research Councils Energy Programme, and Global Uncertainties.

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[1] Kates et al. 2001. Sustainability science. SCIENCE 292: 641–42
[2] Carpenter et al. 2009. Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. PNAS 106: 1305-12

Table 1 SUNR Theme challenges, high-level science goals and TAP actions

Theme Challenges	High-level Science Goals	TAP Actions			Status
		Approved 2008	***Proposed 2009***	Potential 2010	
C1 Extending the resource base	To predict the environmental implications of current and future use of non-renewable natural resources for energy.	Carbon Capture and Storage		Security of Minerals/ Metals Supply; Methane Hydrates; Arctic	★
C2 Meeting the renewables challenge	To improve predictions of the environmental outcomes of extracting renewable energy from natural resources.	Bioenergy scoping	***Algal Bioenergy network***		★★★
		Land-based Renewables	**Marine Renewable Energy**		
C3 Sustaining water and soil life support systems	To develop integrated quantitative understanding of the emergent properties of the water-soil system in response to a changing climate.	Changing Water Cycle	**Macronutrient Cycles**	Virtual Observatory training	★★★
		Virtual Observatory			
C4 Valuing environmental services	To devise methods and metrics to weight appropriately the environmental consequences of decisions relating to natural resource use.	Valuation scoping	***Valuing Biodiversity and Natural Resource Use***	Climate Change Impacts	★★

Status of Theme Challenges relative to each other: ★Slow ★★ on track ★★★ Good. Actions in **bold** require a decision by SISB. Actions in *italics* follow-on from scoping in the 2008 TAP. Potential 2010 actions are for note with respect to the SUNR Theme 5-year plan.

FIVE-YEAR VIEW OF THE THEME 2008-2013

OVERVIEW

To deliver the science to tackle the challenges relating to the sustainable use of natural resources requires a systems approach.[3] The breadth and complexity of the challenges means tangible outcomes will take time to reach, both in terms of developing the science solutions but also in nurturing the research community to meet the science challenges that may require research across disciplinary interfaces. The prioritisation of particular activities and actions over 2008-13 seeks to address these two needs. Pragmatically, meeting these needs requires first, developing methodologies and tools to quantify key processes at appropriate time and space scales, and building these into predictive models that shape decisions relating to the future use of natural resources. Second, growing the fundamental science base needed to meet challenges that appear to be ‘near-market’ issues, and demonstrating the role of environmental science in understanding economic impact and informing policy in relation to the *sustainable* use of natural resources. Some of the big science questions pertinent to this theme include:

[3] http://en.wikipedia.org/wiki/Systems_thinking

- What are the environmental implications of options to replace conventional fossil fuel based systems?
- What land management decisions do we need to make now and in the future to preserve or enhance its carbon sequestration potential? What are the implications for other ecosystem services?
- What combinations of soil and water-derived ecosystem services can flow sustainably from a particular landscape?
- How do we ensure renewable energy options deliver environmental security?
- How can we capture the way that complex systems and patterns emerge out of a multiplicity of relatively simple physical and biogeochemical interactions in the soil and freshwater environment in order to understand their response to and feedbacks on the climate system at local to regional scales?
- Valuing natural resource use still places emphasis on societal/economic need rather than promoting environmental resilience. What science metrics do we need to develop to value appropriately ecosystem services?

To address these and other 'big science questions' an integrated set of actions under the four theme challenges are prioritised over the 2008-13 period. Table 1 highlights the science goals for each of the four challenges, shows the actions approved in 2008, proposed in 2009 and known future actions, and indicates how these map onto the theme science challenges. There are six approved, proposed or future actions in the energy area (Challenges 1 and 2), four in the water-soil system (Challenge 3) and three in the valuation area (Challenge 4). Some actions proposed in the 2009 TAP (algal bioenergy, valuation network) follow-on from scoping actions in the 2008 TAP. Other actions (marine renewable energy, macronutrient cycles) explore new science areas within the scope of the theme. Future actions are indicative of new opportunities (e.g. Arctic initiative) or a high-level strategic need (e.g. climate change impacts).

A ★ grading indicates the perceived status of the four theme challenges with respect to one another. Activities approved or proposed under Challenges 2 and 3 are or will generate significant opportunities for the research community. Scoping for Challenge 4 shows that the environmental science research community needs to grow to address the science need; it also needs to work across social-ecological boundaries. Here, interaction with ESRC and with partners such as DEFRA is important. Challenge 1 needs more work to engage a broader community in spotting and acting on the *environmental* science opportunities, and in interfacing with RCEP and UKERC to meet the science goal set for this Challenge. More broadly, **stakeholders** are important for this theme to help gear NERC investment. Exemplars from the 2008 TAP are the formal partnerships in place with DEFRA and the Environment Agency (EA) under the Virtual Observatory (C3, Table 1) giving access to over £15 million catchment infrastructure and data through the DEFRA/EA Demonstration Catchments initiative.[4] Under the Land-based Renewables action (C2, Table 1), Shell Global Solutions committed £350k and Natural England in kind support (data, skills) to the sandpit leading to two consortia and one network.

ACTIONS APPROVED IN 2008 AND THEIR IMPACT ON THE FIVE-YEAR LANDSCAPE

Prioritised under **Challenge 1**, the £1.6m NERC action on *Carbon Capture and Storage* secured matched funding from EPSRC under the Research Council's Energy Programme (RCEP).[5] The action examines the long-term performance of geological CO_2 storage and the implications of diffuse

[4] www.defra.gov.uk/science/funding/documents/2009/demo-catchments-secretariat.pdf
[5] http://www.nerc.ac.uk/research/themes/resources/events/ao.asp

leakage for marine and terrestrial ecosystems. The announcement of opportunity for the action closes on 29.09.2009. Future actions will prioritise the environmental security of minerals and metals resources and potentially, the implications of exploiting Arctic resources. Under **Challenge 2** the £2.1m action on *Land-based Renewables* is appraising the pressures on UK land use from renewable energy schemes (e.g. bioenergy crops, wind, micro-technologies) to predict the outcomes for the environment (e.g. for carbon sequestration capacity). The sandpit in June 2009 funded two consortia and a new research network and led to further stakeholder support including the Met Office, E.ON and the Forestry Commission. Two proposed actions in the 2009 TAP will build Challenge 2 activity through research on nascent technologies such as algal bioenergy and 'wet renewables' focusing on wave and tidal energy schemes.

The 2008 TAP prioritised two actions under **Challenge 3** to help deliver an integrated understanding of a changing climate on soil and freshwater resources. Water security remains a pressing global issue subject to much debate.[6] The *Changing Water Cycle* (SUNR contribution £2.83m) is an ambitious cross-theme programme that should lead to new insights into the drivers and feedbacks on water resources and climate. The 5-year vision for Challenge 3 is to make significant advances in upscaling our current understanding of land surface and subsurface processes in terrestrial and freshwater environments to interface with downscaled climate models, enabling real progress in unravelling the complexity of the land surface system. The £1.7m activity prioritised under the *Virtual Observatory* provides the platform to integrate soil/water observations and modelling and align them with sensor technologies and cyberinfrastructure development. A strong partnership with DEFRA and the EA secures facilities for the VO (see earlier) and alignment with the £34m UKWIR (UK Water Industry Research) Priority Hazardous Substances project will bring further monitoring data to the VO platform. The cyberinfrastructure element of the VO seeks to future-proof against the anticipated step-shift in space/time observation and model capability through links to existing expertise in the NSF Watersnet programme.[7] The proposed action on macronutrient cycles continues the theme of integrating understanding across different (nutrient) cycles on which future food security and ecosystem health depend.

