Filling in evidence gaps for the safe deployment of offshore Geological Carbon Storage

AGILE Research Initiative

The Agile Sprint 5 team
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Executive summary

Carbon dioxide capture and storage (CCS) is a 'necessity not an option'[1] to halt global warming. Rapid scale-up of CCS[2] is underscored by IPCC global pathway assessments recommending 1-30 gigatonnes of storage globally per year ($GtCO_2yr^{-1}$) by mid-century. The UK has ambitions to capture and store 0.3 $GtCO_2yr^{-1}$[3] which will contribute towards stabilising atmospheric CO_2 concentrations at 1.5°C. To fulfil part of this target the UK's flagship project, Endurance, aims to store 0.45 $GtCO_2$. First injection into the Endurance reservoir is expected before the end of this decade.

This report presents our investigation of the question "What do we need to know to safely store CO_2 in our UK continental shelf seas?" using the Endurance reservoir as a case study. Our 14 month-long research revolved around six key themes across three domains:

1. Reservoir seal mechanisms (sub-surface domain).
2. Induced seismicity (sub-surface domain).
3. Interaction of leaked CO2 with sedimentary blue carbon (marine domain).
4. Identification of phytoplankton stress thresholds (marine domain).
5. Implementation of remote sensing tools for ecological baseline assessment (marine domain).
6. UK geological carbon storage regulation, legislation and governance (governance domain).

We outline scientific evidence gaps and policy trade-offs needed to safely store CO2 in the UK continental shelf (UKCS) and address current regulatory challenges impeding the implementation of offshore GCS in the UKCS. While not definitive or exhaustive, these identified gaps provide a basis for our three central recommendations to policymakers.

Based on our research, we make 3 central recommendations to policymakers; these are:

Consider how data, interpretations and modelling studies that underpin the storage permit and licence application process can be scrutinised by independent authorities	Background studies could be open to academic/public scrutiny without risk of loss of commercial advantage but would have the advantage of making the process of awarding a storage permit appear more transparent to the wider public.	The regulator requires data, interpretations and modelling submitted with a storage permit or licence application to be published, within the limits of confidentiality and commercial competition.
Assess blue carbon stocks in their full extent.	Current regulation focuses on sedimentary blue carbon stocks, overlooking water column carbon stocks, which have traditionally been challenging to quantify due to their high temporal variability. Advancements in satellite-based	Blue carbon accounting should be conducted in a joined-up way, considering both sediments and the water column.

[1] Climate Change Committee. (2019). Net Zero: The UK's contribution to stopping global warming. Available at: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/
[2] IPCC (2022) Summary for Policymakers. IPCC Working Group 3 6th Assessment. Available at; https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf
[3] DESNZ (2023) CCS Vision Statement. Available at: https://www.gov.uk/government/news/new-vision-to-create-competitive-carbon-capture-market-follows-unprecedented-20-billion-investment

	marine carbon data products from NASA and the European Space Agency's Colour Climate Change Initiative now enable the quantification of water column carbon stocks.	
Consolidate understanding of the implementation of the Levelling up and Regeneration Act 2023 in relation to CCS projects and clusters	The Act created significant planning uncertainty because it alters environmental impact assessments (EIAs) to Environmental Outcome Reports (EORs) and consolidates ministerial power to make final decisions for an infrastructure project like GCS. In practice, however, this has generated considerable confusion for project developers.	Legislators may wish to issue a statement of use, clarifying which ministers are responsible for signing off EORs, and which projects are eligible for special environmental exemptions.

Inside cover after exec summary: This report is the final output of Sprint 5 of the Agile Initiative, a programme funded by the Natural Environment Research Council (NERC). The Agile Initiative aims to transform how research responds to the needs of policymakers to deliver timely, policy-oriented, research that focuses on the net zero transition and critical environmental issues. To accomplish this, research is delivered in fast-paced sprints, typically lasting one year. In this sprint, we are addressing the research question; "What do we need to know to safely store CO_2 beneath our shelf seas?" We hope to improve understanding of the environmental risks and opportunities associated with CO_2 storage in offshore reservoirs. We are aiming to deliver new research and integrate existing knowledge from across research and policy areas, identifying gaps and areas requiring further research. Our Sprint concluded in June 2024.

Table of Contents

Executive summary **2**

List of Abbreviations **5**

Introduction **6**

Sub-Surface Environment **8**

Background *8*

Challenges *8*

Methods *11*

Regulating the sub-surface environment *14*

Solutions and Opportunities *15*

Marine environment **19**

Background *19*

Challenges *19*

Methods *20*

Regulating the marine environment *28*

Solutions and opportunities *29*

Governance environment **32**

Background *32*

Challenges *33*

Methods *34*

Solutions and Opportunities *35*

Final Remarks **38**

Reference List: **40**

Appendix **43**

List of Abbreviations

BGS	British Geological Survey
CCS	Carbon dioxide capture and storage
CDR	Carbon dioxide removal
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CO_2	Carbon dioxide
DAC	Direct Air Capture
DAERA	Department of Agriculture, Environment and Rural Affairs (Northern Ireland)
DEFRA	Department of Food, Environment and Rural Affairs
DESNZ	Department of Energy Security and Net Zero
EA	Environment Agency
EOR	Environmental Outcome Report
GCS	Geological carbon dioxide storage
GHG	Greenhouse Gas
Gt CO_2 yr^{-1}	Gigatonne (10^{15}g) of carbon dioxide per year
IFCA	Inshore Fisheries Conservation Authorities
IPCC	Intergovernmental Panel on Climate Change
JNCC	Joint Nature Conservation Committee
NbS	Nature-based solutions
NE	Natural England
NERC	Natural Environment Research Council
NSTA	North Sea Transition Authority
MMO	Marine Management Organisation
MMV	Measurement, monitoring, and verification
Mt C	Megatonne (10^{12}g) of carbon
OEP	Office for Environmental Protection
OFWAT	Office for Water Services Regulation Authority
ONZ	Oxford Net Zero
OPRED	Offshore Petroleum Regulator for Environment and Decommissioning
UKCS	UK Continental Shelf

Introduction

Carbon dioxide capture and storage (CCS) is widely recognised as a crucial bridging technology to help societies move from a high to low emission economy (IPCC AR6 2023). To meet the Paris Agreement target of Net-Zero by 2050, we need simultaneous deep reductions in carbon dioxide (CO_2) emissions and large-scale geological CO_2 storage (GCS) [4]. CCS is one solution in a portfolio of emissions mitigation tools, reducing emissions from industrial sources by capturing CO_2 at source. CDR differs from CCS in that CDR technologies remove emissions that are already in the atmosphere. In essence, CDR contributes to the 'net', and CCS to the 'zero' (see Figure 1). CCS will be required for mitigating emissions from energy and industrial sectors (e.g., power plants, steel, cement, and agrochemical production), particularly those that cannot be otherwise reduced, mitigated, or decarbonised. These *residual* emissions are often regarded as 'hard-to-abate' (Buck et al 2023), for which CCS with GCS is the only durable, permanent solution. All this captured CO_2 – either from CDR or CCS – must be stored in geologic formations (i.e., geological carbon storage, GCS) to permanently separate from the atmosphere and produce positive climate impacts.

GCS will play a critical role in meeting legally binding UK Net-Zero targets by 2050. The UK has a significant part to play (Zhang, Jackson & Krevor 2024) towards injecting between 1–30 $GtCO_2yr^{-1}$ to stabilise atmospheric CO_2 concentrations at 1.5°C (IPCC, 2023). In the UK's 6th Carbon Budget[5], the UK must capture and store 0.075–0.180 $GtCO_2$ from fossil fuel sources and direct air capture (DAC) to reach net-zero targets by 2050. To store 75–180$MtCO_2$, the UK plans[6] at least two industrial clusters (HyNet and the East Coast cluster) by the mid-2020s, both of which rely on offshore GCS.

On current policy trajectories, UK GCS deployment is limited to a storage growth rate of 20% *per annum,* equivalent to 0.175 $GtCO_2yr^{-1}$. Thus, although the 78.5Gt of UKCS *theoretical* storage resources and policy environment is important, we cannot meet Net-Zero unless all sectors – particularly those with the highest CO_2 emissions – move towards Net-Zero simultaneously. This requires concerted efforts and holistic policy to harness the public and private sectors for climate action. This is the third attempt from the UK Government to kick-start a large-scale CCS and GCS industry, so, this time, there is no tolerance within industry for further hesitancy. The risks of failure are high, especially when non-technical variables, like political environment, public perceptions, and legal frameworks are factored in.

The first-mover project in the UK, Endurance, is situated in the Southern North Sea (54.1ºN, 1ºE). Ahead of CO_2 injection, we have assessed the environmental and governance risks associated with offshore geological CO_2 storage (GCS), although it is worth noting that our work is neither definitive, nor exhaustive, and may have applications beyond CCS. This report summarises our independent research and aims to provide policymakers, industry stakeholders, and commentators with the research and policy recommendations for safe offshore GCS.

We have focused on three key themes identified as pivotal to enable safe GCS deployment in the UK offshore continental shelf (UKCS):

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[4] Geological Net-Zero is defined as 'any ongoing production of CO_2 from fossil-fuel sources is balanced by geological CO_2 disposal by 2050.' (Jenkins et al 2023).

[5] According to the Climate Change Committee (CCC, 2020, p.81).

[6] The UK's Net Zero Strategy (2021) and Industrial Decarbonisation Strategy (2021)

i) Sub-surface environment. The area from the CO_2 storage complex up to, but not including, the seafloor
ii) Marine environment. Encompassing the unconsolidated shallow seafloor sediments, and the water column ecosystem.
iii) Governance environment. The legal, regulatory, governance considerations of GCS, and the interplay with the capture and transport components of the CCS value chain.

The schematic representation of this report (Fig.1) illustrates each thematic section. Each section contains an overview of challenges, methods, findings, and solutions or opportunities for practitioners. We conclude with final reflections on the project and outline recommendations for relevant stakeholders.

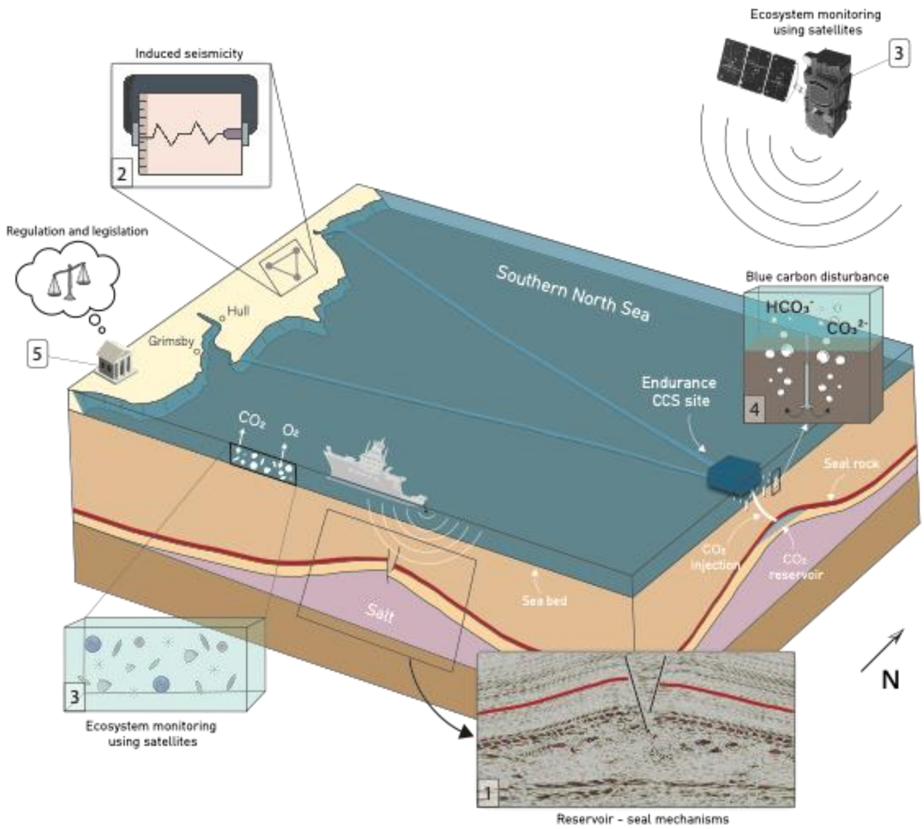

Figure 1 - Schematic representation of the research captured in this report. Sub-surface environment, marine environment and governance environment of the Endurance reservoir. (AGILE team, 2024).

