Unlocking the potential of sensors for our environment

A call to action from a NERC writing retreat

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Summary

Funded by UK Research and Innovation (UKRI), the Constructing a Digital Environment Strategic Priorities Fund (CDE) programme aspired to support the development of a comprehensive 'digital environment' ecosystem that best served scientists, policymakers, businesses, and communities. Emphasising multi-disciplinary and inter-disciplinary collaboration, CDE supported a team of challenge-focused researchers from a variety of disciplines to bring to the fore current and future digital advances in sensors that are critical to addressing environmental concerns. From March 2023 to January 2024, the team worked together to develop frameworks that sought to optimise the benefits of both existing and emerging sensor network technologies and their related infrastructure.

Central to the development of these frameworks was a co-creation writing retreat in July 2023, where we came together to discuss the environmental sensing ecosystems unmet needs and challenges around five themes: **Values**, **Changes**, **Barriers**, **Tools**, and **Lessons**.

The resultant findings and call for action suggest that:

A. Focusing on **People**, **Places** and **Ethics** when making decisions on the whole sensor systems lifecycle (sensor design, deployment, application, and uptake) can ensure that research is more holistic, relevant, ethically sound, innovative, and, at the same time, has the potential for real-world impact.

B. There is a clear need for a better-enabled sensor 'development and use' ecosystem (i.e., frameworks, methodologies, designs, communities) that has strong foundations and support for collaborative and interdisciplinary research to drive ambition for responsible innovation and resilient research communities.

Overall, the findings highlight the vast potential offered by increased sensor utilisation for science and society, as well as broader concerns around data practices and innovation and specific challenges to sensors and sensing for the environment. There is a greater need for responsible data sharing, standardisation and quality assurance, as well as enhanced interdisciplinary collaboration and knowledge transfer between academia and industry. Furthermore, sector-specific barriers to recruitment and retention (particularly from those traditionally underrepresented in the sector) need to be addressed if transformative research is to be delivered and sustainable ecosystems that are diverse and inclusive are to be created.

Key findings and unmet needs:

I: The environmental sensor ecosystem as a trusted authority

To maximize the benefits of environmental sensing and build robust sensor ecosystems, it is crucial to continuously demonstrate trustworthiness to the public, researchers, and commercial entities, thereby enhancing the potential to retain and increase confidence in sensors, sensing methods, and design and data processes.

Unmet needs:

- **Codified ethical practices and processes** that recognise the discrete challenges within the sensor ecosystem – including but not limited to improving policy, regulations, tools, and data collection, management, archiving and storage.
- **Standardisation of environmental sensing data (including metadata)**, in-line with other research on data rigour and governance, in particular, around data and discoverability, processes and benchmarking that can allow for cross-discipline activities.
- **Greater opportunities to share insights**, including lessons learnt from technical failings of sensors and failings of the existing sensor ecosystem. This will facilitate, accelerate, refine and improve sensor accuracy and precision to aid informed decisions, whether in scientific research, environmental monitoring, or everyday applications.
- **Focused investment in support of data coherency** in order to facilitate more accurate analysis and interpretation, enabling novel environmental research and aiding policy-making goals.

II: Accessing the benefits of sensors and sensing for the environment for all

Within the realm of environmental sensing, there is clear contested territory between environmental impact, economic interest, policy making, and the U.N. Sustainable Development Goals. Opportunities to explore this intersection space are critical. These include interrogating the role that researchers can play in addressing public and private concerns on environmental sensors and/or how the digital environment interacts with the material world.

Unmet needs:

- **Frameworks need to be devised that leverage interdisciplinary and transdisciplinary collaboration** which support creative solutions and engagement with communities.
- **Development and sharing of best practice examples and principles** for the effective implementation of outreach activities and initiatives that prioritise and maintain the dignity, rights, safety, and well-being of all participants.

III: Building researcher capacity through transformative communities of practice

There is growing concern about the lack of strategies across the environmental sensor and system to maintain and grow expertise and capability, including the retention of skilled personnel within research teams.

Unmet needs:

- **Development of a central UK sensor hub** for researchers working with environmental sensors that encourages disruptive thinking and challenges established notions about sensors and the digital environment, leading to more nuanced and innovative solutions through the diversity of thought.

The retreat: aims and knowledge generation approach

Aims

The co-creation process and the writing retreat aimed to cultivate novel perspectives from expert participants on the digital environment, with a focus on acknowledging and responding to **people**, **places** and **ethics**. Additionally, the retreat served as a platform to identify both current and future challenges within the environmental sensing discipline and its practice. It allowed us, as participants, to confront and strategise around areas for improvement to address the broader challenges within the UK sensor research and innovation ecosystem. One of the retreat outputs is this paper, which is intended to:

i. Inform funding calls, promote innovation and encourage more interdisciplinary research in environmental sensing.

ii. Be of use and importance to the key stakeholders in the environmental sensing ecosystems, from researchers to environmental conservationists, funders and other vested interested bodies in sensors.

Aims & approach

In synthesising current advances in environmental sensing and sensor networks, those attending paid special attention to best techno-social practices in environmental sensor systems, current and future barriers to innovation, and improving the workplace culture.

Knowledge generation approach

The content of the briefing paper is drawn from a thematic analysis of texts, videos, and images collected between March – July 2023 from 23 researchers from 15 different universities and research centres across the UK. The analysis includes 78 minutes of video content, 20 images, 13 presentation slides, 14 ‘So what’ models,[i] 17 pages of handwritten notes, 8,767 words across five documents, and 35 sticky notes.

Before the retreat, each researcher was assigned to one of five ‘challenge group’ themes (Values, Changes, Barriers, Tools, and Lessons), each with a pre-set question (Table 1).

Table 1: Challenge group themes and questions

Value	1. What is the greatest value to economic, social, political and other dimensions from environmental sensors and sensing in various domains, such as water, air, etc?
Change	2. Considering a whole society approach to the design, implementation, use and exploitation of sensors, what would you change about the environmental network ecosystem to better unlock its value?
Barriers	3. What are remaining barriers to unlocking value from environmental sensors and sensing, in particular within the Digital Environment context?
Tools	4. What tool brings together technologies, techniques, sponsors, and governmental parties to help ease the productisation of environmental sensors and sensing and associated data-to-knowledge pipelines?
Lessons	5. What are the best lessons learned from design and deployment, usages and exploitation of environmental sensors and sensing? Are there cross-domain common lessons? What are the pitfalls of the environmental sensors and sensing technologies that cross domains? Are we learning enough from failure?

In groups of 5-6, we attempted to respond by employing creative and innovative thinking techniques and methods to foster new understandings surrounding environmental sensors and sensing.[1] This also allowed greater methodological freedom for the knowledge generation process, drawing from across disciplines and theorising from the bottom up as well as from the top down to produce new questions, interpretations, and knowledge. For example by asking participants to share photos that depicted 'Unlocking the potential of sensors for our environment,' we were able to amplify diverse viewpoints and interpretations, thereby enriching the collective dialogue and contributing to a broader, multifaceted understanding of the environmental implications of sensor technology.

Figures 1 – 5: Example images submitted to represent 'Unlocking the potential of sensors for our environment'.

