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Executive summary

The RISCS (Research into Impacts and Safety in CO_2 Storage) project assessed the potential environmental impacts of leakage from geological CO_2 storage. Consideration was given to possible impacts on groundwater resources and on near surface ecosystems both onshore and offshore. The aim of the project was to assist storage site operators and regulators in assessing the potential impacts of leakage so that these could be considered during all phases of a storage project (project design, site characterisation, site operation, post-operation and site abandonment, and following transfer of liability back to the state). A secondary objective was to inform policy makers, politicians and the general public of the feasibility and long-term benefits and consequences of large-scale CO_2 capture and storage (CCS) deployment.

The project has developed a set of credible impact scenarios from which to assess potential leakage in a range of terrestrial and marine reference environments. The baseline (most likely) scenario in each case was that of the evolution of the system with no leakage of CO_2. Alternative impact scenarios considered leakage from point sources, such as escape through wells or faults, or more diffuse leakage. Fluxes and impacted areas in each of these scenarios would be very site-specific but illustrative plausible values were presented based upon a detailed literature review. Updates were also made to a publically available database of Feature Events and Processes, which provides a knowledge base and auditing tool for scenario development.

Potential impacts from leakage were examined through field and laboratory experiments and through observations at sites where natural CO_2 seepage is occurring either into groundwaters or marine or terrestrial surface environments. Experimental design and the wider implications of leakage were also studied through modelling of both onshore and offshore systems. The main findings of the project have been compiled in a Guide to potential impacts of leakage from CO_2 storage, which is available through the project website (www.riscs-co2.eu)

The results indicate that leakage most commonly occurs over small areas (metres to tens of metres across) and that dispersion can be rapid in both the atmosphere and in sea water or groundwater. However, dispersal can be limited in unusually still air conditions or when ocean water is stratified such as in areas where dense colder water underlies warmer less dense water under calmer summer conditions. Overall, impacts from CO_2 leakage will tend to be more localised than the effect of other stresses on the environment such as bottom trawling and ocean acidification or, onshore, the effects of extreme weather conditions or pests. Environments already under stress may be more affected by leakage and the timing and duration of any leak will also affect the scale of the impact. In general natural recovery should be rapid once leakage ceases unless unique isolated habitats are affected. Site selection should therefore consider the Conservation Objectives of protected areas such as Natura 2000 sites.

Impacts have implications for leakage monitoring, which needs to be able to detect relatively small features within large areas and distinguish leakage from natural background variability. The latter would be greatly assisted by good baselines and by monitoring parameters other than those directly indicative of CO_2, such as temperature and dissolved oxygen offshore, oxygen, nitrogen and isotopes in soil gas. These vary with CO_2 in natural processes and thus their relationship with CO_2 can be diagnostic of leakage. Monitoring of reference sites away from the CO_2 storage location can assist in understanding the evolution of baselines and further aid recognition of leakage.

Project Concept and objectives

RISCS aimed to develop the knowledge base necessary for both storage site operators and regulators to assess the potential impacts of leaks on near surface ecosystems – both in terrestrial and marine environments. As Europe and the world moves from proof-of-concept small-scale demonstrations to full-scale, full-chain demonstrations of the technology, operators and regulators require both the underpinning information and robust frameworks necessary to make appropriate decisions about the potential environmental impacts of CO_2 storage projects. Such information will also support policy makers, politicians and the general public in their assessments of the feasibility and long-term benefits and consequences of large-scale CO_2 capture and storage (CCS) deployment. The RISCS concept directly responded to the FP7 call Energy.2009.5.2.1: Safe and reliable CO_2 Storage by addressing:

- The potential environmental impacts of leaks from storage sites during all phases and timescales of a storage project (project design, site characterisation, site operation, post-operation and site abandonment, and following transfer of liability back to the state);
- A range of options for CO_2 storage including storage both onshore and offshore, in a variety of geographical locations such as the North Sea, the Mediterranean, northern European terrestrial and southern European terrestrial environments;
- The need, as specified within the EC Directive on CCS[1] and as recommended in OSPAR Guidelines[2] on CO_2 storage in the marine environment, to undertake a robust, methodological and comprehensive assessment of all risks arising from CO_2 storage, including an assessment of the environmental consequences of leaks;
- The needs of environmental protection regulators and site operators to have clear and agreed definitions of credible scenarios for leakage and quantified descriptions of realistic impacts;
- The increased capability to assess and predict the potential consequences of leaks from storage sites will allow both operators and regulators to greatly improve site safety. It will also allow operators to improve mitigation plans that reduce the potential for such impacts throughout the storage project. It will allow regulators and policymakers to design and implement both strategically (i.e. for identifying appropriate sites for lease) and operationally, fit-for-purpose regulations, most especially in evaluating environmental impact assessments;

Significantly, the increased knowledge of potential impacts and their communication through the development of the RISCS' 'Guide to potential impacts of leakage from CO_2 Storage' for CO_2 Storage will directly build confidence in, and address public acceptance of, geological storage. Production of drafts of the Guide, and ultimately the final version, as defined deliverables, to a

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[1] EC Directive 009/31/EC on the geological storage of carbon dioxide

[2] http://www.ospar.org/

quality acceptable to stakeholders, has allowed the overall objectives of the project to be measured and verified.