Sub-Surface Environment

Background

To permanently store CO_2 deep underground, we need to have a good understanding of both the rocks we plan to inject into (the reservoir) and those that trap the CO_2 (the seal). This includes assessing the sealing capacity, lithology, permeability, thickness, and lateral extent of these rock units, along with identifying any geologic faults and fractures that could compromise the seal integrity. The flow properties of the reservoir rocks must also be analysed to determine the appropriate rate and pressure to inject the CO_2. Additionally, to understand how CO_2 will migrate post-injection, we must characterise the reservoir rocks away from the injection site.

This characterisation of reservoir and sealing rocks is analogous to the geological characterisations done by the hydrocarbon and geothermal industries. Methods and techniques for characterising subsurface geology have been developed over many decades, and more recently, they have been adapted and applied to planning for the safe and effective storage of CO_2.

In March 2024, more detailed guidance was issued by the national regulator for the CO_2 storage industry – the North Sea Transition Authority (NSTA) – to further advise companies applying for storage licences and permits on exactly what needs to be done when planning for CO_2 injection and durable storage (NSTA, 2024). This focuses on several areas:

1. Regional geology and basin characteristics.
2. Operational limits (pressure and rate of injection).
3. Interpretation of imaging data.
4. Detailed description of the reservoir and sealing formations.
5. Risks of leakage from wells and natural pathways (i.e., faults and fractures).
6. Faulting and fracture data.
7. Risk of earthquakes triggering by injection (i.e., "induced seismicity").
8. Monitoring methods that will be used to mitigate risks before, during, and after injection.

We have conducted research that focuses on (i) characterising seal integrity for leakage risk, (ii) background seismicity assessment, and (iii) regulatory considerations for the sub-surface. This research encompasses several of the areas identified by the NSTA.

Challenges

The challenges associated with injecting CO_2 into subsurface geological formations can be divided into those associated with drilling and injection operations (i.e., reservoir engineering challenges) and challenges in characterising the geological conditions of the storage site and its surroundings ahead of any drilling or injection operations. Here, we focus on the second group, which includes the significant task of monitoring potential earthquakes that might be induced by CO_2 injection.

Characterising the storage site geology. Characterisation of the storage site involves predicting the geology before wells are drilled to extract or inject hydrocarbon products. This process relies on the analysis of active source seismic data (described below) combined with historical data from exploratory wells previously used for oil and gas exploration. These abandoned wells are a part of the assessment of the site and its context. Active source seismic data provides 2D or 3D images of rocks deep underground by measuring reflected acoustic signals and is routinely acquired to identify and map rock units, such as thin sealing layers that are only tens of metres thick. However, this data has a limited resolution, making it difficult to detect small fractures (i.e., less than 10 m in length), that can affect rock composition and sealing properties. Additionally, the 1D well data (cores, cuttings and physical measurements taken during drilling) used for calibration with seismic data only covers large distances, which means that geological features could go unrecorded over localised areas. Therefore, the primary challenge here lies in identifying small-scale geological irregularities that are not captured by our data.

Predicting fault properties. The standard datasets used for site characterisation generally do not provide means for fully predicting the properties of faults in 3D. This poses a challenge when developing models of fault behaviour during CO_2 injection. Faults can act as a pathway for fluid migration, but others act as a baffle, having very little permeability. Characterising this uncertainty is key. In the Southern North Sea, the reservoir rock units that are targets for CO_2 storage are currently saturated with hypersaline water, or brines. When CO_2 is injected into these rocks, the brines are naturally displaced by the CO_2, which causes pressure in the reservoir to increase. This pressure increase can, in turn, affect the stability of nearby faults, potentially causing them to fail, which may lead to fluid migration.

Mapping heterogeneities in rock strength across the storage site. Due to the resolution limits of the seismic and well log data, we cannot expect to fully characterise the diversity of rocks involved in a storage site and the overlying sealing layers. While rock samples from drilled wells are analysed, this does not accurately represent the true strength of the rocks at a larger scale. Consequently, the fluid pressures that trigger tensile failure in the rock units during injection, potentially causing natural hydraulic fracturing and CO_2 leakage, can be uncertain.

Public perception of induced seismicity. Natural earthquakes continually occur across the British Isles. These earthquakes are typically low magnitude (less than 2) and are generally not felt by the public. These low magnitude earthquakes are also known as microseismicity. The BGS operate a network of seismometers across the UK that detects hundreds of earthquakes annually. In 2023, 300 earthquakes across the British Isles and the surrounding seas were reported, with a magnitude range of 0.1–3.9 (Galloway, 2023). Earthquakes have been detected in the vicinity of several CO_2 storage licence blocks in the Southern North Sea (Figure 1a), the majority of which are significantly deeper (~10 km) than the depth of CO_2 storage reservoirs (~1 km). Industrial activity involving fluid injection, including CO_2 storage, can cause additional microseismicity (e.g., Stork et al., 2015, Kettlety et al., 2021). Whilst it is unlikely that any induced earthquakes will be felt onshore, without an accurate and well-communicated monitoring regime there is the risk of false attribution of natural earthquakes to CO_2 injection. Maintaining public trust and the social licence to operate is crucial to ensuring the success of CCS projects.

Detecting offshore seismicity. Along with the BGS, we estimate that the current UK national seismic network can only reliably detect offshore earthquakes down to magnitude 2.00–2.25 near the Endurance licence block (Figure 1b). This detection limit is likely not sufficient for microseismic monitoring of GCS projects, as it will not observe any of the smaller events which may precede events considered to be of concern. Microseismic earthquakes, whether natural or induced, near or within the storage complex, could affect seal integrity. Monitoring earthquakes during injection helps mitigate this risk and can provide additional information on how the CO_2 storage complex is responding to injection.

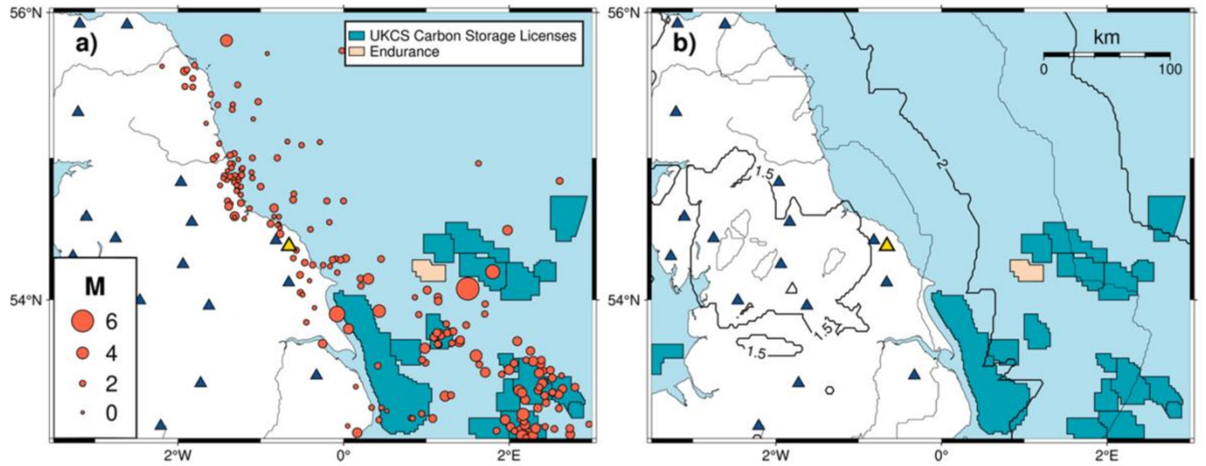

Figure 2 - a) Map of all earthquakes (red circles) that have been detected in the North Sea (Kettlety et al., 2024). b) Map showing the estimated detection limit of the UK national seismic network. The contours show the earthquake magnitude which can be detected at five or more seismometers, calculated following Mölhoff et al, (2018) and BGS assupmtions on network performance (Baptie, 2021). Blue triangles represent the location of seismometers comprising the UK national network. The yellow triangle shows the location of the seismic array deployed for this project.

Cost-effective passive seismic monitoring. Microseismic monitoring of CO_2 injection operations in the North Sea will require additional instrumentation. The minimum magnitude, earthquake location accuracy, and deployment costs vary depending on the instrumentation and methods used. While installing fibre optic cable sensors in wells or deploying ocean bottom seismometers would greatly improve detection and location accuracy, these are significantly more expensive than onshore sensors and have other logistical challenges. In this project we tested the potential of onshore seismic arrays to provide a cost-effective baseline earthquake monitoring tool.

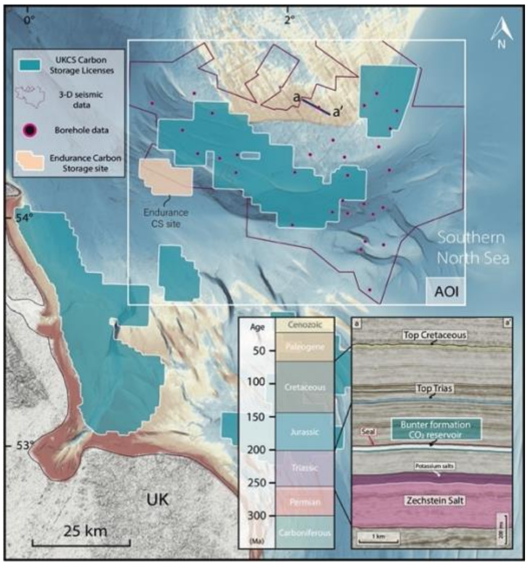

Figure 3 - Study area located over the Southern North Sea, showing data location and subsurface key geological surfaces (aa'). The background map is a bathymetric map obtained from https://emodnet.eu/. Geological chart modified after Taylor et al., (1998).

Methods

Characterising southern North Sea faults. The BGS has undertaken a multi-disciplinary study on the lithological characterisation of the seal units overlying the Bunter formation, the rock unit targeted for CO_2 injection in the Endurance project (Figure 4a). To complement this, we characterised a seal unit in the same region, the underlying Zechstein salts, and examined its role in the formation of CO_2 traps and possible CO_2 migration pathways that may affect seal integrity. We defined a circa 10,000 km² area of interest in the Southern North Sea encompassing many key CCS licensed areas (Figure 3). Within this area of interest, we identified and classified the evolution of 26 key sealing salt structures, including domes that are potential targets for GCS (Figure 4A). We did so by integrating multiple datasets, such as 3D seismic data and geological samples from over 300 industry-drilled wells licenced by the NSTA. This helped us map the CO_2 reservoir rock (the Bunter formation), the overlying layers (which define fault populations), and the underlying geological surfaces of Zechstein salt. This includes the very weak (i.e., mobile) potassium salt rich intervals (Figure 3). We found anomalously thick regions in the uppermost salt layers (Figure 3 aa') within dome structures, which are potential CO_2 traps. Our high-resolution maps of the potassium salts revealed significant anomalies in these structures, with overlying fault systems that could act as potential leakage pathways. We further explored the connection between the potassium salt anomalies and the fault systems above the domes. Our analysis of the distribution of faults (Figure 4A-4B) reveals that, in over half of the salt structures, certain rock layers can be shifted across the area (Figure 4B). This occurs due to faults (cracks) that intersect the CO_2 reservoir rock layer. These densely faulted areas would be riskier for CO_2 storage. This is not the case for the Endurance GCS site, where no faults have been detected. For structures where faults have been imaged, analysis of several key structural parameters (Figure 4B) shows no obvious systematic controlling factor, such as the steepness of geological structure or the thickness of underlying weak potassium salts, governing fault distribution and age of activity. These findings underscore the complexity of the geological processes at play and highlight the need for further site characterisation to fully elucidate these relationships at a particular CO_2 storage site.