Addressing **Challenge 4** on valuation, and following scoping in the 2008 TAP, a cross-theme *Valuation network* proposed in the 2009 TAP would help develop methodologies that use science-based metrics and account for the uncertainties in the data that inform them. The network needs to evaluate critically the relevance of using approaches based on the ecosystem service concept to exploit or protect natural resources. The activity has the potential to influence policy on the allocation of value to natural resource use and is timely as the Millennium Ecosystem Assessment[8] is subject to increasing scrutiny and policy is in place to undertake a UK national ecosystem assessment under LWEC.

ACTIONS PROPOSED IN 2009 AND REQUIRING A DECISION FROM SISB

This second TAP has three goals and the funding scenarios are summarised in Appendix 1:

1. Under Challenge 2, to promote further NERC activity in the energy area and address the goal in the 2009 NERC Delivery Plan to: "*Investigate, using a whole-systems approach, land-based, offshore and coastal renewable energies' sustainability and environmental (chemical, physical, ecological) opportunities and risks*."
2. To initiate a major cross-theme programme on macronutrient cycles under LWEC (Challenge 3).

[6] Barnaby. 2009. Do nations go to war over water? NATURE 458: 282-283 and ensuing correspondence: NATURE 459 p31 (7 May 2009)
[7] www.watersnet.org
[8] www.millenniumassessment.org

3. To develop approaches that value appropriately natural resource use (Challenge 4): following scoping, in the 2008 TAP, the proposal is for a cross-theme action with the Biodiversity theme**.**

Gap analysis of existing investments (see later) highlighted the need to grow the Challenge 1 research community before proposing further actions. These will come in the 2010 TAP.

CHALLENGE 2 - ALGAL BIOENERGY NETWORK (SUNR)

The proposed total budget at the 100% funding scenario is £0.6m for a network operated with the Technology Strategy Board (TSB) KTNs and the Carbon Trust (CT) both of whom will provide in kind support for the network through facilitation, sponsorship of joint events, and access to their research networks. The affiliations will help identify at an early stage the possible economic impact of any further NERC investment alongside existing technological investments. This action is opportunistic, and prioritised because it will help deliver Challenge 2, and will grow environmental science opportunities that capture the burgeoning interest in developing algal bioenergy technologies.[10] The CT is currently investing £3-6m in the R&D phase of a programme that may provide up to £20m to commercialise production under the Algae Biofuels Challenge.[11] The CT endorses the action as follows: *"The formation of the Algal Bioenergy Network would make a valuable contribution to the emerging microalgae biofuels industry and help us avoid the mistake made with many other biofuels, which was to overlook environmental considerations until too late."*

Complimenting the CT focus on microalgae, the algal bioenergy network will also look at macroalgae as an energy source[12] to harness existing capacity in the UK research community. The proposal is for a network because the science is at an early stage and needs to develop the predictive capacity to inform the technological development of energy derived from this source. The ambition is the initial NERC investment levers funded partnerships in the future. The action will meet one of the challenges in the NERC strategy to "*Provide scientific expertise on unconventional energy sources and their environmental impacts.*"

CHALLENGE 2 - MARINE RENEWABLE ENERGY (SUNR)

The proposed budget at the 100% funding scenario is £3.1m. This action is central to delivering Challenge 2 and seeks to understand the exploitation of marine systems for renewable energy relative to their potential impact on bioresources and marine habitats. The SUNR theme report argues: "*Understanding the complex interactions between the hydrodynamics, morphological, environmental and ecological parameters resulting from renewable devices is a key science challenge that NERC is well-placed to address*." The action follows from the SISB recommendation (May 08) that coastal and offshore renewable energy "*should be rapidly scoped*."

Current policy is to meet renewable energy targets offshore rather than onshore[13] - the 2009 UK Budget committed £525m to offshore wind energy.[14] Gap analysis reveals a real opportunity to go beyond simple 'environmental impact statements' and harness the significant capacity of the NERC research community to predict the cumulative environmental impacts of scaling-up to large offshore wind arrays or deploying the newer 'wet renewables' (wave and tidal energy). The Government marine objectives published in April 2009 set high targets for a sustainable marine environment. Thus equally important is the opportunity created in Marine Protected Areas under legislation in the Marine and Coastal Access Bill, to examine the broader impacts of renewable energy extraction on marine ecosystem services through e.g. exclusion zones for fisheries and renewables structures such

[10] "Exxon to invest millions to make fuel from algae" New York Times 13 July 2009
[11] http://www.carbontrust.co.uk/technology/directedresearch/algae.htm
[12] Stanley et al. 2009 Marine Bioenergy, NERC proof of concept report, 119pp. Available on the NERC website.
[13] http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx
[14] www.hm-treasury.gov.uk/d/Budget2009

as artificial reefs. There is a unique opportunity for the NERC to work with the technological development of wave and tidal energy using existing test facilities to predict, through observation and modelling, the environmental implications of marine renewable energy.

CHALLENGE 3 - MACRONUTRIENT CYCLES (SUNR, ESS, EP&HH, BIOD and TECH)

Recent research has started to examine nitrogen-carbon-climate interactions[16] but many of the impacts remain unknown or have a high degree of uncertainty. Coupled, but rarely connected across research networks, are similar suites of complex reactions linked to the science of eutrophication.[17] At a time at which we may be moving towards a 'perfect storm'[18] of risks to food-water-energy security under climate change, this action is prioritised now because we need to ensure our efforts to mitigate and adapt to climate change are not unravelled by changes elsewhere in the system.[19]

This action is central to Challenge 3 in the SUNR Theme Report that call for focus on "*interactions from the hillslope to regional scale appropriate for sustaining the quality of air, soil, water interchanges that sustain life and support the biotic resources on which we depend*." Advancing our understanding the multiple stressors that affect macronutrient (nitrogen, phosphorus and carbon) transformations and transfer pathways and predicting their influence on the resilience of the assimilative capacity of soil and freshwater resources to continue to 'self-purify' is critical.[20]

The action meets the challenges in the NERC strategy to "*develop an integrated approach to understanding air, soil and water processes, recognising their interconnections*" and to "*understand how the biological, physical and chemical interactions in soils determine the extent to which people can use the land sustainably*." The action will help deliver the LWEC objective on Ecosystems with the goal of predicting the capacity of freshwaters and coastal systems to continue to attenuate inputs of macronutrients linked to human activities. NERC has a long history of research in this broad area and a strong science community to deliver it. Past programmes have not achieved real *integration* of the processes, transformations and fluxes of macronutrients cycles so we remain unable to capture the complexity of the system or provide the evidence base to start generating solutions. Technological advances and successful models of research integration (e.g. RELU) help ensure that this action can address this need.