If Europe is to expand the use of full-size, full-scale demonstrations of CCS, there need to be clear definitions of the terms used to assess and predict site performance, and underpinning knowledge to inform both operators and regulators, that must be workable and fit-for-purpose. RISCS has developed key definitions of:

- Credible scenarios for leakage of CO_2 from a storage complex;
- Significant impacts on an ecosystem from CO_2;
- Ranges of CO_2 leakage rates that may cause significant impact.

These definitions were further developed through a combination of:

- Field-scale and laboratory experimental investigations which simulated, under well-constrained conditions, the potential impacts from elevated CO_2 concentrations in the near-surface and surface, in both terrestrial and marine environments (both North Sea and Mediterranean). The successful conclusion of these experiments can be measured and verified through the quality of the progress reports, presentations and published final outputs.
- Investigations of CO_2 leakage in natural systems which specifically addressed key gaps in our understanding that have not been investigated before and are measurable and verifiable in the same way as the field experiments.
- Enhancement of a range of modelling tools that have allowed the site-specific data obtained from the experimental and observational programme to be more widely applied. This will assist in developing environmental impact assessments for CO_2 storage sites (initially the large demonstration projects). The success of this approach can be monitored through the improved and linked models produced.
- Consultation and discussion, throughout the project, with a range of stakeholder groups, both within the RISCS project and external to it. The stakeholders included representatives of electricity generators, oil and gas companies, environmental NGOs, policymakers and environmental protection regulators, as well as research groups. They included several groups involved in parallel studies internationally and recognised experts in the field of safety and risk assessment in CO_2 storage. The input of the stakeholders and their approval of the Guide are a measure of its quality.

RISCS has provided fundamental research on environmental impacts, and refinement of near-surface monitoring techniques, in a European setting, necessary to underpin frameworks for the safe management of CO_2 storage sites. To achieve this, RISCS research focussed on the quantitative assessment of environmental impacts resulting from the exposure to known CO_2 concentrations and fluxes and the development of associated monitoring methods. Research was based around field laboratory experiments, measurements at natural leakage sites and numerical simulations, for both marine and terrestrial ecosystems. Outputs provided the underpinning information necessary to:

- Enable a rigorous evaluation of the safety of storage sites;
- Carry out Environmental Impact Assessments (EIAs) for sites;
- Design storage sites to minimise the probability of hazardous scenarios;
- Help to design near surface monitoring strategies;
- Develop a framework to communicate the safety of storage to key stakeholders (regulators and the public).

Regulatory frameworks governing the geological storage of CO_2 have been developed in some countries across the world. However, several major projects were licensed before this legislation was enacted, under petroleum legislation (e.g. Sleipner, Weyburn, In Salah) or are classed as research or experimental facilities (e.g. ASGARD, Frio, CO_2CRC Otway Project, Nagaoka, ZERT). Within the EU regulations, under the EU Directive on geological storage of CO_2 and OSPAR, it is recognised that issues of potential leakage and long-term stewardship must be addressed if the potential for CO_2 capture and storage to provide substantial reductions in atmospheric CO_2 emissions is to be realised. Additionally, studies on public perception of CCS indicate concerns about the effect of leakages on the environment, particularly onshore, where storage projects have encountered stiff opposition, for example in the Netherlands, Germany and Denmark.

The monitoring principles under the EC Directive specify the need to detect both leakage of CO_2 and significant adverse effects on the environment. Both these goals were central to the RISCS project. They help to underpin the accounting of stored CO_2 and the associated credits awarded under the Emissions Trading Scheme. The Directive should ensure a high level of protection of the environment and human health from the risks posed by geological storage of CO_2.

Main scientific and technical results

Descriptions of Reference Environments and Scenarios

Objectives

The overall objective of WP1 was to develop a comprehensive set of credible CO_2 impact scenarios for a range of near-surface reference environments to provide a sound basis for the regulation and monitoring of CO_2 storage sites. The scenarios aimed to provide input to experiments in WP2 and WP3, the modelling studies in WP4 and the CO_2 flux limits in WP5. A subsidiary objective was to update an existing public-domain database of Features, Events and Processes (FEPs) produced by Quintessa (freely accessibly via http://co2fepdb.quintessa.org/current/PHP/frames.php). This FEP database is both a knowledge base and an auditing tool to be used in the development of scenarios. The FEP database update aimed to take into account the results of RISCS research.