Figure 1: Daphnia as a living sensor of pollution. Image credit Katie Reilly, University of Birmingham

1 See Appendix 1

Figure 2: Photograph of Aurora borealis and shooting star, demonstrating sensor's ability to record and enhance human observations of our environment. Image credit: Visit Greenland

Figure 3: This shows how data from photographic and LiDAR sensors can be used to observe how the high mountain glaciers are responding to the ongoing climate changes.[ii] Image credit: Kriti Mukherjee, Cranfield University

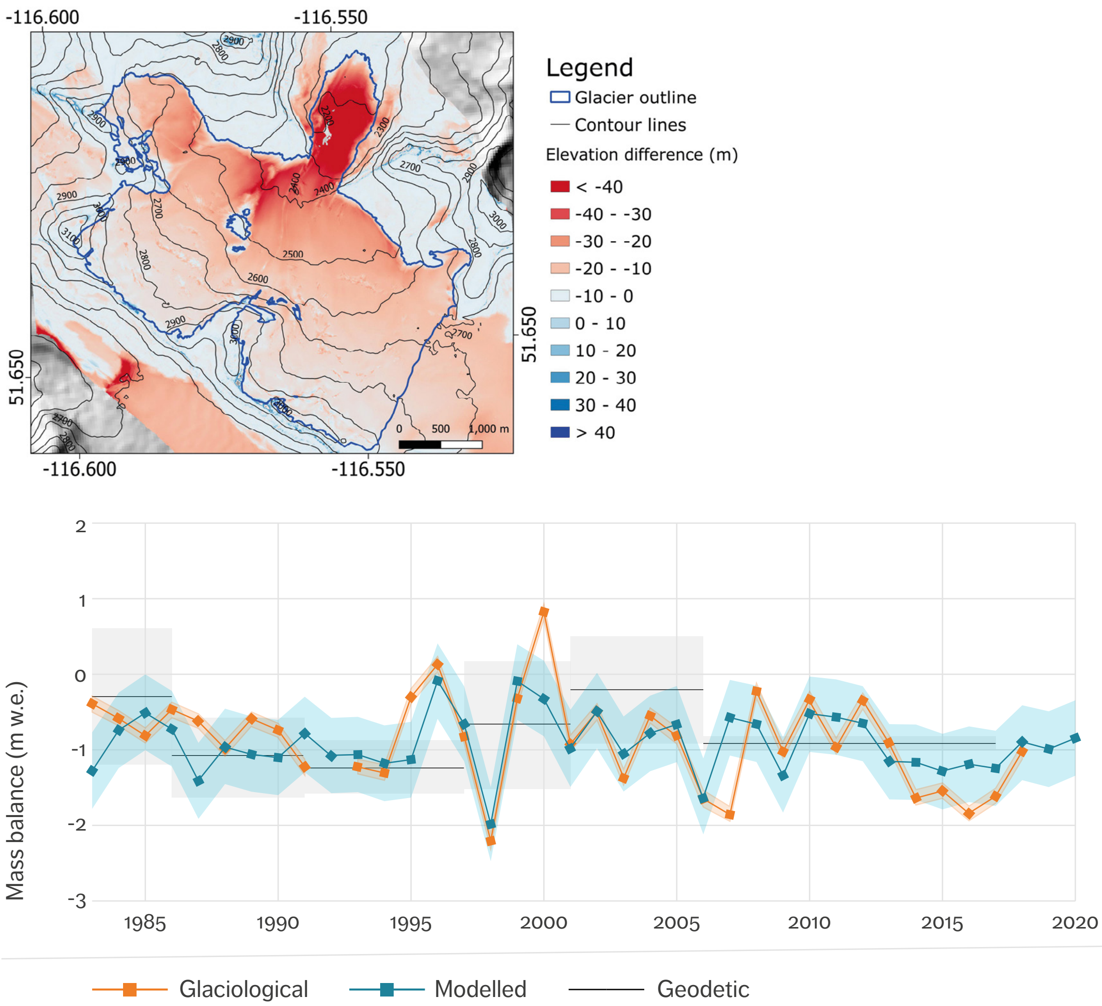
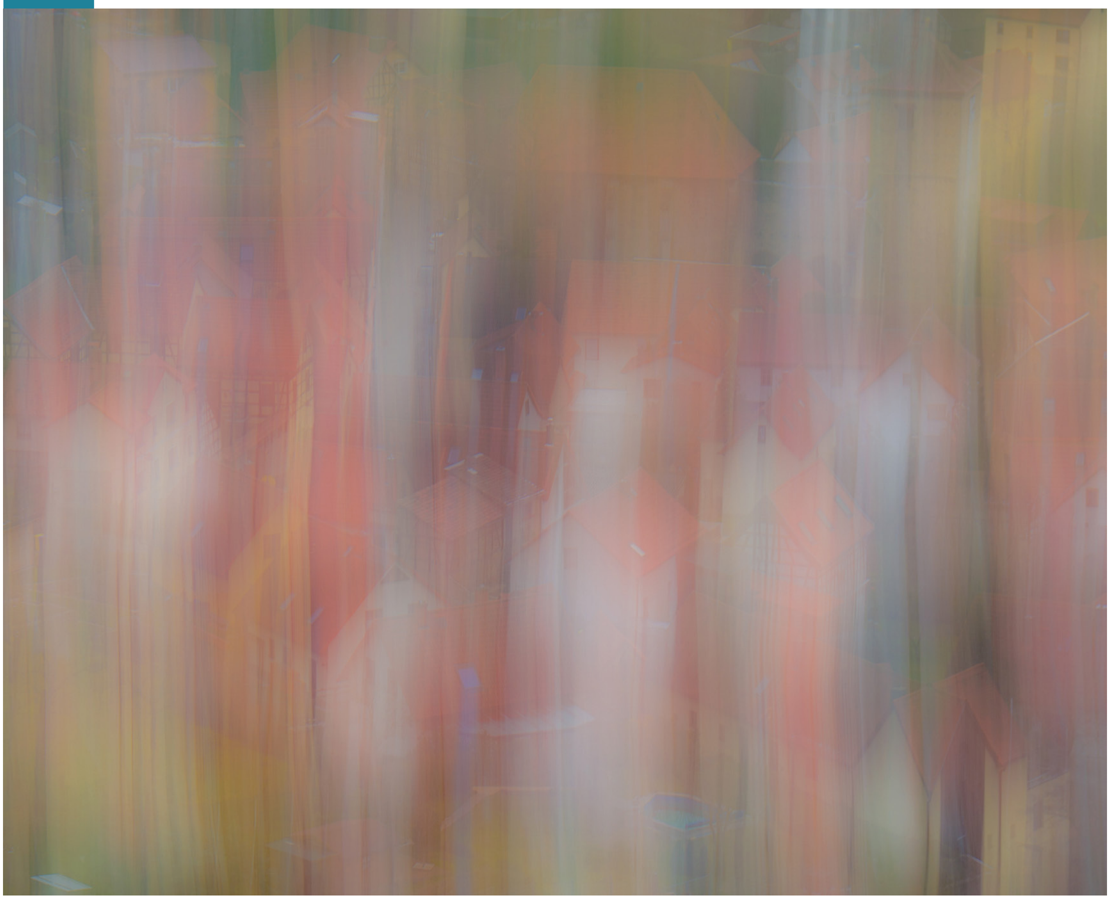


Figure 4: A traditional clay stove in a Rwandan refugee Camp. Image credit: HEED, Coventry University

Figure 5: Motion-blurred houses in village, showing potential of sensors to still yield useful information even when used outside of the normal range. Image Credit: Marco Van De Wiel, Coventry University



To synthesise this diverse body of work into cohort frameworks that identified unmet needs and calls for action, the organising team adopted a hybrid thematic approach.[iii] Thematic analysis is usually a six-stage process: Step 1: Familiarisation of data; Step 2: Generate codes; Step 3: Identify themes; Step 4: Review themes; Step 5: Define themes; Step 6: Write-up.[iv] Due to the unique nature of the data, the method adopted took a shorter three-phase process: first, we draw upon pre-assigned 'challenge themes' when familiarising ourselves with the data. These challenge themes emerged from the questions posed at the pre-retreat workshop. We then revisited the data and introduced new codes before proceeding to the third stage of merging the codes into three frameworks.