CHALLENGE 4 - VALUING NATURAL RESOURCES AND BIODIVERSITY (BIOD, SUNR)

This action will support a research network to grow the science community. It is a priority because we have yet to understand fully the consequences for the environment of decisions relating to natural resource use and to biodiversity as a critical underpinning ecosystem characteristic. "*For too long, an absence of proper green accounting has allowed people to privatise the gains from the environment but socialise the costs.*"[21]

[16] Gruber and Galloway 2008. An Earth-system perspective of the global nitrogen cycle. NATURE 451, 293-296
[17] Smith and Schindler, 2009 Eutrophication science: where do we go from here? TRENDS IN ECOLOGY & EVOLUTION 24: 201-07
[18] Beddington 2009. Biodiversity in a changing world. Linnean Society of London 16 April 2009.
[19] Harris 2007. Seeking Sustainability in an Age of Complexity. Cambridge University Press, 366pp.
[20] Hassan et al. 2005. Ecosystems and human well-being.Ch7 Freshwater. Millennium Ecosystem Assessment Volume 1, p181
[21] Environmental Values. Economist, 13 April 2009

This action is a response to SISB feedback on the 2008 TAPs to consider developing a cross-theme action, and uses the evidence-base from a series of commissioned scoping reports.[23] The action is important in delivering SUNR Challenge 4, with the goal of weighting appropriately the environmental consequences of decisions relating to natural resource use. The desired outcome is the promotion of natural resource use centred on science-based metrics using indices such as carbon sequestration, soil quality, water, and ecosystem services as well as on more commonly used indicators linked to health, food, energy production and wealth generation.

FUTURE AREAS OF SCIENCE FOR THE SUNR THEME 2010-13

The activities outlined below do not need a decision by SISB in 2009 but indicate the areas of science that the theme will develop to deliver the challenges and address any imbalances in the relative prioritisation between theme challenges shown in Table 1. Indicative funding scenarios are summarised in Appendix 1.

MEETING CHALLENGE 1 - Extending the Resource Base

Table 1 highlights the relatively slow progress in delivering the science in this challenge area. Future activities will develop two activities in the short-term (2010 TAP) and explore further one activity in the long-term linked to the proposed Arctic initiative. The first activity will scope the science challenges in relation to the security of minerals and metals supply. The second will evaluate whether combined novel measurement and modelling approaches can quantify the distribution of gas hydrates and predict the environmental implications of their exploitation. It may be possible for the NERC methane network to scope this activity, and provide an input to the Arctic initiative (below). The rationale for developing this area is it addresses two of the three strands of Challenge 1 in the SUNR Theme Report relating to '*making better use of existing resources*' and '*tapping new resources.*'

Natural Resource Use in the Arctic The proposed Arctic initiative offers an opportunity to explore the implications of a changing Arctic environment for the exploitation of resources such as methane hydrates (identified as a future action in the 2008 TAP). The SUNR theme is not part of the initial phase of the action because the focus is on understanding interactions of the atmosphere, sea-ice, ocean and terrestrial systems and the links and feedbacks between them. Additionally, the research community interested in natural resource issues in the Arctic is small and would need to grow before a specific activity in the SUNR theme is proposed. More critically, the science questions that need addressing from the SUNR perspective are not yet clear. Any SUNR investment in the Arctic is unlikely to come into place before the 2011 TAP.

MEETING CHALLENGE 4 - Valuing Environmental Services

Climate Change Impacts The resolution and sensitivity of existing models and the quality of the available data on which to test the models limit our current understanding of the impact of climate change on natural resources. Consequently, we are not able to value, using appropriate science-based metrics, the impacts of climate change on the sustainability of natural resource use, so we are unable to make decisions about their protection or exploitation in the long-term. The rationale for SUNR involvement in this future action is it may provide a model platform at an appropriate resolution from which to build appropriate metrics into valuation methodologies. This activity will also part-support

[23] Hattam et al. 2009 Valuation of Natural Resources: review of state of science at NERC RCCs, PML/BGS/CEH 48pp. Austen et al. 2009 Valuation of Biodiversity: review of state of science at NERC RCCs, PML/CEH/York University 45pp. Graves et al. 2009 Valuation of Natural Resources. Cranfield/Nottingham 136pp. Raffaelli et al. 2009 Valuation of Biodiversity. York/Leeds/PML 133pp

the delivery of Challenge 3 by capturing soil and water process understanding and their sensitivities in climate impact models.

EXISTING MAJOR INVESTMENTS

OVERVIEW

The total estimated contributions of existing (pre-2008) *and* 2008 TAP investments to the SUNR theme is **£42.61m**, comprising £34.24m (80%) directed programmes (DP), £3.1m (7%) in the Research and Collaborative Centres (RCCs), and £5.27m (13%) as consortium grants.[24]

All major DP mapped onto the SUNR theme is either cross-Council (TSEC, RELU) or strategic (ESPA). Small contributions come from QUEST (£2.3m) and UKPOPNET (£0.16m) and two RCC-related initiatives: EHFI (£1.5m) and Sustainable Marine Bioresources (£1.15m). Of the DP investment, only 7% is current because 33% (£10.73m) is *new* investment via the 2008 TAP and has yet to start delivering the theme challenges, and 60% (TSEC, £11.3m; RELU £6.3m; QUEST £2.3m) is ended. Research activity needs to grow to prevent the loss of capacity in the SUNR theme area, and to ensure effective deployment of the skills-base developed in pre-2008 investments. It is anticipated that the small (7%) RCC contribution to the SUNR theme will grow through opportunities created in new DP.

CHALLENGE 1 The TSEC legacy provides some of the research capacity to develop Challenge 1, although the focus was primarily on technologies and policy and not directly aligned to the NERC research community. To meet the gap in research capacity in Challenge 1 the research community needs to grow and/or refocus through targeted research programmes and partnerships, through UKERC phase 2, and through RCEP. This accounts for the relatively slow start in delivering this challenge. There is one major (£2.96m) consortia of high relevance to Challenge 1 on the fate of CO_2 in geological reservoirs. There is significant science capacity in this challenge area in BGS.

CHALLENGE 2 has the smallest DP and RCC alignment of all the SUNR challenges: there is a notional 10% (£1.05m) contribution via RELU and, under TSEC Biosys, some (limited) research on renewables. Gap analysis of the existing investment under Challenge 2 suggested that the research capacity must change direction and grow if it is to deliver the environmental evidence base to support major investments in renewable energy technologies both in the UK[10] and internationally. Consequently, there was significant investment in this Challenge in the 2008 TAP (£2.1m) and further proposed investment in the 2009 TAP (£3.7m).

CHALLENGE 3 The existing DP in this challenge area (RELU, £3.15m) ends in 2009 and the new SUNR investments via the 2008 TAP (£4.5m) are yet to kick-off. One cross-theme consortium on integrated carbon analysis in the Amazon (£1.45m) and three smaller consortia (total £0.86m) map onto Challenge 3. There is a large research community in this challenge area and very significant RCC capability across the atmosphere, terrestrial, freshwater and marine communities to deliver the science. This challenge has a critical role in helping to deliver LWEC objectives[19] and addressing Beddington's 'perfect storm' of interconnected food and water security risks under climate change.[15] The 2009 TAP proposes further investment in Challenge 3.