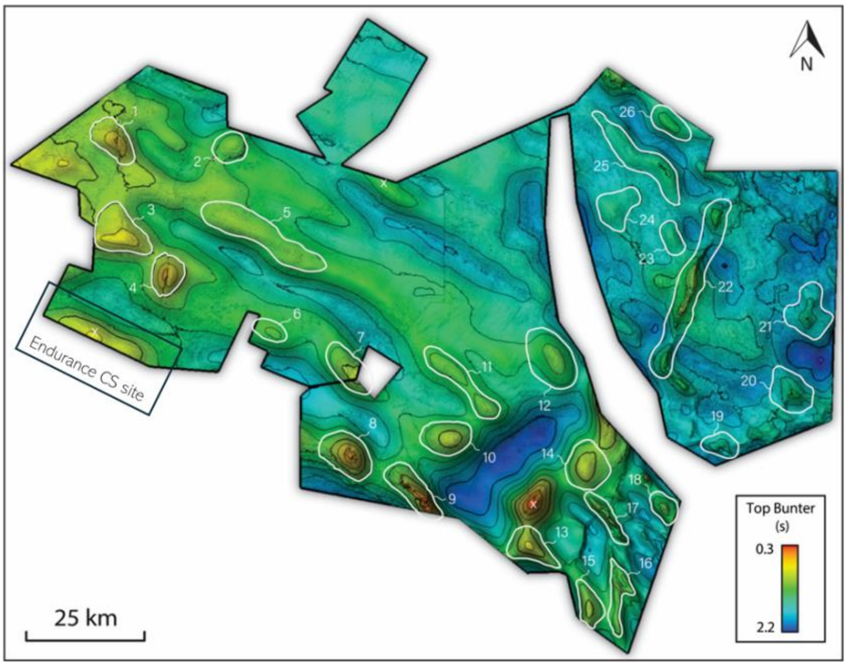

Figure 4 - Map of the top surface of the Bunter Reservoir showing the salt domes studied (white contours). Topography of the top Bunter surface displayed in time units (seconds).

Salt Structure	Thick underlying Potash	Steep >25° (✓) / Shallow < 25°(✗)	Faults detaching into top salt?	Faulted Bunter?	Faulted top Trias?	Faulted top Cret.?	Crestal Graben
1	✗	✓	✓	✓	✓	✓	✓
2	✓	✗	✗	✗	✗	✓	✗
3	✓	✓	✓	✓	✓	/	✗
4	✓	✓	✓	✓	✓	✓	✓
5	✓	✗	✗	✗	✓	/	✗
6	✓	✓	✗	✗	✗	/	✗
7	✓	✓	✗	✗	✗	/	✗
8	✓	✓	✓	✓	✓	✓	✓
9	✗	✓	✓	✓	✓	✓	✓
10	✓	✓	✗	✗	✗	/	✗
11	✓	✗	✗	✗	✗	✗	✗
12	✓	✓	✗	✗	✗	✓	✗
13	✓	✓	✓	✓	✓	✓	✓
14	✓	✓	✗	✓	✓	✓	✗
15	✓	✓	✗	✓	✓	✓	✗
16	✓	✓	✓	✗	✗	✓	✗
17	✓	✓	✓	✓	✓	✓	✓
18	✓	✓	✓	✓	✓	✓	✓
19	✓	✓	✓	✓	✓	✓	✓
20	✓	✓	✓	✓	✓	✓	✓
21	✓	✓	✓	✓	✓	✓	✓
22	✗	✓	✓	✓	✓	✓	✓
23	✓	✓	✗	✓	✓	✓	✗
24	✗	✓	✗	✗	✗	✓	✗
25	✗	✓	✗	✗	✗	✓	✗
26	✗	✓	✗	✗	✗	✓	✗

Figure 5 - The location of the data shown is in Figure 4. Associated matrix illustrating the workflow used in this study to assess the interrelationships between various components of these structures.

Monitoring low-magnitude earthquakes in the North Sea. To test the efficacy of seismic arrays for monitoring the North Sea, we deployed an array of eight seismometers in the North York Moors in late September 2024 (Figure 5). The array is designed to focus earthquake signals from all directions, analogous to a RADAR system. Our design takes learnings from similar seismic arrays deployed to monitor seismicity in the North Sea near Norway (Jerkins et al., 2022). We used an array analysis method known as beamforming, specifically frequency-wavenumber beamforming (Rost and Thomas, 2002), to enhance coherent earthquake signals across all eight seismometers. We recorded and analysed continuous data from October 2023 to April 2024. We searched the data for coherent signals in the seismograms, to associate them with a potential earthquake if the signal was strongly coherent. Our initial analysis has not detected any additional earthquakes in the North Sea over the study period and further data analysis will continue after the project. However, we have used primarily onshore seismicity detected by the UK seismic network to calibrate the array's performance. Our array can detect earthquakes down to a local magnitude of 1.0 at a similar distance from the array as Endurance (Figure 5), demonstrating the capability of seismic arrays to detect microseismicity in the Southern North Sea. A permanently installed array would yield further improvements in detection capability. Beamforming also resolves the direction which a detected signal arrives from. This allows us to project a detected signal from the array to estimate its source location. For our calibration events, we retrieve locations which agree with those reported by the BGS using only the data from our array and some simplistic assumptions of the seismic wave velocities (Figure 5). Our work highlights the potential for arrays to improve our capability to detect and locate microseismicity in the Southern North Sea, especially if multiple seismic arrays are installed along the East Coast of the UK.

Figure 6 - One of the eight seismic stations that form our array. The seismometer is buried up to 1m deep with only the solar panel, which powers the system, and telemetry equipment, left above ground. [Source: Joseph Asplet, 2024]

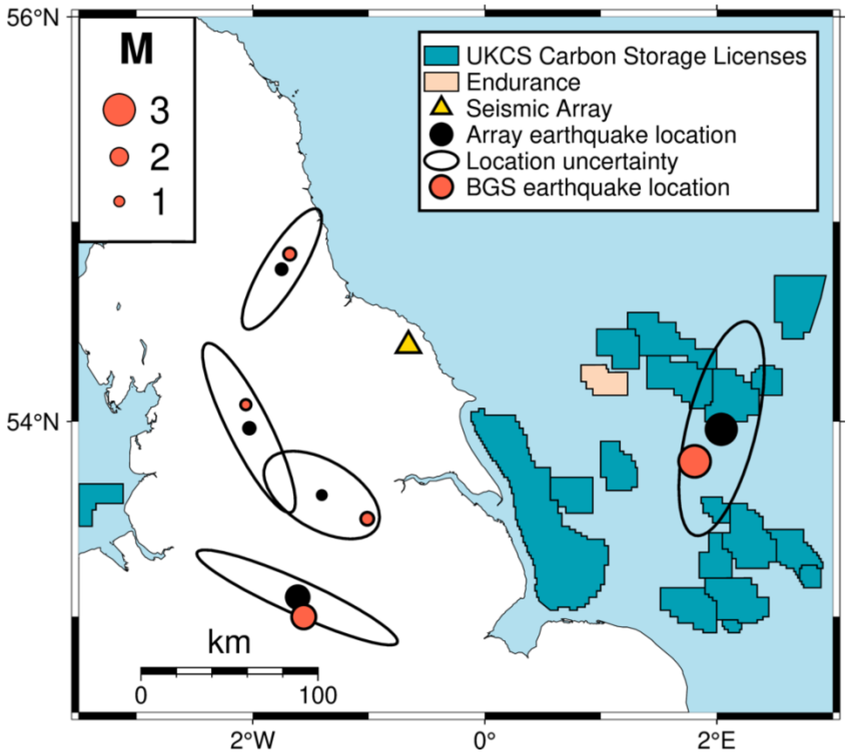

Figure 7 - Map of earthquakes detected and located by our seismic array (black circles) compared to locations reported by the BGS (red circles). Our locations are calculated using only data from the array and simple assumptions of the seismic wave velocities. Earthquake symbols are scaled proportional to the local magnitude reported by the BGS.

Regulating the sub-surface environment

The physical risks associated with keeping CO_2 safely underground are only one component of the challenge. Co-location of GCS with other uses of the marine space, like wind turbines or hydrocarbon production is important, particularly in the crowded Southern North Sea. The NSTA oversees both the hydrocarbon industry and the carbon storage industry, and so provides unique insights into managing conflicts of use of the UKCS. Harmonising regulatory frameworks to pre-empt and manage these conflicts of use is the Offshore Petroleum Regulator for Environment and Decommissioning (OPRED) and the Office for Environmental Protection (OEP), may have responsibility to manage environmental impacts from the GCS facility. A clear understanding of "who regulates what" would help pre-empt regulatory overlap.

Other risks include regulation, building, operational costs, and project financial viability. The NSTA has a range of regulatory powers conferred by the Petroleum Act 1998, the Energy Act 2011, and Energy Act 2016. These powers allow the NSTA to regulate key components for the sub-surface, which include measurement, monitoring, and verification (MMV), the storage complex, leakage events, and operator compliance. Also, the Energy Act 2008 (§C.3) provides the licencing regime governing offshore GCS, and the EU CCS Directive (2009) was transposed into UK law by the Carbon Dioxide (Licensing etc.) Regulations 2010 (SI 2010/2221).

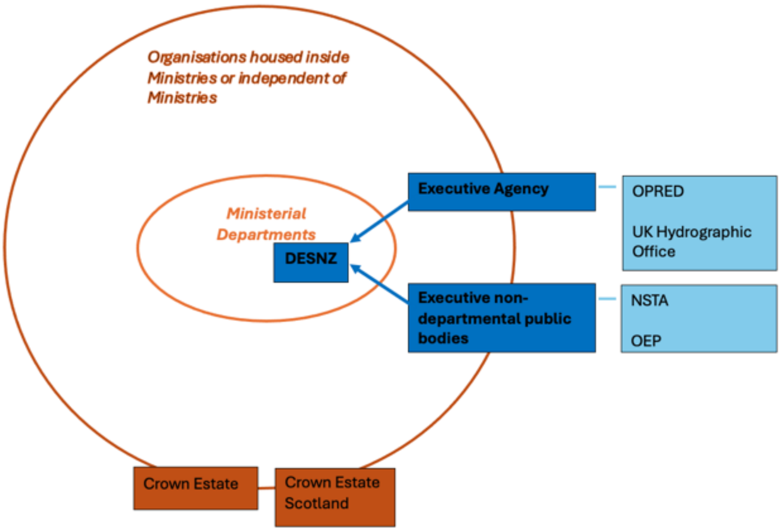

Figure 7. Regulatory bodies governing leakage and seismicity. Green indicates agencies are under the umbrella of DEFRA. Blue indicates agencies are under the umbrella of the DESNZ. The Crown Estate and Crown Estate Scotland are independent bodies who are the property owners and property developers.