Process

The specification of reference environments and definition of impact scenarios was undertaken during the first year of the RISCS project, so that the outputs from the work could be used to inform other RISCS activities. A systematic, evidence-based elicitation process was used. Central to this process was a workshop involving participants from a wide range of RISCS partner originations. The workshop outcomes were audited against established lists of Features, Events and Processes (FEPs) relevant to storage systems, and compared with issues and uncertainties identified for other project activities. The work produced a small number of scenarios that broadly represent the main types of impacts that could occur. The identification of impact scenarios aimed to address the following:

- The identification of plausible temporal and spatial leakage patterns.
- An understanding of the mechanisms by which such leaks could lead to environmental impacts.
- An appreciation of the main features of, and differences between, example reference environments, including different types of marine and terrestrial systems. Consistent with the aims of the RISCS project, these environments have been identified to illustrate all the main types of impact that need to be considered within the project.

Quintessa's FEP database was updated in two main phases: one in the first year of the project and one in the final six months of the project. In each case, the existing database was reviewed, in the light of the RISCS research.

Reference environments

The RISCS project considers the entire European Union region at some point in the future. Therefore it was important for the identified impact scenarios to achieve a balance between not being site-specific and yet not so generic as to be of little use.

A small number of reference environments were identified for environment types in both 'marine' and 'terrestrial' areas. Each group of reference environments include a representative range of receptor classes, which indicate the range of different FEPs that need to be included in the overall analysis. The reference environments are given in Table 1.

Leakage patterns

The potential leakage patterns that might plausibly arise were deduced by the RISCS experts. Features that are most likely to be associated with leakage include wells (for example following well seal failure) and faults and fractures (for example as a result of fault/fracture widening through induced or natural seismicity, or interaction of the storage complex with a fault that had not previously been mapped). Potential diffusion through the rock matrix would be very slow, and would probably only reach the surface if it intersects a fracture. The list of plausible leakage mechanisms / patterns considered is therefore:

- localized release to the surface/sea bed through well failure or through fractures;
- localized release to aquifers that have the potential to be exploited as water resources through a well failure/fractures;
- diffuse effects following fracture / well transport to the sea-bed / surface / aquifers.

Table 1 Reference environments

Terrestrial Environments	Marine Environments
Maritime Temperate Representative of a northern European, cool climate (e.g. UK, Netherlands etc.)	Cool, temperate, deep with deep water (> c. 60 m, typically with depths of several hundred metres) located on the continental shelf remote from shoreline influences (e.g. northern North Sea, or to the west of Norway)
Continental Considers climate associated with northern (but not Arctic) European continental land mass countries	Cool, temperate, shallow with water depth of a few tens of metres, relatively close to land (e.g. southern North Sea)
Mediterranean Representative of warmer, more arid, southern European climates	Warm shallow with relatively warm water a few tens of metres deep, located relatively close to land (e.g. within the Adriatic)
Generic Urban Specifically designed to explore potential impacts to humans should a storage system be located close to a large urban centre	Low salinity (saline, but substantially lower than mean ocean salinity) with water depth of a few tens of metres, located relatively close to land (e.g. in the Baltic Sea)

Receptor classes

A range of receptor classes were identified to be important for assessments of impacts associated with both terrestrial and marine systems. Receptor characteristics will vary across receptor environments according to differences in climate and marine conditions. Examples of receptor classes are provided in Table 2.

Table 2 Receptor classes

Terrestrial Receptors	Marine Receptors
Plants associated with agricultural ecosystems	Benthic biota
Plants associated with natural systems	Pelagic biota
Animals that inhabit agricultural or natural ecosystems	Biogenic calcifying habitats
Terrestrial freshwater bodies / resources (lakes, rivers, springs)	Localized sensitive populations
Aquifers that may be exploited as drinking or irrigation water resources	Biogeochemical cycles
Humans	

Impact scenarios

Having identified key receptor classes the processes that might influence impacts upon them were identified. Variations in receptors and processes across reference environments and associated climate states were mapped to the leakage mechanism / patterns. This enables a range of plausible impact scenarios to be specified. The scenarios are not intended to represent all the combinations of receptors and processes that could occur. Instead, the scenarios together illustrate the key issues and the range of receptor impacts that could occur.