Table 2: Frameworks and codes

Phase 1: Pre-assigned challenge theme codes (*a priori*)							
Values	Changes	Ethics	Barriers	People	Tools	Lessons	Places

Phase 2: Generation of new codes (*a posteriori*)		
Trust; Sustainable Development Goals; regulations; accountability; standardisation; data governance; data sharing; fair; just	Public trust and confidence; engagement citizen science / public knowledge; community capacity building and resilience; end user impact; global inequality; equality; diversity; inclusion	Skills; networks; new advances in technology; sensors; community of practice; digital environment; technologies; methods; knowledge
Phase 3: Merging of codes into frameworks		
The environmental sensor research ecosystem as a trusted authority	Accessing the benefits of sensors and sensing for the environment for all	Building researcher capacity through transformative communities of practice

This method allowed attendees to contribute more expansively as the code represented not only a word or sentence, but also an image, paragraph, speech, or phrase. Similarly, the process afforded us a more deductive approach as we could align thematic codes to the pre-assigned challenge themes (*a priori*), as well as the atypical inductive method that generated new codes (*a posteriori*). After consolidating overlapping, similar, and repetitive codes, we conceptualised three distinct frameworks that brought to the fore people, places and ethics. These frameworks then became the structural foundation for this report, providing a clear and organised representation of the collected data and insights.

Unlocking the potential of environmental sensors within grand challenges

Environmental systems are generally geographically dispersed, temporally evolving, exhibit threshold processes and are mediated by complex interacting elements that operate over a range of timescales. These features map directly to many of the grand challenges society faces, whether they be adapting to changing climate, managing a pandemic, understanding policy decisions for managing urban pollution or responding to unfolding environmental crises. Included within these processes is a tension between the reductionist understanding of environmental processes and a theory of change approach that works back from the changes we want to support. Consequently, decision-making within these landscapes needs to be taken into account and be robust to uncertainty and facilitate environmental sensing protocols that have the potential to constrain key aleatoric and epistemic uncertainties.

Figure 6: Sensors collecting data. Image credit: Elizabeth Bagshaw, University of Bristol

The development of an open and community owned **systems-based understanding** is an opportunity to draw upon a wide spectrum of end-user, community, and academic experience to map the complex human and physical drivers of environmental systems. This approach can support a sensor development and use lifecycle **ecosystem** (defined as a system comprising the people, processes, activities and products) that considers the various uncertainties that occur by chance and those that arise due to a lack of knowledge at the local, regional, and global level within the sector and broader society.

More importantly, the systems-based understanding permits the identification of key knowledge gaps and indicate where and how new information and data can support decision making and policy development through careful survey design. It also can promote innovation in areas where current technologies do not yet sufficiently meet the challenge. Driving this system-based understanding should be a robust interdisciplinary and challenge-based approach that supports a resilient, vibrant and respected sensor researcher and research ecosystem. This ecosystem should focus on empowering decision making (using sensors) that builds societal resilience, fosters innovation to combat critical climate challenges. From an ethical perspective, it should additionally strive for inclusivity and equality of participation and outcome for all.

Current landscape, unmet needs and call to action

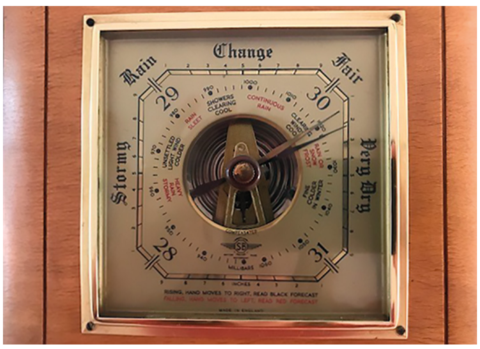
From the analysis of the data, three distinct frameworks emerged: 1) Recognition of the environmental sensor researcher and research ecosystem as a trusted authority; 2) Improving access to the benefits of sensors and sensing for the environment for everyone; and 3) Building researcher capacity through transformative communities of practice. Each framework includes a reflection on the current status of the field, highlighting perceived gaps and areas where needs are not being met. These insights were co-created by and with the participant researchers. Proposed within each framework are specific actions to meet these needs, offering a pathway to research endeavours that focus on unlocking the benefits of sensors for the environment for all.

Framework 1: Recognition of the environmental sensor researcher and research ecosystem as a trusted authority

Current landscape

Sensors can make the invisible visible, detecting shifts in the environment that might otherwise remain unnoticed and in doing so, evidence how the climate crisis is affecting ecological systems. Yet, as the use of sensors becomes more pervasive there is the potential for data to be manipulated to further political agendas or undermine environmental policies.[v] This compounds the public concerns on the quality and trustworthiness of data.[vi] Data sharing across institutions and countries has also prompted questions on how to ensure additional layers of security and considerations around privacy in a globalised world, that protect individual and indigenous rights and maintain trust in international data exchanges.[vii,viii]

Figure 7: 'Whilst being scientific instruments, environmental sensors can also be tactile and/or ornamental. There is something reassuring and trustworthy about tapping a wall mounted barometer to check whether an umbrella is needed before leaving the house for the day'. Image credit: Emma Bee, British Geological Survey.



We believe communicating the potential ethical concerns around sensors, sensing and environmental measurement and the corresponding consequences is central to sensors being seen as a trusted authority within the sector and in the wider community. We propose that some of the historic and current ethical challenges of sensors and sensing can be broadly split into the following categories:

Table 3: Categorisation of ethical concerns related to sensors and sensor data

Ethics of sensors and sensing	Example	Purpose/intended consequence	Misuse / unintended consequence
Using sensors to monitor things that are outside of the stated objectives, with the potential breach of privacy and security	Movement detectors	Detection of physical motion, enhancing security and monitoring capabilities in various environments	Invasive surveillance, potentially fostering societal distrust and heightened concerns around civil liberties and individual rights to privacy
The unbalanced monitoring of different people or places	Monitoring communities by gender, age, ethnicity etc. to allow for more targeted interventions	Facilitates the development of tailored and impactful support measures to improve life chances and options	Inequalities in representation within data is reproducing discriminatory practices
Environmental degradation due to sensors	Sensors incorporating batteries, printed circuit boards and other non-degradable elements	To monitor environmental conditions for research and preservation	Environmentally unsustainable, difficult to recycle and have high energy production costs
Uneven application of data practices, standards and storage	Metadata platforms, datasets, and open access data	Standardised data handling, ensuring reliability and comparability	Inconsistency in data practices across the platforms leading to unreliable or biased outcomes
Limitations of open access and discoverability	Metadata platforms and archiving tools	Facilitating wider access and understanding of data, data aggregation and re-use for development of models, analysis of trends, regulatory decision making etc.	Restricted access or misuse of open data limiting innovation, research advancements, and informed decision making
Working conditions and culture	Field research teams deploying environmental sensors in remote areas	Ensuring fair and ethical conditions by providing adequate training and access to resources that recognise the unique risks to wellbeing working in complex environments	Potential harm includes decreased morale, reduced innovation due to labour exploitation, and high employee turnover

Unmet needs

Data standards

We acknowledge that much has improved around the access, storing and archiving of environmental data, with national organisations, such as the Environmental Information Data Centre (EIDC) and the Scottish Environment Protection Agency (SEPA), producing guidelines to promote greater open access data and transparent data processes. Yet, we still have expressed concern about the variance between data standards, by that we mean the way data (whether sensor or otherwise) is formatted, structured, and documented across the sector. Similarly, even if data standards are compatible, we contend that practices may have evolved between different disciplines resulting in variable recording of data and using a variety of data schema (database models) making cross-sector collaboration more difficult to monitor or implement.