Solutions and Opportunities

The UK has a relatively comprehensive GCS regulatory regime, but some gaps remain concerning monitoring and the definitions of the storage complex and leakage. DESNZ is currently consulting on the most appropriate methods for monitoring offshore GCS (NSTA 2023). Information from the AGILE workshop[7] and stakeholder interviews has highlighted that the most important policy gap is a lack of clarity in the regulations and recent NSTA guidance (NSTA, 2024)[8] on what constitutes safe (i.e., minimal environmental or human harm, low risk) geological storage. Leakage is defined as CO_2 migrating "outside the storage complex" (Annex 1 to EU CCS Directive, 2010 Storage Regulations by section 7(1)(a)). The storage complex includes secondary sealing units, which are shallower than the primary seal formations. In the most extreme circumstances, these secondary sealing formations could be chosen in the storage permit application process to extend to the seabed.

We have identified indications for future research. These include:

- Numerical or analogue modelling of parameters that drive fault formation and reactivation over salt cored anticlines.
- Analysis of fault seals and how faults can influence seal integrity over reservoirs targeted for CO_2 injection
- Investigating non-fault related Seal Bypass Systems
- Reanalysing drilling reports for lost time incidents within Triassic and Permian salts to test for systematic controls on borehole stability and integrity.
- Scoping the potential for seismic arrays to improve earthquake depth locations

[7]A workshop held by the University of Oxford on March 1st with GCS stakeholders in the UK, as part of the AGILE project.

- Optimising seismic array analysis methods for the Southern North Sea, including scoping sites for additional array deployments as the foundation for collaborative monitoring of all licence blocks.

We have identified some opportunities and solutions for operators and regulators. These include:

Recommendation	Rationale	Implementation
Greater consideration of the uncertainty parameters with which operators are working	This could come in the form of a Disclosure statement from operators, with emphasis on the range of sub-surface uncertainty. This emphasis may encourage due diligence and begin building public trust in GCS operators.	As part of the permitting process, the regulator asks for a disclosure statement where the operators state their uncertainty range and agree that they will, with due diligence, meet standards set by the regulator. This format is not legally penalising but encouraging the company to be honest about the knowns and known unknowns.
Reporting out requirements in GCS decommissioning regulations	In oil and gas decommissioning regulation (Petroleum Act 1998) there are relinquishment or surrendering of acreage requirements. These reporting-out requirements allow the Government to hold companies accountable if they are not fulfilling obligations in the licence.	The Energy Act 2016 transferred responsibility from the Minister to NSTA to revoke licences. An amendment to the Energy Act 2008 (s76), may allow this hydrocarbon licencing provision to be extended to GCS legislation.
Consider how data, interpretations and modelling studies that underpin the storage permit and licence application process can be scrutinised by independent authorities	Background studies could be open to academic/public scrutiny without risk of loss of commercial advantage but would have the advantage of making the process of awarding a storage permit appear more transparent to the wider public.	The regulator requires data, interpretations and modelling submitted with a storage permit or licence application to be published, within the limits of confidentiality and commercial competition.
Ask for independent third-party assurance for other recognised authorities at the storage permit stage.	Independent assessment of the technical input into the application for a storage permit will make it clear to interested parties that the process is robust. This is standard practice for many commercial arrangements involving sales of subsurface assets, farm-ins/farm-outs or equity negotiations.	The regulator asks for, or arranges, relevant independent third parties to assess the technical input to storage permit applications.
Develop a model for funding regional monitoring activities in the short- and long-term	Passive seismic monitoring systems are capable of monitoring multiple licence blocks simultaneously. A regional, monitoring approach, shared between operators, would reduce costs and create a consistent baseline.	The regulator requires joint monitoring of projects on a regional level where operators pool resources or contribute to an independent body to operate all onshore passive seismic monitoring arrays.
Develop a strategy for making seismic monitoring data publicly available	Passive seismic monitoring should not be covered by operator privilege in perpetuity. Public datasets enable independent scrutiny and facilitates further academic research, which can be used to improve future monitoring.	Raw seismic waveform data, which can be used for further research, should be published following international standards. All earthquakes detected by monitoring systems should be reported to the BGS. Earthquake detection reports should be presented carefully to avoid misunderstanding or false attribution.
Apply learnings from seismic monitoring of other subsurface activities. If mitigation options like traffic light schemes (TLSs) for seismicity are implemented, they should be risk-based.	Monitoring frameworks exist for other industrial subsurface activities. An example is the BGS serving as an independent monitoring authority for onshore hydraulic fracturing, where a seismicity TLS was implemented. Subsequent research has shown that a risk-based provision, rather than pre-determined thresholds, would improve TLS approaches to induced seismicity regulation. Furthermore, there is scope to share learnings with similar activities such as geothermal and gas storage projects.	Any seismic traffic light system should be risk-based. The regulator should engage with regulators of other activities (geothermal, gas storage etc.,) to share learnings and best practices.
Issue regional and licence-specific guidance on passive seismic monitoring and MRV procedures	The risk thresholds of individual projects depend on many factors such as the proximity and potential hazard to infrastructure or population	Define the scope of the seismic monitoring required in terms of risk thresholds, sensitivity of monitoring, temporal extent, spatial extent, potential

	centres. This would aid operators in planning and licencing/injection permitting process.	impacts on reservoir integrity, and the potential hazards of the project.

Marine environment

Background

A key tenet for a technology like GCS to achieve net-zero status is that its carbon storage capacity must significantly outweigh the carbon footprint associated with its deployment and operation (Holloway et al., 1993). In the marine environment, "blue" carbon refers to the carbon captured biologically by marine organisms and stored in the ecosystem, with the potential for disturbance. In low-visibility (turbid) shelf seas such as the North Sea, those organisms consist mostly of phytoplankton that live in the shallow water column. These tiny photosynthetic cells actively remove carbon from the atmosphere by fixing CO_2 into their organic components while releasing oxygen into the water, providing habitable environments for marine life. As they sink and die, the organic carbon is buried in the sediments, where it remains stored away from the atmosphere. Phytoplankton biomass and their influence on the optical characteristics of the surface ocean have been designated as essential climate variables (Global Climate Observing System, 2024) based on the critical ecosystem services they provide. Given the ongoing anthropogenic climate change and, in particular, ocean warming, these essential climate variables offer a quantifiable measure of ecosystem health and functioning. Thus, conserving marine ecosystems or, rather, minimising the disturbance of their blue carbon stocks and associated ecosystem services enhances the co-benefits of deploying climate change mitigation technologies.

The Endurance site sits in a Special Area of Conservation (Burrows et al., 2021), which provides one of the most productive fishing grounds globally as well as supports offshore wind farms for the generation of renewable energy. The risk of CO_2 or brines leaking from the Endurance GCS reservoir into the water column is very low (BP, 2023). Despite this minimal risk, such an event could potentially lead to seawater acidification and toxicity, posing threats to marine phytoplankton. This may compromise the ecosystem's efficiency in sequestering carbon in the sediments and maintaining a habitable environment. Despite phytoplankton's critical role, the current ecological baseline assessment for the Endurance GCS site (BP, 2023) overlooks the contribution of phytoplankton to total blue carbon stocks and, instead, focuses on phytoplankton diversity and blue carbon in the sediments. Our work addresses three key themes in the marine regulatory environment for GCS that require more attention. First, we aim to investigate the interactions of leaked CO2 with sedimentary blue carbon to estimate the size of the impact on the phytoplankton above the storage in the unlikely event of CO_2 leakage at the Endurance. Second, we seek to identify tipping points (critical stress thresholds) for phytoplankton recovery in experiments simulating the combined disturbance of CO_2 leakage and ocean warming. Lastly, we aim to understand the drivers of natural ecosystem variability in space and time at the Endurance using satellite data. In the absence of *in situ* monitoring at the Endurance, satellites provide the most comprehensive data picture, potentially allowing us to differentiate between natural trends and external disturbances induced by stressors such as storms or human activities.

Challenges

Surveys to estimate leakage magnitude, likelihood, and potential pathways. Identifying areas where sedimentary blue carbon hotspots and leakage exit points coexist is essential. This can be achieved by assessing and monitoring the total amount of carbon in the sediments combined with seismic data to locate potential leakage pathways or geological faults likely to reactivate.

Long-term monitoring of potential leakage impacts. Currently, few studies examine the long-term effects of CO_2 leakage on phytoplankton communities, either in isolation or in combination with other ecosystem stressors. Whilst the risk of leakage during transport, injection, and post-injection from the storage reservoir is considered very low (BP, 2023), even a minor and sustained leakage through surface sediments could perturb seabed and planktonic communities. Such leakage could cause shifts in phytoplankton community composition, with knock-on effects on the rest of the marine ecosystem and the services it provides.

Multi-variate approach to culture experiments. Since a potential CO_2 leak would interact with an environment already changing due to anthropogenic climate change, phytoplankton culture experiments should test how CO_2 leakage interacts with other stressors, such as ocean warming. Understanding the system's non-linear response to multiple, simultaneous stressors would make perturbation studies more realistic. Additionally, the rapidly changing environment due to climate change means that perturbation studies done in the past may not apply to the future marine state.

Optimising the spatial footprint of leakage monitoring. Defining the spatial footprint of the potentially impacted area is crucial, ensuring it is sufficiently large to cover the area of potential leaks yet optimised to minimise computational costs and data storage requirements for regional analysis. Traditionally, the spatial footprint has been informed by ocean circulation models, where local currents control the horizontal and vertical spread of potential leaks of CO_2 and hypersaline fluids. The spatial footprint is site-specific (determined by local geological and hydrodynamic features) and season-specific (as hydrodynamic features change over the seasons).

Implementing cost-effective technologies for baselines and monitoring. The current plan for detecting and quantifying leakage of CO_2 and hypersaline fluids at the Endurance includes deploying a combination of various sensors on fixed platforms (landers and moorings with attached acoustic, optical and chemical sensors) and mobile platforms (ships and autonomous underwater vehicles) (Blackford et al., 2015). Oceanographic instrumentation is expensive to deploy and maintain, and there is a growing interest to also capitalise on less carbon-intensive technologies like satellites currently orbiting the Earth.

Reducing the cost of assessing marine ecosystem's health status. The marine ecosystem is complex and heterogeneous at very small scales, and describing it often requires exhaustive and costly *in situ* surveying of its various biological, chemical and physical variables. Ecological baseline assessments thus tend to be multivariate exhaustive descriptions (Blackford et al. 2021). Moving towards synthetic metrics that reliably capture the marine ecosystem's status would make monitoring more cost-effective and efficient.

Methods

Investigating the interactions of leaked CO_2 with sedimentary blue carbon. We began our investigation by estimating the sedimentary blue carbon stock in the Endurance area. For this purpose, we acquired seabed sediment samples from the British Geological Survey (BGS) sample repository covering various locations across the area (Figure 8). Chemical analysis in the laboratory and integration of the results across the site led us to an estimate of total sedimentary blue carbon stock (both organic and inorganic) of approximately 20 megatonnes of carbon (Mt C). However, in a very low probability scenario of a leakage event, the sedimentary blue carbon which is disrupted drops to less than 0.010 Mt C. Then, we investigated the dynamics of CO_2 dissolution in sediments to understand its impact on sedimentary blue carbon. We set up a vertical gas bubbling column (Figure 9) where sediments were bathed in seawater bubbled with CO_2 for five days. Sediment samples were collected daily to measure the changes in carbon content. The bubbling experiments showed that some of the bubbled CO_2, which is simulating a leak, is neutralised by alkalinity released from the inorganic carbon fraction, specifically in the form of calcium carbonate present in the sediments. Conversely, the organic carbon fraction remained constant throughout the experiment as it did not react with the CO_2 and stayed intact. This suggests that GCS sites with significant inorganic carbon in the sediments will neutralise some of the leaked CO_2, thus minimising the impact on the plankton above the storage site. In contrast, sites with sediments rich in organic carbon have a lower risk of blue carbon loss from a leakage event but lack the neutralisation potential.