CHALLENGE 4 The existing DP in this challenge area (RELU, £2.1m) ends in 2009. There is some legacy in TSEC and a current skills base in RELU that may be used to grow the research community. However, scoping for the proposed action revealed the small and fragmented nature of

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[24]Source: NERC portfolio mapping exercise updated version, August 2009

the science community so it is necessary to build capacity here across the research councils and with stakeholder interests via LWEC. The proposal is for a 2-year (£0.5m) network in the first instance in the 2009 TAP.

WIDER STRATEGY ISSUES

Training Investment will focus on developing the skills base in environmental cyberinfrastructure to meet the anticipated step-change in the spatial and temporal resolution of data as observational capabilities, sensor networks and collaborative model platforms (e.g. OpenMI)[25] move forward under Challenge 3. The specific training need is at the postgraduate level to support the Virtual Observatory (VO) funded in the 2008 TAP. The specific skills are cross-disciplinary and are at the interface between environmental sciences and computing technologies. It is not feasible to re-focus current NERC training priorities because these are weak at addressing cross-disciplinary needs. The proposal is for £0.80m at the 100% funding scenario to support a cohort of postgraduate studentships linked to the VO based on £70k per 3.5-year studentship. The 2010 TAP will bring this action forward with the interim period used to build the appropriate partnerships to facilitate the **Knowledge Exchange** elements of the skills needed

Environmental informatics Without investment in cyberinfrastructure in terms of training and informatics, this area of NERC science will lack the data handling, statistical and interpretative skills to match the anticipated advances in observation technologies. This was the case in the early stages of Systems Biology when advances in e.g. metabolomics and proteomics, were not matched by a capability to interpret the vast amount of data they generated. Innovation in data and information management within NERC will help support the development of the VO cyberinfrastructure. This can build on national capability in e.g. the CEH Environmental Information Data Centre and through collaboration with international researchers in cognate areas (e.g. NSF CUAHSI hydrologic information system).[26]

THEME INVESTMENTS

The theme investments committed in the 2008 TAP totalled £8.23m, split between the four SUNR Challenges (C1-C4) as 19%, 26%, 55% and 2%, respectively. The SUNR theme also committed 25% (£2.5m) of the overall NERC contribution to ESPA. The investments requested in the 2009 TAP at the 100% funding level total £6.95m from an available budget range between £9.7m and £11.4m, split across the theme challenges as follows: C2 (£3.70m), C3 (£3.0m) and C4 (£0.25m). A further £4.0m is committed to support future indicative activities in Challenge 1 (£2.2m) and Challenge 4 (£1.0m), and to support the wider strategic needs of the theme through cross-disciplinary studentships (Challenge 3, £0.80m). If it were to go ahead, a future (undefined) activity in the Arctic would significantly increase the investment in Challenge 1.

There are <u>four</u> proposed actions requiring a decision by SISB. Two of the actions are SUNR alone; the other two actions are cross-theme, and the SUNR theme leads one of these. The prioritisation and size of the proposed investments in the 2009 SUNR TAP reflect the strategic science need, the capacity of the research community to meet that need, and opportunistic openings such as partnerships (e.g. with DEFRA) or critical policy-drivers (e.g. the Marine and Coastal Access Bill). Taken action by action, the justification for the proposed investments is as follows:

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[25] Open Modelling Interface and Environment OpenMI - www.openmi.org
[26] http://his.cuahsi.org/

(A) Algal Bioenergy network - the request is for a small commitment to establish a network that the Carbon Trust and the TSB KTNs have agreed to give in-kind support. The network will start to build the science-base for this nascent renewable energy technology that has little current regard for, or understanding of, the environmental implications of the proposed energy options. Through these new partnerships, the ambition is the research community will grow and future funded partnership opportunities be identified. There is significant capacity in the NERC marine centres to support the network.

(B) Marine Renewable Energy - This action could place NERC at the forefront in research to deliver environmental solutions for wave and tidal technologies, and the science to support major UK investments in offshore wind. Two commissioned scoping reports show that the research community is large, though not currently focused in this area and has the skills base to meet the science need.

(C) Macronutrient Cycles - An ambitious cross-theme programme to advance and integrate our understanding of the interplay between macronutrient cycles and climate change is proposed. The science community is large - particularly in the NERC RCCs. The delivery mechanism will focus on science at the interface between the NERC atmospheric, terrestrial, freshwater, and marine communities. NERC has significant national capability to support this action and some current investments in the research centres to help advance the science rapidly.

(D) A network for Valuing Biodiversity and Natural Resource Use - Four commissioned scoping reports demonstrated the clear science need but fragmented nature of the science community: the network will focus on and grow research capacity relating to science-based metrics to deliver valuation options. The alignment with LWEC goals is high through the support of the UK national ecosystem assessment.[19]

Algal Bioenergy Network

In the medium-term, energy derived from third generation biofuels such as micro- and macro-algae will be increasingly important as part of the energy mix both in the UK and globally.[1] As the science is at an early stage and the research community is small, the proposal is a short (2-year) network to scope rapidly the environmental science potential in this area, build the research networks and secure key partnerships. The network is an opportunity for NERC to lead and coordinate the development of the environmental science evidence base with the goal of ensuring that industry includes the environmental dimensions in developing the technologies and supply chains. The Carbon Trust endorses the network (see SUNR Strategic TAP). The Technology Strategy Board will facilitate the action through their Knowledge Transfer Network. The action will start in 2010/11 to map onto the R&D phase of the Carbon Trust's Algal Biofuels Challenge.

SCIENCE CASE

The potential of microalgae as a renewable energy source attracts much hype.[2] To be a feasible source for biodiesel, the current price for microalgae production needs reducing by at least one order of magnitude and the scale of production of lipids from microalgae needs increasing by three orders of magnitude.[3] The technology for upscaling production is in its infancy but is subject to considerable investment: the Carbon Trust is investing up to £16m in the *Algae Biofuels Challenge.*[4] In July 2009, ExxonMobil announced an investment of $600 million over 5 years to produce liquid transportation fuels from algae in partnership with Venter's Synthetic Genomics biotechnology company.[5] Interest is driven both by the potential productivity of microalgae, which is tenfold greater than that of agricultural crops and because unlike first-generation biofuels, microalgae do not require arable land, or freshwater, or compete with food production.

Like microalgae, macroalgal forests are more productive (1000-2000 $g\,C\,m^{-2}\,yr^{-1}$) than many terrestrial systems. It is feasible to cultivate macroalgae (seaweed) in open waters in the UK but the science base is limited with respect to the efficiency of use of UK seaweeds for biofuel production; the implications of cultivation on the marine water column; and the spatial sensitivity of seaweed communities to harvesting.[6] Seaweed grows best in areas of high primary productivity (e.g. rivers enriched with sewage, fish farms) and in areas of strong tidal exchange that ensure a constant nutrient supply. Combining mariculture with offshore renewable energy installations is feasible[7] but most research has focused on fish assemblages on artificial reefs, which ignores the integral role of macroalgal communities in the development of reef ecosystems.