Figure 8: Bespoke open source hardware light logger deployed alongside AudioMoth audio logger to measure the impact of anthropogenic disturbance on bird and bat species. Image credit: Kristofer Chan, King's College London

Standardisation requires a shared ontology of concepts and a critical mass of individuals across the sensor research ecosystem to utilise this ontology. Similarly, while guidance on best practices such as FAIR principles (findable, accessible, interoperable, reusable) may address generic concerns around data standards, more needs to be done to promote sector-specific protocols and processes that reflect and respond to the complexity of collecting data in harsh environments and remote areas.

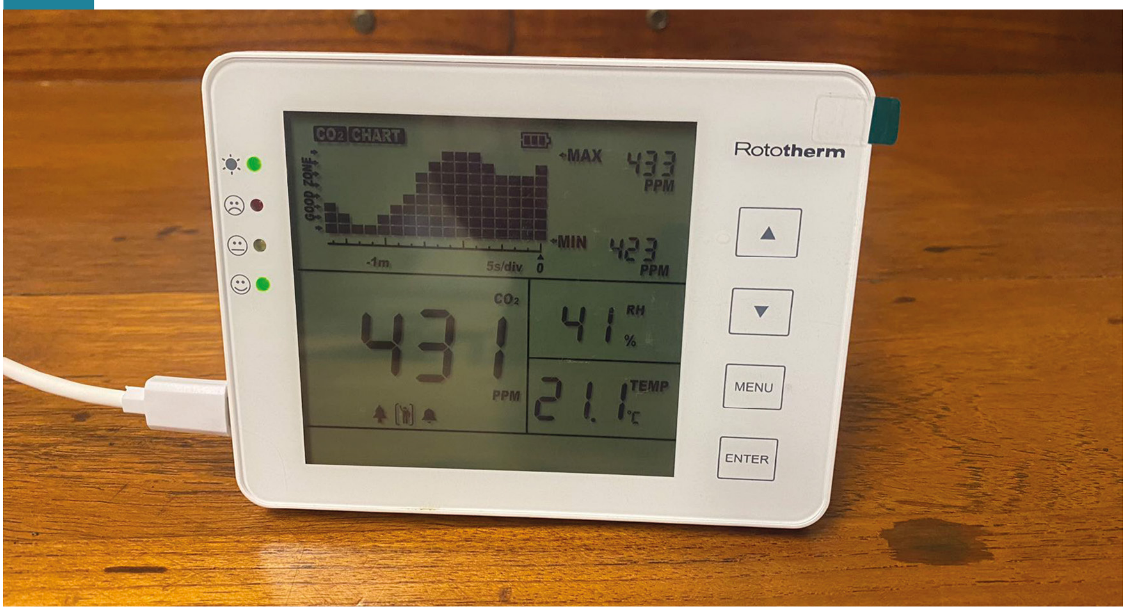
Table 4: Some examples of UK environmental organisations guidelines on data and metadata standards

Organisation	Example of data standard guidelines
The Environmental Information Data Centre (EIDC)	CoreTrustSeal
Joint Nature Conversation Committee (JNCC)	MEDIN data standards
Scottish Environment Protection Agency (SEPA)	Code of Practice for Statistics
The UK Centre for Ecology and Hydrology (UKCEH)	Sensor Data and Metadata Standards Review for UKCEH
British Antarctic Survey	Metadata guidance
Marine Environmental Data and Information Network	MEDIN data standards
Ordnance survey	Geospatial Standards for UK data providers
British Geological Survey	National Geoscience Data Centre Standards

Open access data and discoverability

Open documentation supports the iterative development and refinement of best practice through the sharing of experiences and data.[ix] However, given the cross-cutting nature of environmental sensors and sensing, there are still challenges around the discoverability of relevant data. The introduction of metadata platforms, such as the UK Centre for Ecology and Hydrology (UKCEH) 'Environmental Information Platform',[x] is bringing together data from across disciplines, but there remains a gap in having a unified resource that provides an overarching view of all these platforms and their functionalities.

Figure 9: An indoor carbon dioxide monitor. Image credit: Feng Mao, University of Warwick

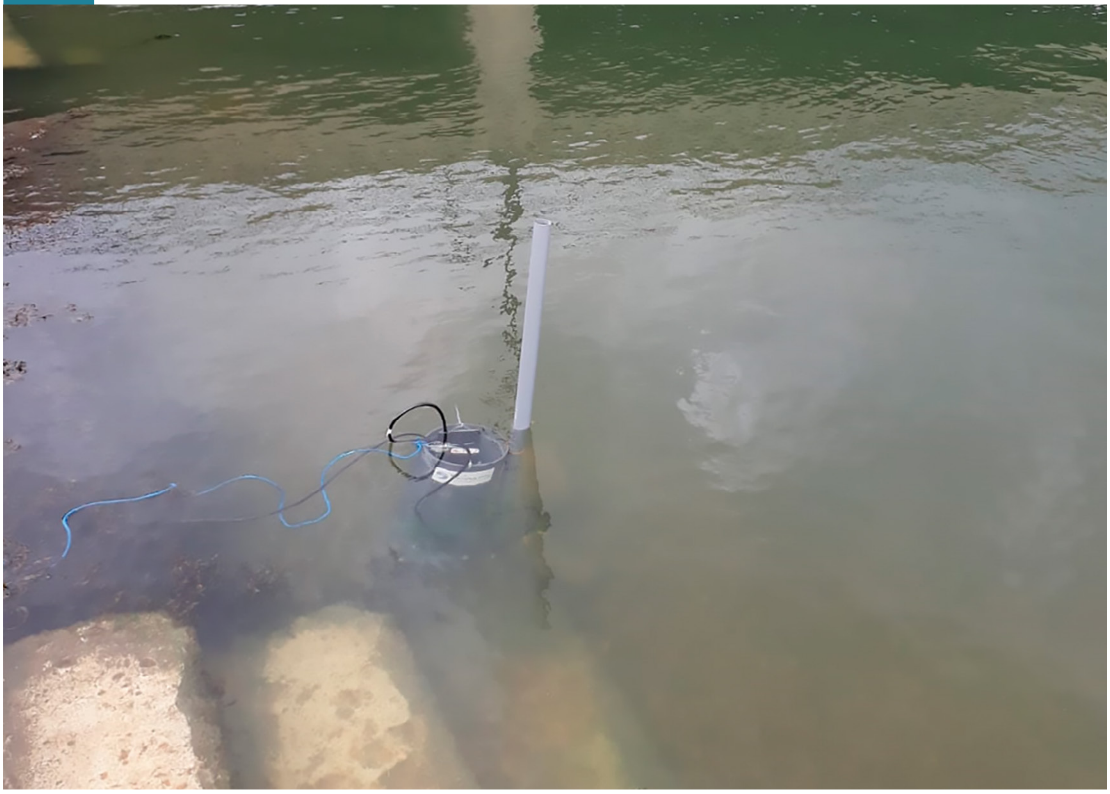


Data platforms act as gatekeepers to data, and if not designed to be sufficiently inclusive, representative or visible, may limit opportunities to make environmental knowledge democratic. There is also more to be done about the issues around data ownership and rights, which includes more emphasis on the impact of unequal systemic power structures that decide who gains the most benefits from access to data and which communities are excluded.