Impact of leakage on pelagic phytoplankton. To understand how quickly phytoplankton recover after facing a leakage disturbance, we set up controlled exposure experiments in the laboratory and monitored their biomass and photosynthetic activity. We chose to culture three groups of marine phytoplankton representative of the North Sea: diatom, cyanobacteria and green algae. We grew them in artificial seawater and let them acclimate for 15 days to specific conditions of temperature, salinity, and light (Figure 10). Next, we exposed them to three different treatments for 11 days: (i) elevated CO_2 levels at approximately 4000 parts per million (around ten times current atmospheric CO_2 levels), (ii) warming of +3°C (a worst-case scenario contemplated by IPCC projections), and (iii) a combination of both. Following the treatment period, the cultures were monitored for an additional 15 days to assess any recovery. The culture experiments showed that elevated CO_2, either alone or in combination with warming, significantly increased the growth of the cyanobacteria and green algae. In contrast, diatoms exhibited a much lower growth rate compared with the control conditions. During the recovery phase, the impact of previous exposure to stressors persisted, affecting the growth rates of all phytoplankton groups. These results indicate the long-lasting effects of warming and CO2-induced acidification on the phytoplankton communities, compromising their normal functioning.

Ecological baseline assessment using remote sensing technology. To detect a CO_2 leak before it impacts phytoplankton communities, we need a method that can distinguish baseline, pre-operational ecological variability from changes induced by a leak. This is the purpose of an ecological baseline assessment, which we have developed for the Endurance GCS site by surveying phytoplankton biomass (Figure 11), water column blue carbon stocks generated by phytoplankton (Figure 12), and the environmental variables that control them. Our ecological baseline assessment uses publicly available remote sensing satellite data (https://www.oceancolour.org, https://oceancolor.gsfc.nasa.gov/l3/, https://data.marine.copernicus.eu/products) to develop a comprehensive long-term view of the baseline status of the marine ecosystem above the Endurance. The UK Centre for Environment, Fisheries and Aquaculture Science (CEFAS) contributed a rich dataset of *in situ* North Sea environmental and biological variables, essential for ground-truthing satellite data and providing information during periods when clouds obscure satellite visibility (Figure 13). This validation process allows us to assess the reliability of satellite-based tools in establishing baseline assessments within optically complex shelf sea environments, where non-algal particles and coloured dissolved material can obscure the signal of the phytoplankton. The acquired satellite data show that phytoplankton bloom dynamics in the Endurance area are correlated with global mean temperature, pH and water clarity. Phytoplankton within a 100 x 100 km^2 area centred on the Endurance fixes approximately 1.6 Mt C annually, contributing to the water column blue carbon stocks. This value is consistent with other modelling studies (Kossack et al., 2023) and *in situ* observations (Joint & Pomroy, 1993) in the North Sea. For comparison, the UK's woodland and forests removed 4.9 Mt C from the atmosphere in 2021 (JNCC, 2023).

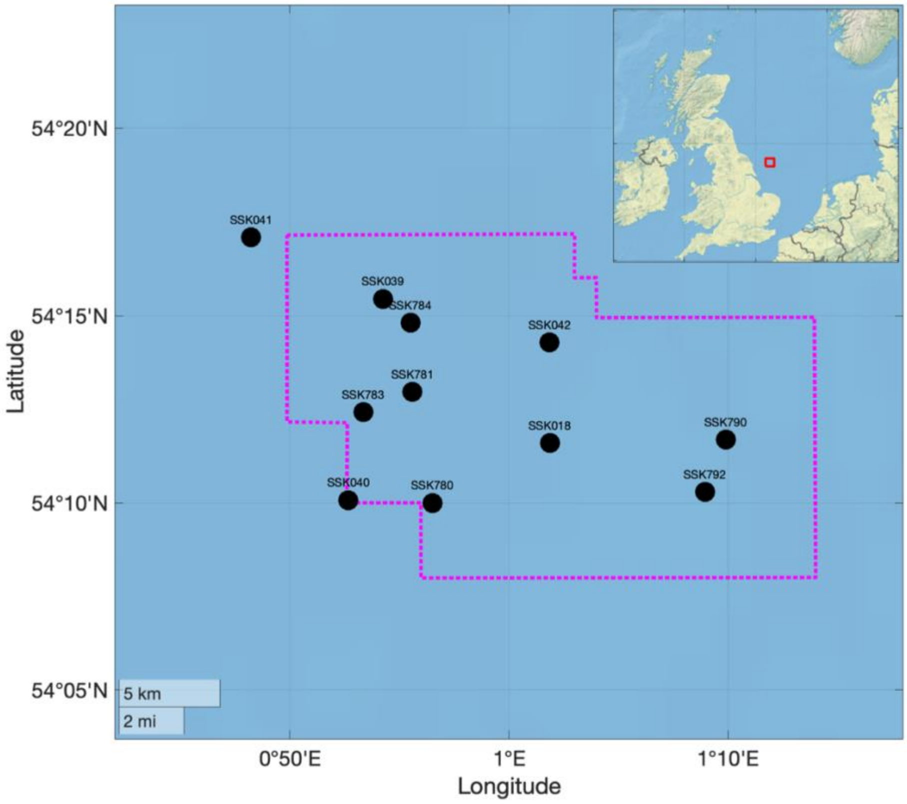

Figure 8. Locations of seabed sediment samples collected from the British Geological Survey for estimating sedimentary blue carbon stocks. The boundaries of the Endurance GCS site are shown in fuchsia.

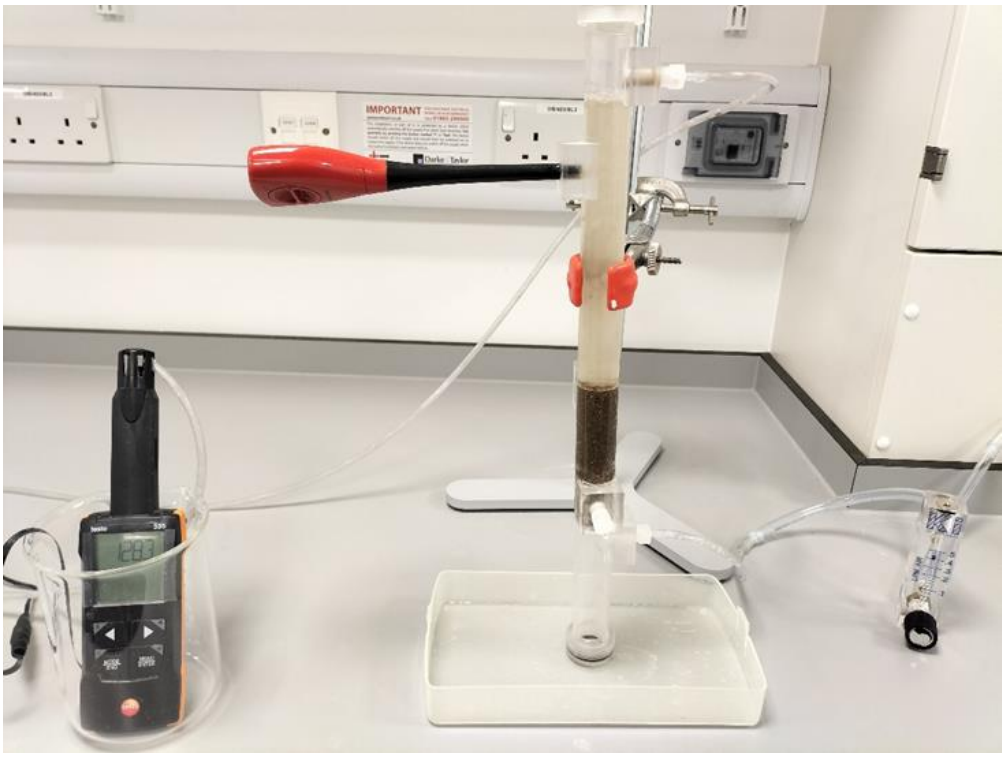

Figure 9. Vertical gas bubbling column used for CO2 bubbling experiments on sediments.

Figure 10. Experimental setup with phytoplankton culture containers (microcosms) used to test the effects of CO2 leakage and warming on phytoplankton communities.

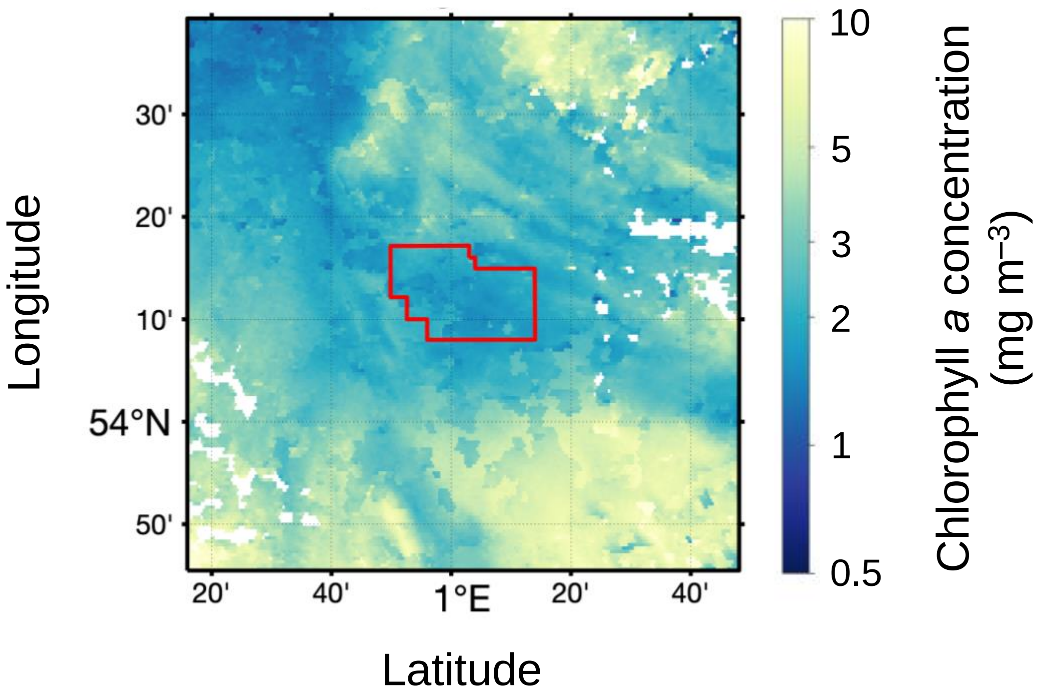

Figure 11. Satellite image of chlorophyll a concentration (a proxy for phytoplankton biomass) in May 2020, with a spatial resolution of 300 m. The assessment area covers 100 × 100 km2 around the Endurance GCS site (inner shape delineated by red boundaries). Data are from the Ocean Land Colour Imager (OLCI) sensor aboard the European Space Agency's (ESA) Sentinel-3 satellite.