Significant knowledge gaps exist in understanding the potential of algal-based bioenergy. Questions remain regarding whether marine biomass could be harvested from wild or cultivated algal resources; if land-based microalgae technologies can be transferred to freshwater and marine environments; and critically, in understanding the positive and negative impacts of scaling-up production on the wider environment. Some research exists on the technicalities of harvesting wild

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[1] House of Commons Environment, Food and Rural Affairs Committee 8th Report. 2006. Climate Change: The Role of Bioenergy.
[2] Green scum and great expectations. ENDS Report 413, June 2009: 32-35
[3] Wijffels. 2007. Potential of sponges and microalgae for marine biotechnology. TRENDS in BIOTECHNOLOGY 26: 26-31.
[4] http://www.carbontrust.co.uk/technology/directedresearch/algae.htm
[5] Service. 2009. ExxonMobil Fuels Venters efforts to run vehicles on algae-based oil. SCIENCE 325: 379.
[6] Stanley et al. 2009 Marine Bioenergy, NERC proof of concept report, 119pp. Available on the NERC website.
[7] Buck et al. 2004. Extensive open ocean aquaculture development within wind farms in Germany. OCEAN and COASTAL MANAGT. 47: 95-122

or cultivated algal resources.[8] New work, including that in NERC Centres[9] is evaluating options for contender species. Most research programmes are at an early stage and would benefit from a network to exchange knowledge on the environmental implications of energy generation from this source.[10] There are potential biosecurity risks from large-scale cultures or algal farming and harvesting whose effects on ecosystems could be immense.[11]

The high-level science goal is to understand the opportunities and risks to the quality of freshwater and marine environments of using algal biomass as a source of renewable energy. Some of the secondary goals that the network could develop into future research proposals include:

(1) Identifying the possible feed stocks and conversion technologies that may emerge over the next 10 years for deployment, including evaluation of micro- vs. macroalgae options and freshwater vs. marine.

(2) Assessing the environmental implications of imports of algal resources for bioenergy use.

(3) Predicting the environmental consequences of the deployment of micro- and macro-algal systems in the UK for bioenergy and other value-added co-products.

The key anticipated outcome is the generation of opportunities for the research community to focus on developing the evidence base to inform decisions on e.g. the best algal feed stocks for the UK; the most appropriate locations and environmental implications of macroalgal production; and predictive modelling of the implications of scaling up microalgae production on the environment. Critically, the network enables early evaluation of the environmental and economic impact of algal bioenergy through development of a 'sustainability framework' using analogues developed for terrestrial bioenergy deployments.[12] The network will also ensure close engagement with technological developments in this area.

EXISTING INVESTMENTS AND NATIONAL CAPABILITY (NC) NEEDS

NERC has significant capacity in the marine and freshwater sciences community to form a network to deliver a science-based evaluation of the opportunities for algal biomass as an energy source. There are no existing major NERC investments in this area as it is a recent technology. Table (A) gives the existing NC and external funding in the RCCs. Notable are the Culture Centre of Algae and Protozoa (CCAP) hosted at SAMS, and expertise in photobioreactor technology at PML. Also shown are the major investments funded by RCUK and Industry. As the proposal is for a network, there is no need for new NC and there are no major logistical requirements.

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[8] National Renewable Energy Lab 1998. NREL TP-580-24190 Aquatic Species Programme: Biodiesel from algae, 328pp

[9] http://www.biomara.org/ EU (Interreg IVA) BioMara: Sustainable fuels from Marine Biomass, €6m (2009-2012) led by SAMS (see Table 1)

[10] NERC SUNR Marine algal bioenergy workshop, London, 29th September 2008

[11] Bagla. 2008. Seaweed invader elicits angst in India. SCIENCE 320: 1271.

[12] Global Bioenergy Partnership: www.globalbioenergy.org

Table (A) NERC National Capability, relevant externally funded research in NERC Centres and RCUK funding

DESCRIPTION	LEAD CONTRACTOR	FUNDING SOURCE	SUMMARY	VALUE & TIMESCALE
Culture Collection of Algae & Protozoa (CCAP)	SAMS	NERC National Capability	National collection (~2500 strains) of marine, freshwater and terrestrial algae, protozoa and cyanobacteria. Provides genomics and strain repository; molecular services; species identification; and services for aquaculture and biotechnology, in collaboration with European Centre for Marine Biotechnology www.ecmb.org	~8 FTE
BioMara: Sustainable fuels from Marine Biomass	SAMS	EU (Interreg IVA)	Methodologies to harness algal biomass from macro and microalgae as a biofuel source	~ € 6m (2009-12)
ISMAR: Extraction of active compounds from marine microalgae	PML/ PML Applications Ltd	DTI (DBERR)	Approaches to scale-up microalgae culture process and recover high value bioactives	£534k (2006-09)
Biorefinery carbon capture as direct replacements for petro-chemicals	PML/PML Applications Ltd	Technology Strategy Board	Methods to optimise commercial biosynthesis of PHA and antioxidants in CX86 (proprietary thermophilic algal strain)	£896k (2009-11)
YASMIN: Optimising yield of antioxidants in microalgae	PML	BBSRC	Photobioreactor technology to optimise bioactive yield via biosynthetic pathways and conversions and using waste CO_2 and NO_x emissions to enhance growth of microalgae	£294k (2007-10)
RELEVANT RCUK FUNDING OUTSIDE NERC CENTRES				
SUPERGEN Phase 2	Aston University	RCEP	Bioenergy consortium (marine sub-theme, *c.* £500k)	£6.4m (2007-11)
Bioenergy Centre	Six research hubs	BBSRC	Sustainable Bioenergy Centre (Cambridge, Dundee, York, Nottingham Universities & Rothamsted Research	£27m (2008-13)
RELEVANT INDUSTRIAL FUNDING				
Algae Biofuels Challenge	Under review, decision August 2009	Carbon Trust	Development and commercialisation of microalgae biofuel technologies with potential to reduce CO_2 emissions. c. £500k per project; £3-6m available.	£20-£30m (2010+
Seaweed Anaerobic Digestion	At tender stage	ITI energy	Anaerobic digestion of macroalgal biomass	£3.2m

Note: there are various projects under review in EU FP7 in the Life Sciences, Energy and Environment areas totalling c. €4m. The new Japanese *Ocean Sunrise Project* on seaweed bioethanol production will produce bioethanol from farming *Sargassum horneri* over 4.47 million km^2 of unused areas of their exclusive economic zone.

Marine Renewable Energy

The Climate Change Act 2008 sets a target of an 80% reduction in greenhouse gas emissions below a 1990 baseline by 2050.[1] The expansion of renewable capacity is part of the solution. In 2007, 1.78% of energy used in the UK was from renewable sources such as hydro and wind.[2] The target by 2020 is 15% of all energy (electricity, heat and transport) from renewables. Land constraints favour energy generation from offshore wind[3] and 'wet renewables' (tide, wave), although the technology for the latter is immature.[4] The UK has significant capacity to develop further its marine renewable energy sources because of its extensive (20,000km) coastline, high winds, strong currents and large tidal range. The UK marine environment extends over 710,000km^2 of sea and seabed habitat to a depth of some 2500m. Harnessing its energy is a major engineering challenge reliant on a limited environmental evidence base e.g. only 10-15% of the biological data required to regulate effectively human activities in relation to UK continental shelf waters currently exists.[5] Despite this challenge, incentives are in place to develop the technological capacity quickly for deployment in coastal and shelf seas in the medium-term: wave, tidal stream, tidal barrage and lagoon technologies have the highest banding for renewables obligations in the 2007 Energy White Paper. As part of the recent Low Carbon Transition Plan[6] DECC announced up to £60m support for the wave and tidal sector and a further £120m to advance offshore wind.