Sensors' accuracy and precision

Sensors capture and translate the physical attributes of an environment into a quantifiable parameter.[xi] Over the past decade, the size and cost of sensors has decreased, with associated lower energy demands that can allow for deployment within remote locations and within mobile settings, for example on the back of motorbike taxis[xii] or bicycles.[xiii] Sensors have also increasingly adopted standardised communication methods (e.g. through SPI, I2C or UART communication). Many sensors, however, produce measurements that have low accuracy and or low precision when compared to industrial equivalents. Some sensors are essentially research-grade instruments that have been miniaturised using lower cost components to reach a price point that allows for their manufacture as sensor devices. These however can often be the same sensors as those used in industry-standard handheld equipment. Other sensors use technologies that would not be used for regulatory or research grade instruments, as although better technologies exist, this comes with higher costs, a larger size, and greater energy demands. The variability in sensor quality and technology, which leads to inconsistencies in data quality and accuracy can, for those outside of the sensor ecosystem, raise concerns about their dependability for crucial applications and decision-making.

Figure 10: A sensor measuring pore water chemistry in river sediments. The sensor revealed very different data during (accessible) low tide and (inaccessible) high tide, illustrating the need for sensors even in relatively proximal and accessible environments. Image credit: Allison Schaap, National Oceanography Centre



The uncertainty of sensors does impact on the way instruments are perceived as trustworthy in collecting data. Although there are ways of improving sensor accuracy and precision, the timeline for subsequent verification and field testing in difficult and complex environments, as well as the subsequent correction and calibration, is protracted. To build trust in the design of sensors, it is crucial to foster a culture that not only acknowledges but also openly discusses the inherent uncertainties and constraints in designing and deploying sensors for the environment. We suggest that a concerted effort within the community to candidly showcase the capabilities of sensors in environmental monitoring while also clearly delineating their limitations will result in greater confidence across the sector and societally. We also advocate for the sharing of standardised sensor blueprints, such as common designs with proven field-deployment, tested and constrained accuracies, and the ability for the community to collaboratively improve such designs (e.g., KCL Geography's Environmental Monitoring Logger designs;[xiv] the FreeStation Initiative;[xv] the Cave Pearl project).

Participants' quotes

> 'A lot of data at low confidence and without any meaningful information doesn't add value to science. This is a waste of resources.'

> 'We need more open-source tools and technologies so that people with less expertise can access those and use to solve problems. Generating minimum standards for everyone to follow and help guide newcomers to the field'.

> 'Standardisation and reproducibility are the key. It takes time to "agree" on the numbers we collect. But this is what makes an application a tool and not a concept.'

Call to action

- Committed collaboration of research bodies that bring together expertise in environmental sensing and sensors in the implementation of standards to create a bespoke data framework that reflects the unique challenges of the global environmental sensor ecosystem.
- Community signatories from across the sector that commit to broadening open data access, enabling best practice and greater access to existing sensor technologies, test sites or communities.[xvi]
- More emphasis on practices that allow for comparability and quality measures by interrogating the suitability of data structure, format and output syntheses. This includes adoption of good practice, such as giving more support and space for researchers to explore open methodologies and statements of uncertainty.

Framework 2: Improving access to the benefits of sensors for the environment for all

Current landscape

Sensors and their data are key enablers of the digital transformation, which is reimagining the way people connect with their surroundings, their community, and society at large. To date, there has been limited research on understanding why or how sensors, and sensor data, are used by individuals and communities at large.[xvii] In centring decision making about the sensor design, deployment, and application on **people**, at the individual and community level with global citizens we will leverage new technologies that bridge digital and participatory divides at all levels. Incorporating principles of human-centeredness, geographical context, and ethics into the study of environmental sensors has the potential to aid a collective community awareness aimed at addressing critical worldwide ecological challenges, including climate change, deforestation, the decline of biodiversity, and pervasive social disparities.[xviii]

Figure 11: Image representing the barriers to unlocking the benefits of sensors for all of the environment. Image credit: Carl Watson, British Geological Survey

Unmet needs

Interdisciplinary, multidisciplinary and transdisciplinary collaborations

Despite increasing efforts by individuals and institutions to foster engagement across disciplines and sectors, entrenched barriers to interdisciplinarity still persist within the sensor research ecosystem. [xix,xx] Interdisciplinary, multi-disciplinary and transdisciplinary approaches allow for greater incorporation of diverse viewpoints, including those of end-users and communities. This not only enriches the research and development process but also ensures that the outcomes are more aligned with the needs and realities of the wider community.

Table 5: Barriers to interdisciplinary working

Interdisciplinary, multi-disciplinary and transdisciplinary collaborations	**Limited access to relevant networks**: Limited knowledge on how to connect and engage with others from outside a particular discipline.
	Historical siloing of disciplines: Challenges of overcoming existing disciplinary structured funding schemes, publication processes, and institutional reward systems, as traditional academic evaluation systems may not properly acknowledge or credit interdisciplinary work making it more less viable for researchers to enter into the field.
	Knowledge gaps and hierarchies: Difficulty in creating a shared understanding and prioritisation of which lenses to view the challenge through (on what to study from a variety of different world views) in addition to different methods and theories.
	Institutional and Research Council remits: Academic and research institutions may be structured in a way that discourages cross-departmental or cross-disciplinary collaboration due to differing objectives, policies, or funding mechanisms.
	Lack of Incentives: Without proper incentives or recognition for interdisciplinary work, individuals may not be motivated to engage outside their specialisation.

Figure 12: Nurturing the next generation of researchers in sensors. Image credit: Let's do Engineering, Heriot-Watt University.

Community engagement

Early and effective engagement, co-production and co-evaluation with stakeholders (both top-down and bottom-up) will maximise the utility of the outputs but there are long standing barriers that prevent certain communities from accessing the full benefits of sensors and sensing.

Table 6: Structural barriers to accessing the benefits of environmental sensors for all

Barrier	Outcome of the Barrier	Impact
Necessity of specialist skills	Difficulty in recruiting, training and/or retaining talent.	Gap in technical skillsets can lead to suboptimal design and use of sensor technologies, affecting overall effectiveness. Training so digitally focused researchers lose the capabilities or desire to engage in tangible experimentation and assembly of sensors.
Digital divide and data literacy	A divide in digital literacy and data access exacerbates the gap between technology-rich and technology-poor communities.	Due to insufficiently developed infrastructures access to advanced technologies may be limited in some global south regions. This contributes to inequalities and excludes certain populations from reaping the benefits of sensor-based solutions.
Data colonialism	Powerful data players (e.g., tech giants, developed countries, governments) appropriate big data from other players (e.g., developing countries and individuals); a challenge in open data.	Limited access to advanced technologies in less developed parts of the world creates inequalities and excludes certain populations from reaping the benefits of sensor-based solutions.
Resources and cost	Sensor technologies may be expensive to design and maintain.	Leads to unequal advantages/ disadvantages to people from different parts of the world.