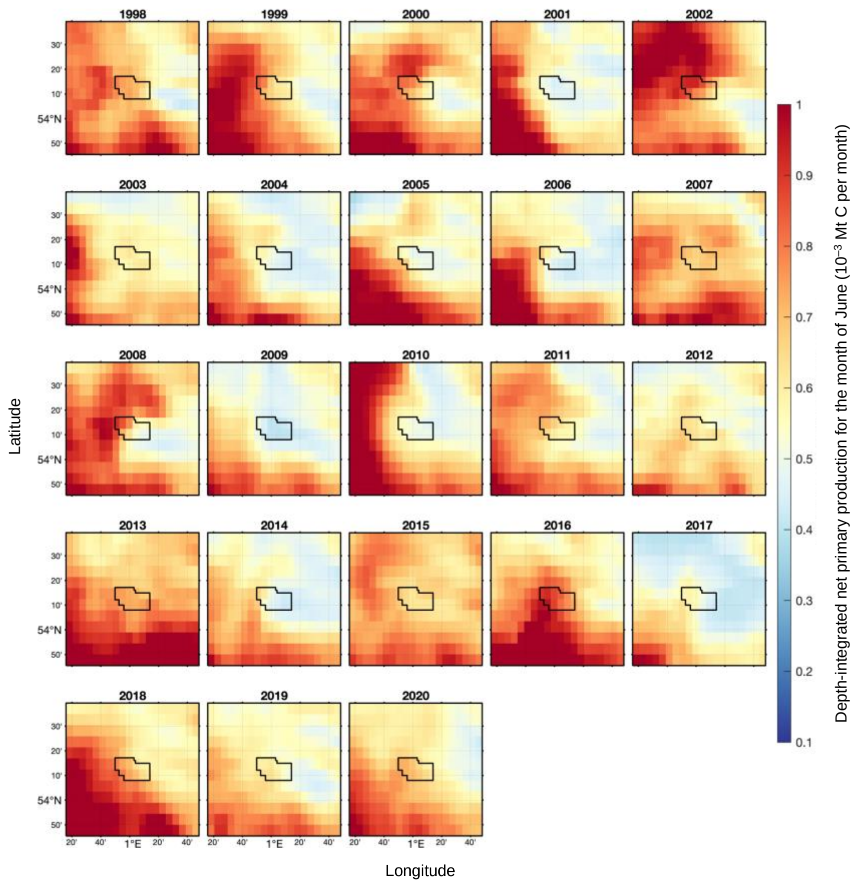

Figure 12. Satellite-based images showing spatial variations in the monthly standing stocks of water column blue carbon (in megatonnes of carbon per month) for June from 1998 to 2020. The

assessment area covers 100 x 100 km^2 around the Endurance GCS site central point (inner shape delineated by black boundaries). Data are from the European Space Agency (ESA) Biological Pump and Carbon Export Processes (BICEP) project's dataset of monthly marine phytoplankton net primary production.

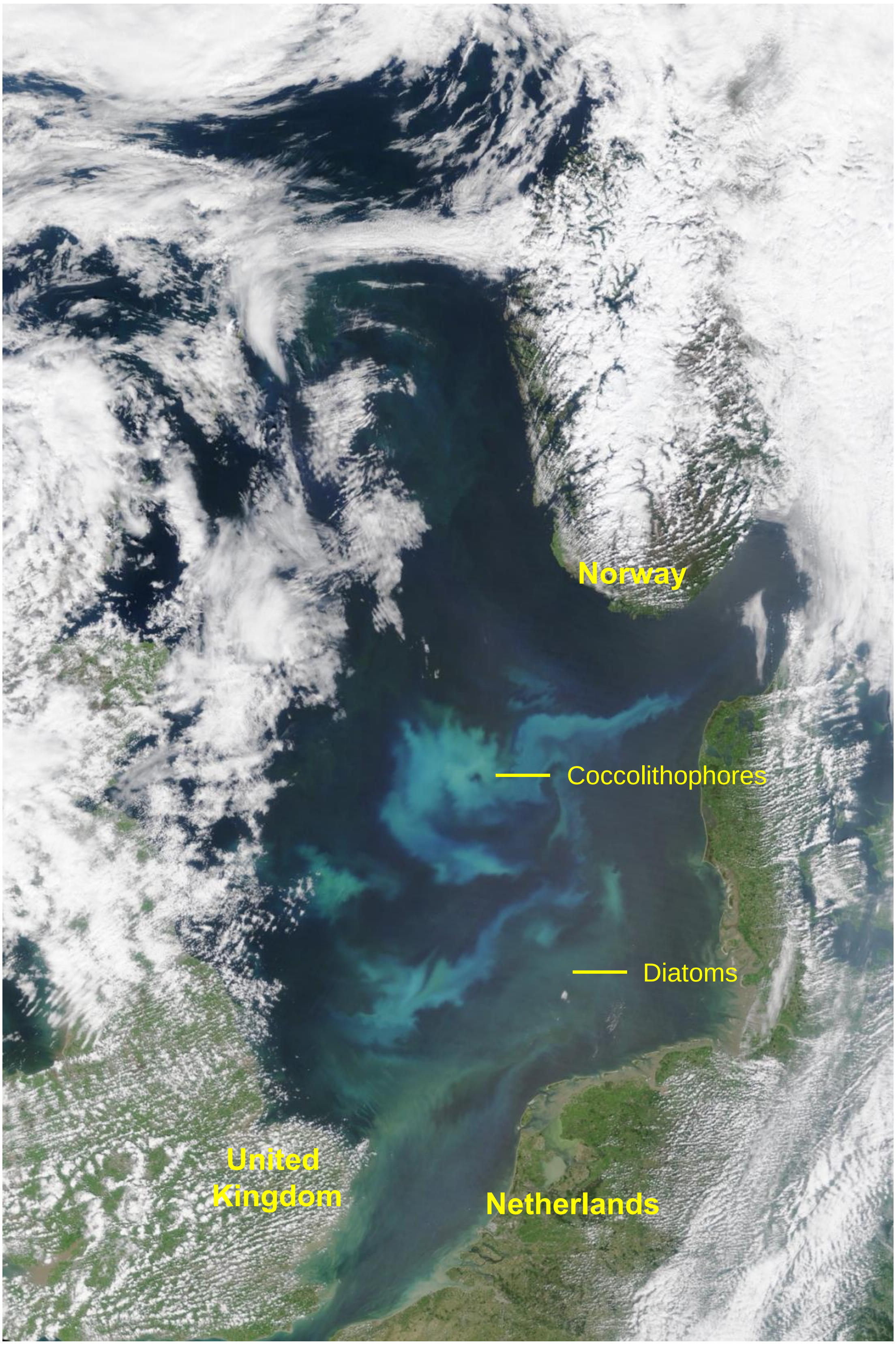

Figure 13. True colour satellite image of a phytoplankton bloom composed of coccolithophores (turquoise) and diatoms (green) in June 2015 in the North Sea. Image credit: Jesse Allen, NASA Earth Observatory, using MODIS data on NASA's Terra satellite.

Regulating the marine environment

The UK marine environment is governed by a collection of regulatory bodies (Figure 14), which include government ministries like DEFRA and DESNZ, non-executive bodies like JNCC, and executive agencies like CEFAS. Each body's jurisdiction depends on how it interacts with the onshore-offshore areas, the distance offshore of the marine activity, and the activity requiring regulation (including, but not limited to fishing, trawling, offshore wind, hydrocarbon extraction, geological carbon storage or deep-sea fibre-optic cables).

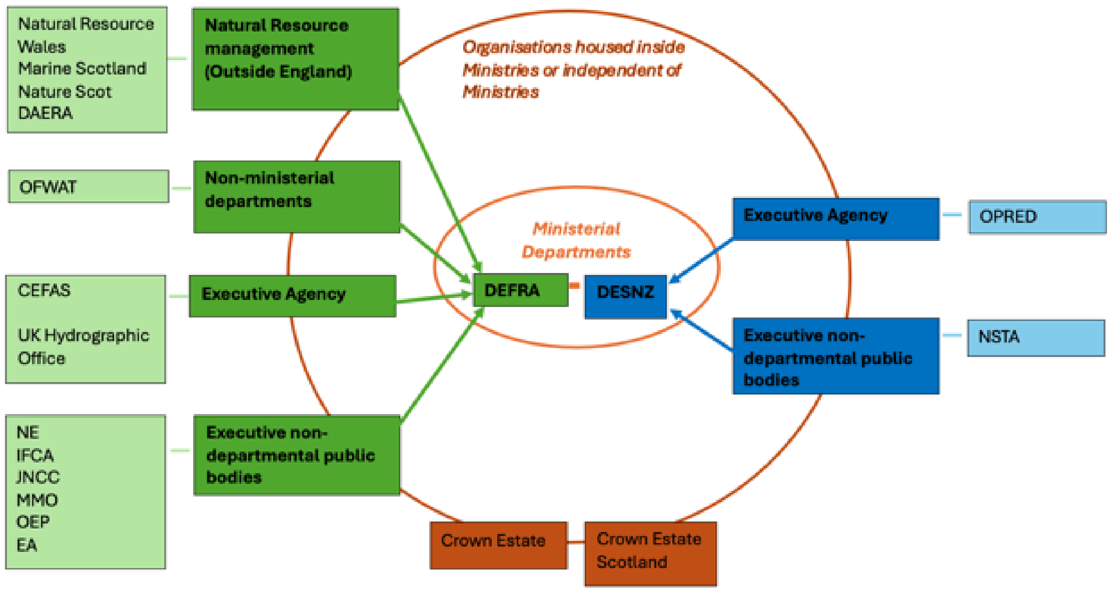

Figure 14. Regulatory bodies overseeing the UK marine environment. Green indicates agencies are under the umbrella of DEFRA. Blue indicates agencies are under the umbrella of the DESNZ. The Crown Estate and Crown Estate Scotland are independent bodies who are the property owners and property developers.

Offshore GCS involves over 20 different governmental agencies and public bodies[9]. For example, CEFAS, OPRED and resource management authorities (like OEP) have mandates for

[9] CEFASCentre for Environment Fisheries and Agricultural Science

DAERA	Department of Agriculture, Environment and Rural Affairs (Northern Ireland)
DEFRA	Department of Environment, Food and Rural Affairs
DESNZ	Department of Energy Security and Net-Zero
EA	Environment Agency
IFCA	Inshore Fisheries Conservation Authorities
JNCC	Joint Nature Conservation Committee
MMO	Marine Management Organisation
NE	Natural England
NSTA	North Sea Transition Authority
OEP	Office for Environmental Protection

environmental protection and may simultaneously oversee blue carbon in offshore GCS licence blocks. Although DESNZ is the main decision-maker and co-ordinator, having so many regulators involved can add complexity for DESNZ managing or harmonising marine regulation for blue carbon within planning, licensing, and permitting for offshore GCS. It is crucial to balance these regulatory complexities to allow companies to build and operate GCS facilities swiftly and effectively, whilst also maintaining robust environmental protections for the marine ecosystem and blue carbon. The key take-away is that governance and regulation of the UKCS involves many actors, so although this regulatory mapping is specifically for offshore GCS, these challenges apply to other research fields and has implications beyond GCS research.

The UK regulation of the marine environment concerning carbon is nascent but developing. The key features are;

- Regulation of blue carbon in UK coastal and offshore waters is not currently included in the UK's GHG inventory (Kershaw et al., 2022).
- A blue carbon framework for the benthic and pelagic realms for UKCS has not been developed yet by NEIRF[10] (Ward et al., 2023). While a global blue carbon code is being developed by the International Union for Conservation of Nature and Natural Resources (IUCN) (del Mar Otero, 2021), it focuses on afforestation and reforestation in mangroves, rather than benthic or pelagic ecosystems.
- DEFRA and CEFAS are working on the UK Blue Carbon Evidence partnership, which aims to enhance the regulators' understanding of blue carbon in relation to offshore GCS (Underwood et al., 2023).
- DEFRA's 25-year Environment Plan (2018, Chapter 5, p. 104), considers the marine environment and identifies habitats important for ecosystem carbon sequestration. The plan also mentions ocean acidification because of carbon sequestration, either natural or via CCS. This aligns with the 'Because the Ocean Initiative' Declaration under the Paris Agreement (2015), and the UK's obligations under the OSPAR convention (1992) to protect the marine environment in the North Atlantic coast.
- The 2022 UK Climate Change Risk Assessment (UKCCRA) highlights risks to UK natural carbon stores from industrial carbon sequestration facilities (Priority Risk Area 3) and urgently calls for a baseline assessment of all blue carbon stocks (UKCCRA 2022, p.25).