Marine renewable technologies place structures on and above the seabed that add physical complexity to areas where it did not exist before. Such structures provide new surfaces for the attachment of epibenthic flora and fauna, provide a trophic focus and a refuge for fish populations, and modify sediment regimes and water column structure and flows.[7] The exact nature, scale and significance of these biophysical changes for a particular location depend on the size and spatial arrangement between structures within the larger field; on the prevailing physical, chemical and biological characteristics of the location; and on the physical characteristics of individual structures. Although there is considerable research on offshore wind energy, the science base addresses short-term issues at installation or array scale: we are unable to forecast the implications of deploying renewable infrastructures over larger spatial scales or under a changing climate. Wave and tidal stream devices are at an earlier stage of deployment. Their small, modular form presents science challenges in relation to their spatial arrangement, degree of connection between these units (alignment, pattern), and whether there is potential for whole system benefits (e.g. fisheries protection zones).

An exceptional opportunity exists for NERC to lead and deliver the environmental science to predict the outcomes of marine renewable energy deployment tensioned against other demands on the marine environment such as the establishment of Marine Protected Areas under the EU Marine Strategy Directive.[8] The evidence base does not exist at present to support strategic decisions on how

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[1] Committee on Climate Change. 2008. Building a low-carbon economy –The UK's contribution to tackling climate change. First report December 2008.
[2] BERR, Digest of UK Energy Statistics, 2008, Table 7B, HMSO
[3] £525m funding for offshore wind energy in 2009 budget http://www.hm-treasury.gov.uk/Budget2009
[4] Parliamentary Office of Science and Technology, POSTnote 324, Marine Renewables, January 2009, 4pp
[5] Science and Technology Committee, Tenth Report of Session 2006-07. HC 470
[6] http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx
[7] NERC scoping report (2009) Ecological benefits and impacts of large-scale offshore and coastal renewable energy, PML/SAMS/Hull, 124pp
[8] Parliamentary Office of Science and Technology, POSTnote 310, Marine Conservation Zones, January 2008, 4pp

to maximise energy generation from a spatially and temporally variable supply:[9] we need this to minimise deleterious changes associated with near-shore, downstream and field-local environments that may be in conflict with other requirements such as protection of bioresources in marine conservation areas in support of the forthcoming Marine and Coastal Access Bill.

The high-level science goal is to:

- Understand the environmental benefits and risks of upscaling marine renewable energy schemes on the quality of marine bioresources (including biodiversity) and biophysical dynamics of open coasts.

A secondary goal, which will be addressed with partners is to:

- Predict the long-term security of wave and wind energy potential in marine environments under a changing climate.

Key anticipated outcomes are: (1) the evidence base to predict the environmental implications of future marine renewable energy options at appropriate scales, and (2) the research capacity to deliver decision support about the biophysical properties of coastal and marine environments to promote offshore and near-coastal renewables development with enhanced environmental benefits.

EXISTING INVESTMENTS AND NATIONAL CAPABILITY (NC)

Table (B) shows the existing NC to support the action. No new NC is proposed but there may be a future need for access to undersea wave hub observatories. The symbol C against the RCC activities indicates research outcomes that will align with the goals of the action. The NERC Oceans 2025 programme is an exemplar of the cross-disciplinary working needed to deliver this action, and has the NC and baseline data (e.g. ocean circulation, sea level/climate models and wind-stress climatology) to support it.

New or existing structures exist as demonstrator sites to test the science so reducing the logistical challenges of this action. Both the European Marine Energy Centre (EMEC)[10] in Orkney and the Cornwall WaveHub[11] were engaged in helping shape the action[12] and can facilitate monitoring of changes in sediment transport, wave (height, frequency), wind (vector, strength) and benthic/fishery benefit. Wave Hub and EMEC received £9.5m and £8m, respectively under DECC's Low Carbon Transition plan, with a further £22m for a Marine Renewables Proving Fund for testing and demonstrating wave and tidal technologies.

PARTNERSHIPS AND STAKEHOLDER ENGAGEMENT

DEFRA and TSB will partner the action and other partnerships will be explored. To cement the partnerships and broader stakeholder engagement a capacity-building phase is included in the action delivery.

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[9] Pöyry. 2009. Impact of intermittency: how wind variability could change the shape of British and Irish electricity markets. 30pp

[10] EMEC is a consortium of Scottish Government, BERR, Carbon Trust, Scottish Enterprise, Orkney Islands Council + European support

[11] See www.wavehub.co.uk - £28m from South West RDA + £6m for Peninsula Research Institute in Marine Renewable Energy (www.primare.org)

[12] NERC workshop report, Marine Renewable Energy, 26th Feb 2009, 15pp

ACTION INVESTMENTS AND RESEARCH PROGRAMME (RP) DELIVERY MECHANISM

The RP will focus on the UK continental shelf and will contribute to the Research Councils Energy Programme. The main pathway for economic impact is working with the companies developing and implementing the technologies at EMEC/WaveHub. The direct cost to NERC comes in supporting the capacity building to facilitate this engagement.

Table (B) Major existing investments (NC and RP) relevant to the SUNR action

NERC RCC	DEPLOYMENT OF EXISTING NC TO SUPPORT PROPOSED ACTION	D/C
BGS	Coastal seas observing systems, seabed and habitat mapping Marine Data Archive Centre	D D
NCEO	Remote sensing capability: satellite altimetry, Synthetic Aperture Radar, High Frequency (HF) Radar, Marine X-Band Radar	C
NOCS	Oceans2025 Theme 8 (WP 8.3 Towards multi-use of data) Coastal seas observing systems, seabed and habitat mapping	C D
PML	Oceans2025 Theme 9 (WP 9.6 Development of next generation of hydrodynamic-ecosystem models; WP9.7 Reducing uncertainties to improve operational forecasts, climate change simulations and environmental risk assessments) SO10 Western Channel Observatory (PML/MBA) Coastal and inshore vessels	C C[†] C[†]
POL	Oceans2025 Theme 8 (WP 8.6 Telemetry) Irish Sea Observatory SO7 UK contribution to the GLOSS sea level network NF1 British Oceanographic Data Centre, BODC Marine facilities and services	C C[†] D D C
SAMS	Oceans2025 Theme 8 (WP 8.8 Water column and sea-bed platforms) Marine facilities and services; coastal and inshore vessels	C C
SMRU	SO14 Long-term observations of marine mammal population dynamics	C
EXISTING RESEARCH PROGRAMMES (RP) - PROGRAMME AND KEY PROJECTS		
BGS	Marine Geoscience Programme (E3074S Offshore Quaternary Mapping and Thickness)	C
NOCS	Oceans2025 Theme 1 (WP 1.4 Risk assessment of 21st century climate change) Oceans 2025 Theme 5 (Application of scientific knowledge to the management of ocean resources (UNCLOS)	C C
PML	Oceans 2025 Theme 3 (Environmental impacts of global change on ecosystem function in estuaries and coastal seas) Oceans2025 Theme 4 (Marine biodiversity and ecosystem function) UKERC Phase II Energy and Environment Theme (with POL)	C C C
POL	Oceans 2025 Theme 3 (WP3.5 Coastal morphodynamics and bathymetric evolution) Oceans 2025 Theme 6 (WP 6.1 Decadal variability of the northwest European shelf seas)	C C