Citizen science

Community engagement through citizen science has shown that a whole society approach to the design, implementation, use and exploitation of sensors results in decision-making that reflects end-user needs and perspectives and an ethically sound approach for data collection and dissemination.[xxi] Notwithstanding, we contend there needs to be more considered and critical thinking within the sensor ecosystem on whether citizen science projects are sufficiently planned or prepared for the negative outcomes that might arise from participatory engagement. We are concerned that without critical interrogation around meaningful participation, there is the potential for these types of projects to reinforce communities as passive recipients if they have little or no input into the project design and are used only for data collection.

Figure 13: Air of the Anthropocene. Image credit: Francis Pope, University of Birmingham

Sensor data can feed back to communities through educational and/or artistic pieces to close the distance between communities and the environmental systems that they are exposed to and initiate interactions whereby they can interact with the resulting data stream. An example of public engagement with sensors and sensor data is the collaboration between artist Robin Price and atmospheric scientist Francis Pope in their 'Air of the Anthropocene' project which generated light paintings of air pollution. Through photography that captures air pollution levels, this project makes the unseen visible, encouraging people to engage with debate on air pollution as a critical environmental challenge both in the UK and globally.

Increasing transparency and ensuring responsibility towards communities in citizen science ventures may lead to discoveries of less visible but pernicious inequalities, a heightened recognition of vulnerabilities and promote an ethics of care. To achieve this aim, we consider there needs to be more focus on how to embed communities and individuals into the design, delivery and outputs, without overburdening and with mechanisms that deliver data back to the community in user-friendly formats, empowering them with the information needed to drive change. The outcome would be improved technological literacy on sensors and sensing and the role these systems play in building societal resilience and accelerate climate action.

Table 7: Suggested guidance on implementing citizen science projects that promote meaningful participation.

Project development steps when working with communities
Engage with end users in design criteria development: Initiating dialogues with end users to collaboratively determine the design criteria, ensuring that the project outcomes are user-centric and relevant. This includes early identification community informed project legacy, exit strategies and ways to disseminate findings.
Project transparency and quality assurance: Be transparent regarding project requirements, tool selection (such as open-source programs), intellectual property concerns, and adherence to high-quality standards. This also includes discussion around privacy and consent.
Goal setting and adaptive planning: Collaborate with communities to set realistic objectives, using tools like community workshops or interactive online forums for input and feedback, while maintaining the flexibility to revisit and revise these goals. Thereby fostering a culture of openness and adaptability that incorporates invaluable local knowledge and experience.
Cultivate a collaborative network: Consider ways to bridge the gap between the research community and those invested in environmental issues by inviting community advocacy groups, special interest groups, and local leaders onto advisory boards, as well as conferences and report launches.
Iterative project reconstruction: Share design protocols and feedforward data with communities throughout the research process to ensure there is meaningful participation in decision-making. Revise design according to feedback.
Sensor deployment and data collection: Implementing sensor deployment to generate initial datasets, embracing a constructive approach to failure as a learning opportunity.
Maintaining open lines of communication: Adopt alternative forms of communication like immersive virtual reality experiences or community storytelling events, ensuring ongoing, bi-directional engagement that keeps communities informed and involved, while drawing on innovative and culturally resonant communication methods.
Data reciprocation: Sharing data and results with communities, in tandem with the scientific community and the broader public to maximise the benefits and demonstrate how sensors and sensing support greater digital literacy and environmental awareness.
Disseminate findings widely: Informed by community suggestions, disseminate findings through creative and accessible mediums like art exhibitions, documentary films, and interactive digital platforms, reaching beyond the immediate scientific context to influence policy, shape practice, and enhance public understanding.
Leverage findings for future endeavours: Draw on community insights and outcomes, embedding these perspectives into the core of new research ambitions, to inform and initiate projects that are deeply rooted in and responsive to community needs and aspirations.

Participants' quotes

'I'd like to see more of an appreciation of "understanding" - of places and people and ethics – as opposed to "doing" in all aspects of sensors design and deployment.'

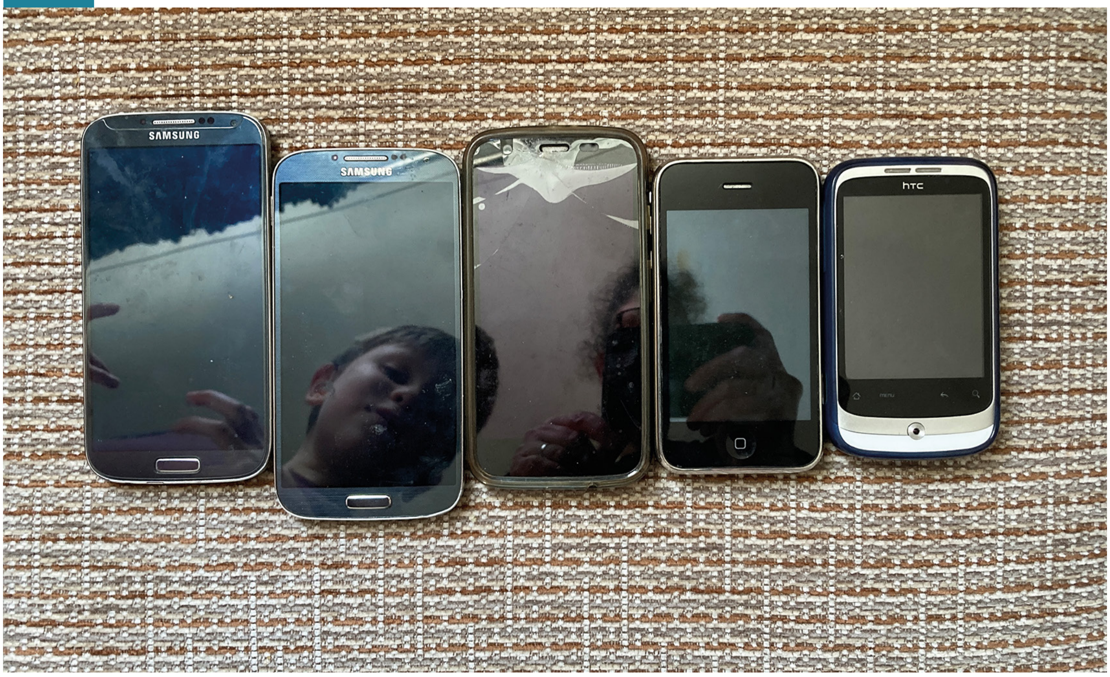
'Transdisciplinary work is more difficult than it looks. We acknowledge the "language" barrier – but this is not the most difficult part. I believe the different values we have in our home disciplines and the value labels we attribute to various aspects of the sensing system, or a sensing project play an important role.'

'A key concern I have is what we do with sensor data related to pollutions for example. While knowledge is empowering, it also highlights disparity (in wealth) for example – if you learn your local water/air are polluted but cannot move that knowledge it is likely to increase stress/feelings of powerlessness.'