Solutions and opportunities

Recommendation	Rationale	Implementation
Case-by-case studies for deploying offshore net-zero technologies	Blue carbon stocks vary significantly by location and, particularly for water column blue carbon, also depend heavily on the time of the year. This spatiotemporal dependency necessitates case-by-case studies of the marine environment to ensure the safe deployment of offshore net-zero technologies. This recognises that findings from	Ecological baseline assessments should be conducted locally for each offshore GCS site.

OFWAT Office for Water Services Regulation Authority
OPRED Offshore Petroleum Regulator for Environment and Decommissioning
[10]UK government's Natural Environment Readiness Fund (NEIRF)

	the Endurance GCS may not be applicable to other GCS sites or even other offshore net-zero technologies, such as wind farms.	
Investigation of the sedimentary inorganic carbon buffering effect against acidification	CO_2 leaking into the sediments from the reservoir beneath induces the dissolution of carbonate minerals (inorganic carbon) naturally present in the sediments. This dissolution releases alkalinity that neutralises the acidity induced by the leaked CO_2. This has a potential protection effect on the organisms living in the sediments and water column, which might not tolerate changes in pH.	Quantifying the stock of inorganic carbon in the sediments could help analyse the recovery potential of an area affected by a leakage of CO_2 from the subseafloor.
Multi-stage survey to assess the total amount of sedimentary inorganic and organic carbon in license areas	Assessments of sedimentary blue carbon at risk of disturbance should be done during the different stages of the project. This includes a preliminary assessment during well drilling, infrastructure building, and each subsequent stage of the project.	Due diligence is required to ensure that GCS operations do not disturb more carbon than the potential storage capacity. An inventory of sedimentary carbon in the pristine storage site will help measure total disturbance in the case of a leakage event and attribute carbon loss, linking these adjustments to the project's carbon credits.
Assessment of blue carbon stocks in their full extent	Current regulation focuses on sedimentary blue carbon stocks, overlooking water column carbon stocks, which have traditionally been challenging to quantify due to their high temporal variability. However, advancements in satellite-based marine carbon data products from NASA and the European Space Agency's Colour Climate Change Initiative now enable the quantification of water column carbon stocks. Additionally, NASA's newly launched PACE mission offers the potential to provide more highly resolved data products, further enhancing our ability to assess and protect blue carbon stocks.	Blue carbon accounting should be conducted in a joined-up way, taking into account both sediments and the water column.
Need for long-term mesocosm studies	Enclosed experimental systems known as mesocosms (larger) and microcosms (smaller), enable testing the effect of perturbations on natural assemblages of organisms under controlled environmental conditions.	Long-term mesocosm studies, although costly and not always easy to access, should be combined with microcosm studies (culture experiments) to enhance our understanding of the broader and long-term ecological consequences of CO_2 leakage events in marine environments, especially in a more dynamic and warmer ocean. This combined approach will help assess phytoplankton stress thresholds more accurately.
Phytoplankton biomass and productivity as indicators of a healthy marine ecosystem	Phytoplankton biomass and growth rates are valuable biological metrics that can integrate numerous marine ecosystem processes, including physical, chemical and biological factors. Furthermore, they can be monitored from space daily with a resolution of	Phytoplankton should be used as an additional indicator of the health status of the marine ecosystem using a variety of ocean observing platforms (*in situ* and satellite)

	approximately 1 km, making them excellent indicators of the state of the marine ecosystem.	
Need for satellite time-series data to monitor episodic disturbances and future change	Remote sensing can augment the spatiotemporal coverage of *in situ* oceanographic observations, providing both historical and real-time data at high resolution and offer a low-cost, non-labour-intensive solution to traditional *in situ* sampling. These features make satellites an effective tool for establishing baselines against which to measure future changes, maximising detection whilst minimising cost, particularly considering the high spatiotemporal heterogeneity of the marine system.	Satellite remote-sensing data should be used as an additional tool for baseline assessments and ecosystem monitoring.
Testing the strength of leakage in the satellite signal using analogues	Before implementing satellite-based baseline assessments, we must test them against analogues of leakage scenarios, such as natural CO_2 seep sites or controlled sub seabed CO_2 release experiments. If satellite data from these events fall outside the range of long-term mean dispersion, it likely indicates that the satellite signal is detecting a disturbance in the ecosystem. Additionally, we need to test how future changes in the frequency and intensity of extreme events, which may introduce more intra-seasonal and inter-annual variability within the marine system, may also impact our ability to attribute anomalies specifically to GCS operations.	Need to fund research that looks at the feasibility of detecting CO_2 and brine leaks using satellite data. There are outstanding questions regarding resolution and sensitivity which require further research.
Ecosystem monitoring by impartial organisations	Ecosystem monitoring should be entrusted to impartial organisations with extensive knowledge of the oceanographic and ecological characteristics of UK's shelf seas and equipped with advanced marine instrumentation for monitoring, such as CEFAS. A workshop with stakeholders of the Endurance GCS site held at Oxford (1st March 2024) highlighted the need to strengthen the connection between the GCS industry and the UK environmental agency CEFAS, which routinely monitors the North Sea.	CEFAS has pioneered the development of marine automated measuring buoys (known as SmartBuoy systems) that collect high temporal resolution *in situ* oceanographic data in UK shelf seas. These SmartBuoys are currently the only direct (*in situ*) observing system routinely operating near the Endurance. Collaborating with government agencies and oceanographic centres will also ensure access to real-time and historical *in situ* oceanographic data in the North Sea collected from cruises and buoys. This collaboration is crucial for validating satellite observations and extending baseline assessments into the future.

Governance environment

Background

This section details the (i) legislation, (ii) regulation, (iii) public acceptance, and (iv) governance challenges associated with the deployment of CCS in the UK. The creation of policy for the CCS industry is the responsibility of the Department for Energy, Security and Net Zero (DESNZ). The Minister of State for DESNZ has authority over the industry, granted by powers conferred through primary legislation (or the parent act and statutory instruments). Ministers of State for DESNZ introduce secondary legislation provided it is within their "granted powers" and consistent with primary legislation. The NSTA has the regulatory responsibility to administer many aspects of offshore GCS in the UKCS, including, but not limited to, licencing and permitting. Thus, DESNZ instructs the NSTA to execute the regulations and implement the policy. Figure 15 illustrates the regulatory frameworks for the entire GCS project lifecycle and below we explain each of them, which are deployed in various stages.

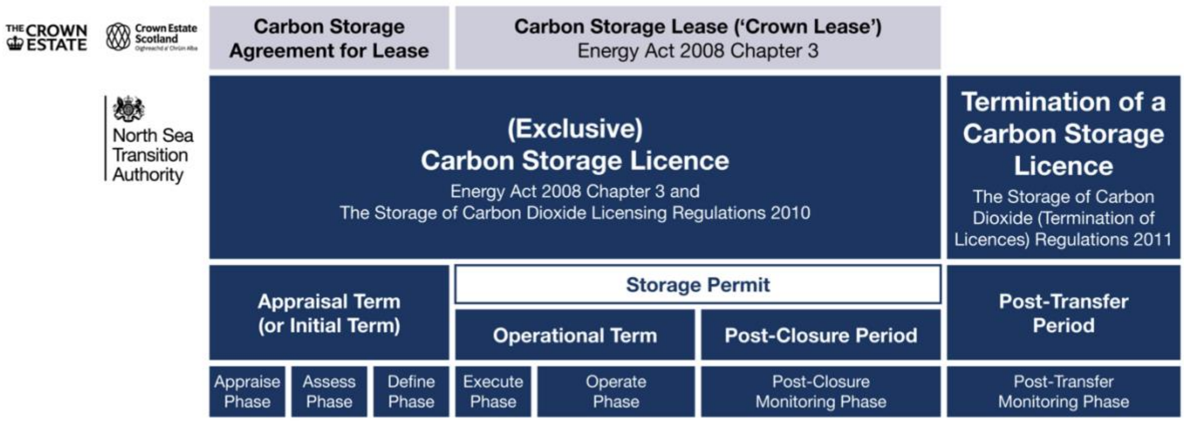

Figure 15 - Phases in a carbon storage licence (NSTA 2023, p.9).

Developing a GCS project first involves applying for a licence, which is a lengthy process including financial and compliance checks. The issuance of a license is contingent on the NSTA deeming the operator safe and responsible. While the frameworks for licencing are statutory, it is worth highlighting that the finer details of implementation are not in practice as no UK GCS project is operational yet. As the GCS industry scales and the regulatory framework is tested (on the Endurance reservoir), unforeseen challenges may arise, requiring remediation.

The second stage involves securing a permit. Unlike a license, which can cover multiple projects, a permit applies only to a specific project. Although the NSTA (2024) has published permitting guidance documents, these have not yet been implemented and may require amendments as operational challenges arise.

A third stage relates to the operational phase of a permit. The most significant issue at this stage is the pressure-fronts developing in reservoirs, which may extend beyond the licence block area. This is a risk mitigation issue which needs addressing by NSTA guidance. In practice, companies may adjust their injectivity, or conduct pressure management via brine release. However, pressure mitigation measures must be balanced with maximising CO2 storage in pore-space, so oversight by the NSTA of pressure management across the whole basin may help balance these tradeoffs.

The final stage relates to risk mitigation post-closure. The NSTA obliges companies to conduct MMV on the reservoir for 20 years post-closure, and the NSTA performs the data verification. If there have been no incidents after 20 years, the Government will take responsibility for the well. For companies, this is a long-term liability, so to mitigate long-term storage risks, private insurance companies are beginning to step in. They provide insurance to de-risk projects (Howdens, 2023), however, this aspect of the insurance industry remains nascent. Other investment concerns include the long-term costs of reservoir Monitoring, Measurements and Verification (MMV). As highlighted in the sub-surface chapter, companies may be hesitant to invest if the monitoring is too capital-intensive, requiring trade-offs between costs and the suitability/regularity of MMV methods (Turrell et al 2022). As the end goal of GCS is to safely store as much CO_2 underground as possible, funds may be better spent on new storage operations assuming appropriate MMV methods are employed, rather than excessively monitoring reservoirs with very low risks of leakage.

Challenges

There is a dynamic policy environment and rapid technological developments. This makes developing an evidence base for CCS particularly difficult because work needs updating constantly. Also, this makes communicating research– in workshop settings, or to politicians and the public – more challenging. This was particularly evident in the workshop, where representatives from oil majors were engaging with concerns raised by environmental NGOs. Representatives from the hydrocarbon industry were using different terminology and communication styles in comparison to the NGOs, so finding common definitions and uses was key to successful communication. Understanding how policy developments across diverse government sectors intersect is important to achieve a holistic picture. Indeed, this may be an important challenge to policymakers too.

Coordination of regulators and legislation. The landscape of key legislation governing CCS undergoes frequent updates and amendments. There are many factors contributing to this. First, Brexit has necessitated the rescindment of key implementation of EU Directives[11]. Second,

[11] The Storage of Carbon Dioxide (Amendment) (EU Exit) Regulations 2022 rescinds UK implementation of the EU 2009 directive, the 2010 Storage of Carbon Dioxide Regulations, and the termination of licenses regulations 2011.