SAMS	Oceans2025 Theme 3 (Topographic regime control over shelf sea systems) Oceans2025 Theme 4 (Marine biodiversity and ecosystem function)	C C
OTHER RELEVANT FUNDING		
POL	JOULE (JIRP106/03 (Liverpool/POL) Tapping Tidal Power Potential of the Eastern Irish Sea)	
EU FP7	EQUIMAR (Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact - involves EMEC, SAMS, SMRU)	
MBA	WaveHub (Understanding space use of fish in relation to Wave Hub)	
PML	Energy Technologies Institute (pilot programme on marine energy Project ReDAPT to test and install a 1MW tidal turbine at EMEC Orkney to deliver detailed environmental and performance information, www.energytechnologies.co.uk)	
RCEP	SuperGen Marine energy research consortium	
International A large number of marine renewable options (wind, wave, tidal) are planned or operational. These are given in Annex of the NERC Marine Renewable Energy Scoping Studies available on the NERC website.		

D = dependency
C = contribution to action.
C = existing priority investment where outcomes will align to the needs of the proposed action

†For NC in specific locations whether it is a 'dependency' or 'contribution' to the action will depend on the geographic focus of the research.

Macronutrient Cycles (SUNR, BIOD, EP&HH, ESS, TECH)

Macronutrient cycles - nitrogen (N), carbon (C) and phosphorus (P) - are pivotal in the stability of global biogeochemical cycles, in sustaining natural resources and in protecting human health and biodiversity. Human activities have enhanced global cycles of N and P by on average 100% and 400%, respectively.[1] Our perturbation of these natural cycles is changing the balance of *interactions* between them but the singular focus on C cycling in climate change research constrains our understanding of feedbacks between cycles and may result in unintended outcomes as our effort shifts to mitigating climate change impacts.

Globally, N used in food production and in fossil fuel combustion contributes *c*.160 Tg N annually to the N cycle, exceeding that supplied naturally by biological N fixation on land (1.5*x*) or in the ocean (1.1*x*).[2] Phosphorus is the linchpin for metabolism in biological systems, accounting for *c*.2-4% of the dry weight of most cells. Yet it is present in minute quantities in the Earth's crust (0.09wt%) and has no stable atmospheric gas phases. Consequently, ecosystems depend on its aqueous transfer and because ambient pools are small in natural habitats, P *flux* not quantity has evolved as the critical ecological driver.[3] Human inputs of P from sewage, industry and agriculture have hugely distorted this balance. In its most bioreactive form, the net input of dissolved P from land to coastal waters is double that of pre-human input fluxes (*c*.4-6 Tg P a^{-1}).[4] Elevated N and P compromise the ecosystem services on which we depend through degradation of natural resources (soils, freshwater) and loss of biodiversity; they affect human health through poor drinking water quality and for N, through reductions in air quality. Evidence is growing that aquatic nutrient enrichment strongly influences the fate and effects of other non-nutrient contaminants, including pathogens.[5] Profound ecosystem-level changes are now evident. Globally, dead zones (hypoxia) cover an area of *c*.500, 000km^2 but predominate in coastal shelf seas important for bioresources with consequent economic impact.[6] Highly contested is the claim that exclusive focus on P control in rivers has exacerbated N-limited downstream eutrophication in estuaries and coastal waters.[7] Dual N and P control along the entire freshwater-marine continuum may be the solution.[8] Similar debates exist in the atmosphere-terrestrial-freshwater domain linked to the yet unresolved contribution of anthropogenic N to a changing climate.[3]

The **overall goal** is to quantify the scales (magnitude and spatial/temporal variation) of N and P fluxes and nature of transformations through the catchment under a changing climate and perturbed C cycle. We define 'the catchment' as covering exchange between the airshed[9] and land surface through to the estuaries.

Delivery of the overall goal is through three **secondary goals** linking different science areas and a fourth goal concerned with impacts. All science goals have technology science challenges embedded

[1] Falkowski et al. 2000 The global C cycle: a test of our knowledge of Earth as a system. SCIENCE 290: 291–6.
[2] Gruber and Galloway 2008 An Earth-system perspective of the global N cycle. NATURE 451: 293-6.
[3] Karl 2000 Phosphorus, the staff of life. NATURE 406: 31-3.
[4] Filipelli 2008 The Global P cycle: past, present, and future. ELEMENTS 4: 89-95.
[5] Smith and Schindler 2009 Eutrophication science: where do we go from here? TRENDS in ECOLOGY and EVOLUTION 24: 201-7.
[6] Diaz and Rosenberg 2008 Spreading dead zones and consequences for marine ecosystems. SCIENCE 321: 926.
[7] Conley et al. 2009 Controlling eutrophication: N & P. SCIENCE 323:1014-5; Schindler & Hecky 2009 More N data needed. SCIENCE 324: 721-2
[8] Paerl 2009 Controlling eutrophication along the freshwater–marine continuum. ESTUARIES and COASTS 32: 593-601.
[9] http://en.wikipedia.org/wiki/Airshed

in them. These goals must interface with one another to deliver the overall science goal and significant resource is allocated in the programme for this role (later).

S1 To evaluate the nature and scale of macronutrient (N, C) exchange between the airshed and terrestrial system and consequences for losses (N, P, C) to freshwater and atmosphere systems (atmosphere-terrestrial-freshwater feedback system).

S2 To determine the role and spatial and temporal variation of macronutrients (N, P, C) on key limiting processes and ecosystem functions (i.e. decomposition, productivity) and consequent export at the catchment scale (terrestrial-freshwater systems).

S3 To advance understanding of the co-limitation of N/P for eutrophication control along the entire freshwater system to the estuarine boundary (freshwater system).

S4 To determine the implications of nutrient enrichment on the fate and effects of other non-nutrient contaminants, including impacts on human health (i.e. pathogens, ozone) and biodiversity.

Whilst NERC has invested in research on single nutrient cycles in the past e.g. N (GANE) and C (TIGER), and attempted cross-sector integration (LOIS), two critical developments drive the need for this action now:

First, no prior programmes addressed *integrated* macronutrient cycles through simultaneous estimation of N, P, C cycling, and their feedbacks. Nor have they addressed the challenge of understanding system thresholds and cascades with respect to macronutrients. New research in *Nature*[10] and *Science*[7,11] is emerging to suggest the lack of integrated analysis is short-sighted; may lead to unforeseen consequences for our natural capital through e.g. N saturation and prolonged eutrophication; and could result in assumptions being built into predictions of climate change impacts that are misleading.