Call to action

- Citizen Science projects are collaboratively designed by communities, researchers, industry experts, and policymakers to guarantee impactful engagement. This approach enhances data accessibility, usability, and shareability, fostering a decision-making process that is deeply rooted in community insights and needs.
- National organisations, such as UKCEH and BGS, appoint champions roles either at a local, institutional, or national level to bring together those working with sensors and environmental advocacy groups to promote best practices around community engagement.
- NERC, along with other research bodies, to fund more interdisciplinary workshops to scope grand challenges that can highlight key knowledge gaps across fields and promote diverse perspectives.

Figure 14: Sustainability, ubiquity, and sensors. Image credit: Pinar England, Coventry University



Framework 3: Building researcher capacity through transformative communities of practice

Current landscape

To continue to unlock the benefits of sensors for the environment we foresee the need for a sensing ecosystem that cuts across disciplines, sectors, and technologies and fully considers **people**, **places**, and **ethics**. The UK's 25 Year Environment Plan[xxii] recognises the need for a holistic, comprehensive and long-term approach to protecting and enhancing the environment. Whilst there are examples of effective sensor test environments in the UK and beyond, access to these facilities is either challenging because of access limitations (for example, facilities held by individual universities or institutes) or technological / logistical hurdles (for example, difficulties in incorporating prototypes into differing test systems).

Figure 15: The new Kivi sensor, a "smart -pebble" designed to capture riverbed movements.[xxiii] Image credit: Georgios Maniatis, University of Brighton

There are over 750 long-term ecological research (LTER) sites, internationally coordinated through the ILTER network, where long-term studies of the structure and function of ecosystems provide a sustained, multifaceted perspective on their response to changes and external drivers.[2] They are inherently interdisciplinary, and some sites have explicit links with policy formation or educational purposes.[xxiv] Enabling researchers to maximise the benefits of UK environmental monitoring systems and promote research excellence requires an infrastructure that can address common barriers when sensor testing. This includes, but is not limited to, deployment and maintenance of systems that provide training opportunities for the next generation of environmental scientists (e.g., EnvironmentalSensorHub.org; cryoskills.com), enabling upskilling of cross-disciplinary and technical expertise that can be undertaken alongside specific research projects to maximise sites.

2 See Appendix 2.

Research excellence

The development of sensor systems typically necessitates extensive educational and technical expertise across multiple disciplines, including advanced materials, physics, biology, embedded systems, and communication systems. With the growing integration of digital technologies and machine learning methods in sensors and sensing, there is an increasing need for skills in computer science, computational modelling and statistics. To ensure the continued advancement and research excellence in the environmental sensor ecosystem, it is vital to enhance the utilisation of existing and past sensor research. This enhancement requires evaluative research and testing of current systems, as well as proactive exploration at the beginning of development and deployment phases. This process involves exploring potential new developments within relevant scientific and practical communities and collaboratively fostering the creation of design repositories, protocols, and guidelines for the design and use of sensor systems.

Enabling digital environment researchers to access sites and test prototype technologies, with access to background data will be instrumental in helping them to validate in a safe space the performance of new sensing solutions. It will also enable data scientists to test new pipelines from field to database and explore emerging solutions for data interrogation and manipulation using validated environmental datasets.

Unmet needs

Digital sensor test playgrounds

To fully realize scientific and societal gain from environmental sensors and to build a community of practice we propose a network of 'Environmental Sensor Test Playgrounds'. In these 'playgrounds', developers can access standard test facilities to incorporate their prototype environmental sensor/system into an instrumented landscape. The Playgrounds could employ features from existing environmental monitoring landscapes, as well as routinely collecting meteorological, air, soil and water measurements via standardized sets of instruments. To further ambition, these centres will provide a plug and play telemetry network (using radio, cellular and satellite systems) and a pipeline from field data into online data management systems.

Table 8: Environmental testing site best practice to build research capacity and support ambition

Environmental testing site best practice	A well-supported standardised setup for provision of power and communications
	Access to personnel with experience in the engineering of devices to ensure robustness and reliability while translating new technology from the lab to the field
	A remotely-accessible data repository designed to FAIR, CARE, and TRUST standards
	The provision of or access to standardized alternative sampling or measurement methodologies for validation
	Models of the site's key environmental parameters

Figure 16: An off-grid sensor payload deployed via Unmanned Aerial Vehicle (UAV) for the remote monitoring of radiation levels around Chernobyl. Image credit: Interface Analysis Centre, University of Bristol.

We note that this proposal is far from radical: instead, it takes best practice from existing systems and applies them within a UK science context to benefit the environmental science community. The approach has the advantage of lowering of logistical overheads as researchers would have less need to source power and telemetry options for their field tests. The potential to expand and maximise technological support through provision of advice, blueprints for sensor design, to data pipeline systems advice on sensor deployment and data management, will generate creative new spaces for innovation and lower the barriers to conducting tests of novel solutions to the environmental problems of the future. As well as providing test sites, the Playgrounds will support long-term, autonomous data collection from proven off-the-shelf sensing systems (for example, standard meteorological or water quality data). The standard data obtained by the Playgrounds could lead to a long-term repository of UK (and beyond) environmental data that can be used to track the impacts of climate change and multiple stressors.

Figure 17: 'Black Box' flight recorder, challenging the idea of instrumentation adopting a 'black box' approach. Image credit: Wikimedia Commons

We contend that creating an ecosystem with access to more shared research sites fosters not only technological advancements but also the growth of a collaborative community that is resilient, adaptive, inclusive and committed to mutual learning and support. We believe these playgrounds would be pivotal for driving innovation and leadership and elevating the visibility and importance of sensors and sensing for the environment, which often appears less prominent or acknowledged than other disciplines due to its cross-cutting applications. Providing alternative spaces for researchers working across the sensor ecosystem can be the catalyst for a more robust, sustainable community of practice that recognises, signposts and celebrates the field's contributions.

Table 9: Some examples of the proposed Playground outputs to build the capacity and capabilities of researchers

Action	Output	Outcome
Mapping of where sensors have been deployed and to what effect in remote and difficult terrains.	Systematic catalogue of tools, projects, places when working in complex environments.	Enhanced clarity on outcomes, evaluation results and Technology Readiness Levels (TRL) specification for difficult environments.
Adopt a positive failure approach to evidence-based evaluation.	A systematic evidence-based evaluation and associated dissemination of signposting of pitfalls and drawbacks.	Increased robustness of new sensor systems evaluation and embedding a culture of resilience that supports continuous improvement.
Development of translation business models.	Increase availability and ease of use of guidance on sensor-specific standards, development for industry.	Accelerated adoption and enhancement of prototyped tools and systems by a broader community.
Knowledge hubs and curated design banks.	Data banks with associated processing chains.	Maximising of deployment opportunities, facilitation of cross-examination of performance by others; cross-evaluation and stress testing to improve robustness and rigour.
Open designs, specifications and user manuals for instruments produced	Lonely Planet style guides on various environments – what to look for, what to look out for, what have others found.	Expedited adoption, production, and testing processes, which contribute to higher success rates in deployment and result in significant time savings.

Participants' quotes

‘The advances in technology often do not translate to advances in sensing or advances in science or decisions making.’

‘Very often use of most advanced technology is the main focus, not the most appropriate one [to address the specific research or environmental sensing challenge]. This limits the best utilisation of available resource.’

‘Uptake of environmental sensing is low because lack of ability (or mostly confidence) in researchers trained in environmental sciences.’