The Retained EU Law (Revocation and Reform) Act 2023 'sunset[s]…EU-derived subordinate legislation and retained direct EU legislation' (Westlaw 2023) and revokes the whole EU decision for:

1. Commission Decision of 17 August 2012 amending Decisions 2010/2/EU and 2011/278/EU as regards the sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage (2012/498/EU)
2. Commission Decision of 18 December 2013 amending Decisions 2010/2/EU and 2011/278/EU as regards the sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage (2014/9/EU)
3. Commission Regulation (EU) No 1031/2010 of 12 November 2010 on the timing, administration and other aspects of auctioning of greenhouse gas emission allowances pursuant to Directive 2003/87/EC of the European Parliament and of the Council establishing a system for greenhouse gas emission allowances trading within the Community
4. Commission Decision of 3 November 2010 laying down criteria and measures for the financing of commercial demonstration projects that aim at the environmentally safe capture and geological storage of CO_2 as well as demonstration projects of innovative renewable energy technologies under the scheme for greenhouse gas emission allowance trading within the Community established by Directive 2003/87/EC of the European Parliament and of the Council (2010/670/EU) (Westlaw 2023).

updates to international protocols, like the London Protocol[12], will require implementation in regulation, based on legislation in the UK statute book, so that the UK can import CO_2 from European partners to store in UKCS. Third, there are many factors which have not yet been considered in depth by policymakers or legislators because CCS is an emerging industry. For example, although the Health and Safety at Work Act 1974 (HSWA) can be used to regulate safety, there is no UK regulation specifically governing health and safety in onshore components of the CCS value chain, or offshore GCS. (HSE 2013).

Economic viability. Although economic viability is not directly a governance issue, the long-term economic viability of CCS (including GCS) is a government (and HM Treasury) issue. Most projects currently rely on public funding in the form of government subsidies, low-interest loans, or targeted financial support mechanisms. Note that the total costs for building and operating a UK offshore GCS industry remain uncertain and politically sensitive due to the lack of operational projects in the UK. The costs of a GCS project depend on several factors including the type of carbon capture (point source capture, BECCS, or DACCS), the capture process technology, the transport method, and the storage location. Estimating operational costs is made more complicated by the regulatory requirements for MMV activities pre-, intra-, and post-operation, which have a high cost, and so consume much of the project budget. Currently, these costs are tied to regulatory rules that require MMV activities to continue for 20 years after the well is closed before responsibility can be transferred to the UK Government[13].

Carbon pricing. Energy producers and industrial operators in the UK are subject to carbon pricing under the UK Emissions Trading Scheme (UK-ETS), which incentivises CCS by imposing compliance costs (penalties) on emissions. However, the UK's carbon price (and before it, the EU-ETS carbon price), has been too low to support CCS deployment. To address this the government has introduced distinct business models for different types of emitters. These models guarantee a fixed return (the 'strike' price) above the ETS price (the 'reference' price) for each tonne of CO_2 captured and safely stored. This hedges against price volatility and de-risks investment for investors at the capture end of the supply chain. Additionally, the government supports the transport and storage segments of the supply chain through a Transport & Storage business model. This business model establishes an economic regulatory regime linked to a user-pays revenue model, supplemented by a government support package which ensures a steady flow of income for storage operators even if CO_2 flow from capture facilities is interrupted.

Methods

Researching governance, policy and regulation requires qualitative methods including document analysis, coding, archival, interviews, and polling data gathered via the interactive stakeholder workshop held in Oxford on 1st March 2024. For the interviews, we contacted over 100 stakeholders and conducted 23 semi-structured interviews. For the workshop, we invited over 100 stakeholders, and 65 people attended in-person. The interviews were analysed using NVivo and cross-checked using document analysis.

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[12] The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) or "London Protocol" for short, prevents dumping of waste and marine pollution. (International Maritime Organisation IMO). More information available at: https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx

[13] Page 36, Guidance on applications for a carbon storage permit (NSTA, 2023).
"The post-closure monitoring plan should be for a duration of at least 20 years, as outlined in regulation 7 of the termination regulations [The storage of carbon dioxide (termination of licences) Regulations 2011], unless the storage operator can demonstrate to the NSTA that data-based evidence gathered through monitoring indicates that the stored CO2 will be completely and permanently stored."

Solutions and Opportunities

Our research has helped us to identify some key opportunities, and potential solutions which policymakers and legislators may consider implementing. We begin with indications for future research, and then recommendations for regulators and legislators and suggestions for implementation.

Our research is not a complete summary of all the evidence gaps, and environmental risks relating to offshore GCS. Indications for future research include:

- Following developments to the Levelling Up and Regeneration Act 2023, and how this influences the planning regimes for CCS and offshore GCS projects.
- Deeper understanding of the post-2035 funding models for the industry after government CfDs and subsidies end.

The following are recommendations for regulators to current evidence gaps that we have identified:

Recommendation	Rationale	Implementation
Clarify legal liability surrounding licence blocks	Lawyers acting on behalf of industry operators, have identified a lack of provision for liabilities between licence blocks (oil-producing, carbon-storage). Lack of clarity regarding these liabilities hinders further project developments. Provisions for licencing and permitting are laid out in the Energy Act 2008. An amendment would clarify this uncertainty for project developers and projects from other industries in the vicinity of a GCS reservoir.	Provisions for licencing and permitting are laid out in the Energy Act 2008 §C.3. An amendment, or a Henry VIII clause, which is signed by the Minister of State without going through Parliament. This would clarify this uncertainty for project developers and projects from other industries in the vicinity of a GCS reservoir.
Provision for cross-border reservoirs and liabilities between Norway-UK shared continental shelf	Lawyers acting on behalf of industry operators have identified a lack of provision for liabilities related to pressure fronts extending beyond the UKCS, to the Norwegian Continental Shelf.	Remedying this is a matter for Ministers of State and their counterparts in the Norwegian Government. Options include bi-lateral agreement, and joint statements of intent.
Need for integrated marine planning across different marine uses (e.g., carbon storage, offshore renewable infrastructure, fishing, marine protected areas, deep- sea mining or shipping)	Siloing of marine spatial planning from GCS considerations, with potential seabed licensing conflicts between offshore renewable infrastructure, seabed cables, fishing, trawling, deep-sea mining and GCS. Some of these risks are being addressed in the Crown Estate's Marine Route Map (because of recent use conflict between renewable operator and oil developer), but there are questions of hierarchy and prioritisation of use of the marine space.	Publish the decisions reached at the Marine Planning Forum, run by the Crown Estate, and use this consensus to design a marine planning system which crosses all sectors using the marine space.
Clarify GCS post-closure monitoring	Regulators should clarify these obligations, and draw-up statutory regulations. This may provide a	These obligations could form part of a new set of

obligations for leakage and induced seismicity.	clear baseline for project developers so they may allocate necessary capital and provide certainty for future developments. These obligations could form part of a new set of regulation aimed specifically at retrofitting oil and gas during the decommissioning phase for GCS, and regulation for decommissioning GCS.	regulation aimed specifically at retrofitting oil and gas during the decommissioning phase for GCS, and regulation for decommissioning GCS. Amendments to the eligibility criteria in the hydrocarbon decommissioning regulation would allow for hydrocarbon infrastructure to be re-used for GCS.
Clarify transfer liabilities of CO_2 between operators along CCS value chain	This is needed so that fellow operators, and the insurance industry, can attribute risk and divide OPEX. In the current regulation there is no clear understanding of when CO2 is counted as "delivered" into the storage reservoir. This has implications on the carbon credit system(s), and company's revenue stream from the UK/EU ETS.	Regulators may also consider multi-client MMV, where operators can pool resources to monitor adjacent fields and pipelines. Pooling resources this way can be a more cost-effective method of monitoring, and this may also standardise the data collection formats for regulators.
Create steady policy to support CCS/GCS developments over time	Robust, consistent policy, with adequate forward planning is seen as essential by industry representatives, and commentators, and as of yet, unaddressed in the regulation. Policy changes in the past have hampered the development of CCS in the UK (e.g., scrapping in 2015 of the £1bn fund dedicated towards CCS).	Implementation of steady policy is difficult as policy is determined by the politics of Ministers. One solution would be to make critical policy levers statutory, so it is more difficult to be amended in retrospect.
Consolidate understanding of the implementation of the Levelling up and Regeneration Act 2023 in relation to CCS projects and clusters	The Act created significant planning uncertainty because it alters environmental impact assessments (EIAs) to Environmental Outcome Reports (EORs) and consolidates ministerial power to make final decisions for an infrastructure project like GCS. In practice, however, this has generated considerable confusion for project developers.	Legislators may wish to issue a statement of use, clarifying which ministers are responsible for signing off EORs, and which projects are eligible for special environmental exemptions.
Mandatory leakage response	There is a need to ensure that the impacts on the surrounding ecosystem and attached carbon credits are quantified. It also fosters close communication between the project operator and regulator.	Project operators should rapidly respond to any leakage, document the event and submit a report of the leakage event.
Final carbon reporting	If there has been significant carbon loss from the storage complex, measuring carbon at the beginning and end of the operations (net carbon sequestration of the project) is crucial. This information is relevant for future carbon storage operators, financiers, capture and transport operators and regulators. Additionally, brine	At the end of the project, the total sedimentary carbon quota should be provided, especially if there has been a leakage or brine release for reservoir pressure management.

	contains heavy metals, which may cause unforeseen disturbances to sediments and benthos, which also need to be reported.	

Final Remarks

This report examined the environmental and governance risks and opportunities of offshore carbon storage in the UK. We examined the state of knowledge of offshore carbon storage on the U.K. continental shelf, and identified some evidence gaps; both policy, and scientific, that may need addressing to safely store CO_2 in the UKCS continental shelf sea.

We reiterate that considerable study has contributed to the Endurance reservoir, and that leakage risks are very low. However, in this report, we have identified several scientific evidence gaps for operationalising offshore GCS in the UK. Given this, our research made recommendations (and suggested methods for implementation) to address these identified risks for U.K. offshore GCS.

The geological storage industry is still nascent, and we cannot rely on GCS as our only avenue of climate mitigation to meet our 1.5°C climate targets. Given this, the U.K. Government must simultaneously explore other climate mitigation like nature-based solutions (NbS), removals, demand-reductions, efficiency gains, public education campaigns, and mobilising public-private partnerships to hasten climate action.

In summary, our key recommendations to address the evidence gaps are;

Consider how data, interpretations and modelling studies that underpin the storage permit and licence application process can be scrutinised by independent authorities	Background studies could be open to academic/public scrutiny without risk of loss of commercial advantage but would have the advantage of making the process of awarding a storage permit appear more transparent to the wider public.	The regulator requires data, interpretations and modelling submitted with a storage permit or licence application to be published, within the limits of confidentiality and commercial competition.
Assess blue carbon stocks in their full extent, including by the use of satellite remote-sensing data	Current regulation focuses on sedimentary blue carbon stocks, overlooking water column carbon stocks, which have traditionally been challenging to quantify due to their high temporal variability. However, there is a need to quantify inorganic carbon in marine sediments to estimate its protection effect against increased CO2-induced acidity; conducting phytoplankton stress experiments that, on top of leakage, consider climate change impacts; using remote sensing of ocean colour to map water column blue carbon stocks and detect leakage signals in surface waters. Advancements in satellite-based marine carbon data products from NASA and the European Space Agency's Colour Climate Change Initiative now enable the quantification of water column carbon stocks. Additionally, NASA's newly launched PACE mission offers	Offshore GCS regulation should consider the risk to blue carbon stocks to their full extent, that is, sediments plus the water column.

	the potential to provide more highly resolved data products, further enhancing our ability to assess and protect blue carbon stocks.	
Consolidate understanding of the implementation of the Levelling up and Regeneration Act 2023 in relation to CCS projects and clusters	The Act created significant planning uncertainty because it alters environmental impact assessments (EIAs) to Environmental Outcome Reports (EORs) and consolidates ministerial power to make final decisions for an infrastructure project like GCS. In practice, however, this has generated considerable confusion for project developers.	Legislators may wish to issue a statement of use, clarifying which ministers are responsible for signing off EORs, and which projects are eligible for special environmental exemptions.

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