Second, recent technological advances now enable the direct quantification of fluxes and transformations in coupled macronutrient cycles only inferred in previous programmes. There are major advances in e.g. automated sensor technologies and isotopic techniques that allow speciated monitoring, unravelling previously encoded information on the transformations and cycling of macronutrients. Advances enable e.g. quantification of N fluxes in gases and aerosols and new techniques to unravel P biogeochemistry via e.g. sequential enzymatic hydrolysis.[12]

Building on these critical advances, this action will integrate the observation and modelling of macronutrient cycles at a range of spatial and temporal scales using the catchment (100’s to 1000’s km^2) as the basic research scale. Operationally, the objective is to unpick the contributions and feedbacks across scales by integrating: atmospheric exchange at short (seconds-hours) timescales and its buffering at the land/freshwater surface (**S1**); terrestrial and freshwater transformations and macronutrient flow pathways in rivers at timescales from days to weeks across sub-catchments (10’s to 100’s km^2) (**S2**).

Key anticipated outcomes include first, improved fundamental understanding of N, P and C biogeochemical cycles leading to a quantitative understanding of the impact of macronutrient fluxes on the capacity of the biosphere to sequester CO_2 from the atmosphere and on risks to the quality of soil and freshwater resources and biodiversity. Second, the evidence base to quantify N attenuation in the system together with the role that other macronutrients have in this process (e.g. C/N and N/P).

EXISTING INVESTMENTS AND NATIONAL CAPABILITY (NC)

Table (C) shows the deployment of existing NC to support the action. The relevance of some NC[†] depends on where observations are needed. There is no need for new NC, and there are no

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[10] Bardgett et al. 2008 Microbial contributions to climate change through carbon cycle feedbacks. ISME Journal: 1-10.

[11] Galloway et al. 2008 Transformation of the N cycle: recent trends, questions, and potential solutions. SCIENCE 320: 889-92.

[12] Monbet et al. 2009 Dissolved organic P speciation in the waters of the Tamar estuary, England. GEOCHIMICA et COSMOCHIMICA ACTA 73:1027-38.

dependencies in the existing RCC activities but indicated by the symbol C are the large RCC activities whose outcomes can contribute positively to the action.[13]

No current directed programmes or consortia contribute to this proposed action. Directed programmes that are ending (QUEST, RELU) have helped develop the cross-disciplinary research communities needed to deliver this action. New programmes (Ocean Acidification, Changing Water Cycle, Virtual Observatory, VO) offer platforms into a broad research community; ESPA and a number of European programmes (e.g. NitroEurope[14], NiNE[15], COST869[16]) facilitate international linkages.

ECONOMIC IMPACT

A pathway to economic impact lies in harnessing new technologies and building the knowledge base to inform measures to balance sustainable natural resource use with food security needs, particularly in the context of reducing the cost to the economy of treating nutrient pollution of freshwater, marine and atmospheric sectors. Alignment with the TSB Sustainable Agrifood Innovation Platform[17] is agreed and will help deliver NERC's goal of working with partners to develop a major role for environmental research in the green economy.[18] TSB and partners are investing £10m per year over 5-years in the innovation platform.

Table (C) Major existing investments (NC and RP) across all five themes contributing to the action

NERC RCC	**Deployment of existing National Capability (NC) to support proposed action**	**D/C**
CEH	Environmental Information Data Centre (EIDC)	D
CEH/BGS	Pang and Lambourn Observatory	C†
NCAS	Facility for Airborne Atmospheric Measurements (FAAM) Weybourne Atmospheric Observatory	D C†
POL	Irish Sea Observatory	C†
PML	Western Channel Observatory WP 9.5 Simulation of carbon, nutrients & production of climate-active gases in marine ecosystems (underpinning modelling capability)	C† C
NOCS	Ferry box (Portsmouth-Bilbao) *(nb: externally funded DEFRA + Private sector)* Oceans2025 WP 8.1 4D Biogeochemical sensors	- C
SAMS	Oceans2025 WP 8.7 Sensor optimisation; WP 8.8 Water column & seabed platforms	C
BGS	Surveys and mapping; Groundwater sampling, analysis and monitoring	D
NCEO	NERC EO data centre	C
Existing Research Programmes (RP) - Programme and key projects		
BGS	Land Use and Development (E2086S87 Carbon and peat dynamics, E2089S87 Soil Processes & Geochemistry) Groundwater science resources (E2069S81 Groundwater- surface water interaction; E3344S Agrochemicals in aquifer systems)	C C
CEH	BD-1 Observations, patterns & predictions for biodiversity (BD-1.3 Long-term/large-scale monitoring and experiments to detect a environmental change) BD-3 Managing biodiversity & ecosystem service in changing environment	C C

[13] Discussed with RCCs at a NERC workshop on 12 May 2009
[14] www.nitroeurope.eu
[15] www.nine-esf.org
[16] www.cost869 Mitigation Options for Nutrient Reduction in Surface Water and Groundwaters
[17] http://www.innovateuk.org/ourstrategy/innovationplatforms.ashx
[18] NERC 2008-09 Annual Report, p7

	(BD-3.1 Methods to quantify the link between biodiversity and the provision of ecosystem goods and services) WA-2 Ecohydrological processes (WA-2.1 Sources, fluxes and pathways of water, chemicals and sediments) BGC-1 Monitoring & interpretation of biogeochemical & climate changes (BGC1.1 Concentrations, fluxes & forms of current/emerging pollutants; BGC1.3 Changes in biogeochemical cycles and implications for ecosystem function) BG-02 Biogeochemistry & climate system processes (BGC2.2 Surface atmosphere exchange of energy, carbon, and water and responses to land use and climate change)	C C C
NCEO	Theme 3 Atmosphere (Sub-Theme 2: Quantification of trace gas / aerosol distributions and emissions	C
NOCS	Oceans2025 Theme 2 (WP2.5 Physical processes & supply of nutrients to photic zone)	C
NCAS	Decadal and regional climate change (S6: Emerging issues in modelling chemistry/climate interactions) Improving prediction for human exposure to air pollution (AP2 Production, transport and removal of photochemical oxidants)	C C
PML	Oceans2025 Theme 2 (WP 2.2 Microbial cycling of the major elements; WP2.3 Quantifying impact of high CO_2 world on marine biogeochemical cycles) Oceans2025 Theme 3 (WP 3.12 Environmental impacts of global change on ecosystem function in estuaries & coastal seas; WP 3.11 Implications of biotic processes for ecosystem functioning) Oceans2025 Theme 4 (WP 4.1 Scales of variation in biodiversity in coastal and shelf seas using western channel observatory)	C C C
SAMS	Oceans2025 Theme 3 (WP 3.7: Role of topography in determining the spatial variability in horizontal dispersion; WP 3.8 Pelagic & benthic biogeochemical processes) Oceans2025 Theme 4 (WP 4.5 Microbial mediation of primary productivity and algal biodiversity)	C C
International	Links to international activities include: LIFEWATCH, SOLAS, and JULES; ESF NiNE (Nitrogen in Europe), NitroEurope, IMBER, LOICZ, ESSP, COST869 and CGIAR	

D = dependency
C = contribution to action.
C = existing priority investment where outcomes will align to the needs of the proposed action
†For NC in specific locations whether it is a 'dependency' or 'contribution' to the action will depend on the focus of the research, which is not known at this stage.