Call to action

- Develop a plan for 25-year (minimum) investment in a sensor research infrastructure that links existing environmental sensor testbeds and establishes additional sensor networks and their digital twin equivalents spanning the breadth of the UK and global ecosystems of interest.
- Promote the repurposing of existing activities and programs to support the conservation of resources.
- Explore the integration of a Digital Environment layer into the UKECN, enabling the implementation of standard telemetry, power and data management systems to form the Digital Environment Playground network.

Figure 18: Perito Moreno Glacier. Image credit: Burcu Yüksel Ripley

Appendix 1

Writing retreat programme and methods.

- Stage 1: The preparation stage (May 2023 - 4 weeks prior to the retreat and continuing up to the event) saw attendees work individually using a digital platform to springboard discussion and share insights through videos.
- Stage 2: An in-person writing retreat (4th - 5th July, Coventry University).
- Stage 3: Co-created Briefing Paper (August – December 2023).

During Stage 1 and 2, participatory methods using image elicitation,[xxv] video storytelling,[xxvi] and mind mapping[xxvii] provided an opportunity to probe more deeply and uncover more complex and nuanced reflections. By using a less formal structure and actively positioning attendees in the process, these methods encourage the researcher and participants to shift toward a co-construction of knowledge.

1. Photo elicitation

- **Task**: Attendees submitted a photograph that represents “Unlocking the potential of sensors for our environment”.
- **Aim**: To elicit different perspectives that uncovered underlying assumptions, shared and divergent values and deeper insights.[xxviii]
- **Outcome**: Captured experiences and meanings around sensors and sensing for the environment to support a dialogic exchange between attendees.

Due to time constraints and project limitations, this exercise was intended to be an evaluation of the sector rather than a visual analysis. Visual analysis engages with concepts around material culture, visual anthropology, content and historical analysis, iconography, social semiotic analysis, film analysis and ethnomethodology.

2. Video storytelling

- **Task**: a short video (1-3 minute) that captured an experience, a challenge, or an opportunity relating to sensors and what lessons, values, tools, barriers, or change could be shared with the group.

As a research tool, video storytelling has the capacity to communicate findings to a wider audience, as well as an alternative form of data collection.[xxix] Using video storytelling as an archive would allow the lead authors to revisit and review attendees’ insights in context and the overlaps of knowledge between disciplines.

- **Aim**: To produce an archive to revisit and review attendee's insights in context

Outcome: Identified the debates and discourses that were primary concerns for participants, including how these topics informed their understanding of maximises the benefits of sensors for the environment for all.

3. Mind mapping: 'So That Model'

- **Task**: using sticky notes put together building blocks using the 'So That' Model i.e., what things are needed to write to produce outcomes that achieve aims.

This simplified model of the Theory of Change articulate underlying assumptions which can be tested and measured. While as the mapping is both analytical and artistic, this permits attendees to communicate the challenges and allows for a re-imagining of the sensor ecosystem through new forms of expression.[xxx]

- **Aim**: To develop a 'So That Model' to structure information graphically to synthesise, recall, represent, and generate new ideas.
- **Outcome**: Clarity on long-term goals, identified measurable indicators of success, and formulated actions to achieve goals.

Figure 19: Mapping: 'Changes' theme group. Image credit: Coventry University.

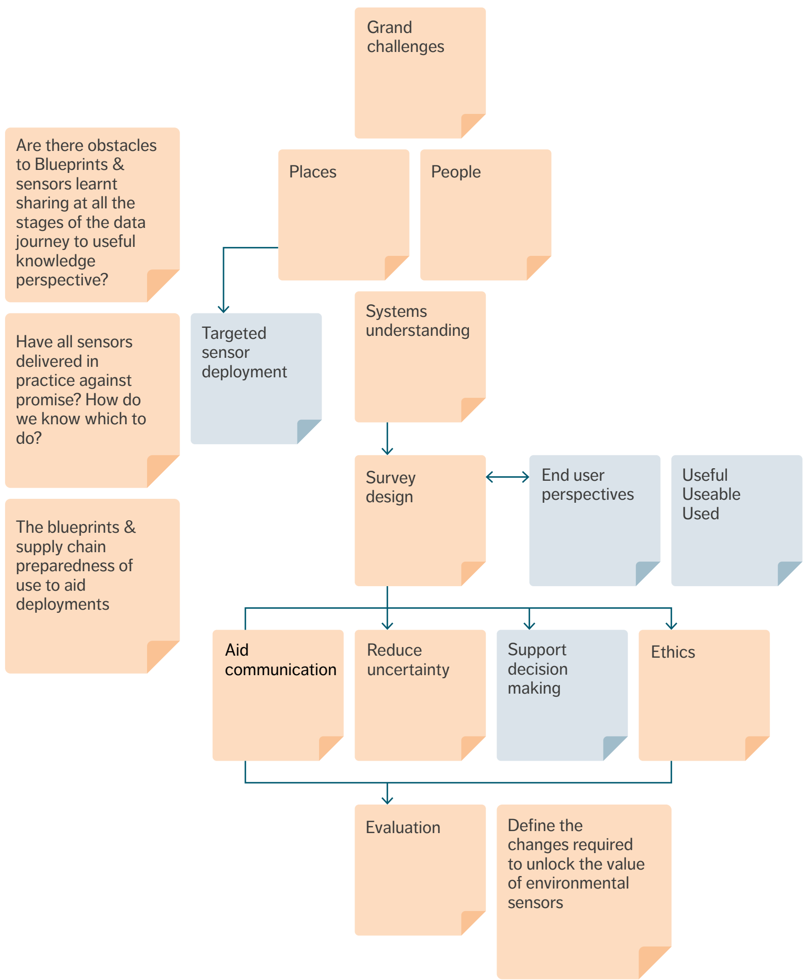
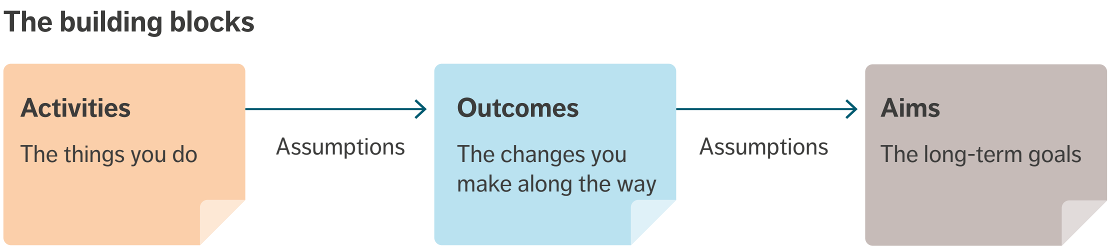


Figure 20: Image credit: Task Devised by Daniel Range and Tom Fisher (Coventry University).



Appendix 2

List of some of the long-term environmental monitoring sites or programmes in the UK.

Name	Operated by	Sites, ecosystems, focus	Link	Some data since...
Environmental Change Network	CEH	Terrestrial (11 sites), rivers & lakes (many)	CEH ECN	1992
Llyn-Brianne Observatory	Cardiff University	River catchment	Llyn-Brianne	1981
Western Channel Observatory	Plymouth Marine Laboratory, Marine Biological Association, Natural Physical Laboratory	Oceanography, marine biodiversity, atmosphere / air-sea exchange; technology testing	WCO	~1900
Halley Research Station	British Antarctic Survey	Antarctica	Halley	1950s
Automatic Urban and Rural Network (AURN)	Defra	Air quality	Defra AURN	1970s

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