As a baseline a 'normal evolution' scenario was identified for each kind of storage system, corresponding to the expected evolution of the system, with no CO_2 leakage. 'Alternative evolution' or 'impacts' scenarios were then identified that describe potential low-likelihood CO_2 leakage scenarios. For terrestrial environments these alternative evolution scenarios are as follows:

- Direct release to atmosphere, via a well (high flux for a relatively short time period – e.g. days)
- Localized release to soil as a result of wells / faults / fractures, leading to high concentrations of CO_2 in the near surface
- Localized release to soils as a result of wells / faults / fractures, leading to long-term low concentrations of CO_2 in near surface
- Localized release to freshwater lakes via fractures / faults
- Diffuse releases to surface and near-surface systems
- Localized release to aquifers that may be exploited as drinking or irrigation water resources
- Release to an urban environment

For marine environments the alternative evolution scenarios are:

- Localized direct release of free CO_2 via the sediment or directly to the water column above the sea bed via a point source
- Diffuse direct release of free CO_2 via the sediment or directly to the water column over a wide area
- Localized release of CO_2-charged water through the sediment or directly to the water column via a point source
- Diffuse release of CO_2-charged water through the sediment and subsequently to the water column over a wide area

Fluxes and impacted areas in each of these scenarios would be very site-specific and therefore it is not appropriate to make predictions. However, illustrative plausible fluxes and impacted areas were designed, based upon a detailed literature review. Were leakage to occur, then higher fluxes are more likely during operations than during the post-operational period, because after injection has ceased pressure gradients driving flow of CO_2 in the reservoir will decrease. Since it is expected that any leakage fluxes during an operational period would be recognized and remedied, higher leakage fluxes are likely to be of shorter duration than smaller leakage fluxes in the longer term.

Update of the FEP database

The review of the FEP database in the light of the RISCS research identified one new FEP ("Marine Stratification and Mixing") and revealed that substantial modifications were desirable for a further 8 FEPs (out of a total of 179 FEPs). These modifications have been made, together with a large number of minor ones and the revised database has been made publically available.

Marine Impacts

Understanding the potential impact of leakage on the marine environment requires the collation of a number of separate factors. For any possible leakage scenario we need to predict the spatial footprint, the degree of chemical perturbation and the duration of exposure. We need to know how the chemical perturbation relates to normal conditions, e.g. the baseline and the impact of these perturbations on marine ecosystems. Given these we can also say something about appropriate monitoring strategies. Modelling techniques can contribute in all of these areas, indeed providing the only methodology by which we can assess footprint, perturbation and duration for a wide range of leakage scenarios. The following summarises the main outcomes of the RISCS project with respect to marine system modelling.

Modelling footprints, perturbation and exposure

Dispersion of CO_2 plumes in seawater is a complex process, but all the relevant dynamics can be explicitly described or adequately parameterised in mathematical models. Initially highly buoyant gaseous CO_2 dissolves rapidly, forming potentially dense plumes of water containing higher concentrations of CO_2 that will tend to sink in the water column. Whilst local currents will determine the mean direction of a leakage plume, especially in cool temperate shallow and deep marine reference environments like the North Sea, tidal mixing is the main method of plume dispersion. Generally, tidal movement forces water masses in an elliptical pattern, accelerating dispersion. As shown (Figure 1) the resulting plume revolves around the leakage centre, with implications for both impacts and monitoring.

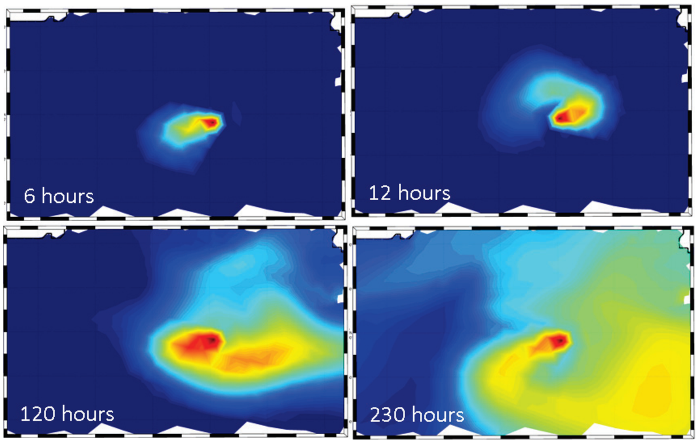

Figure 1 Initial evolution of leakage plume showing tidally driven circulation pattern.

Model based studies indicate that dispersion can be relatively rapid so that only the neighbourhood of a leak event is likely to be strongly impacted, although this area could be metres or kilometres across, depending on the leakage rate. However, tides and currents will combine to make plume behaviour complex such that the CO_2 concentration and pH is prone to oscillate at any given point in space. Deeper regions of shelf seas and most oceans stratify seasonally, i.e. when summer heating creates a warm less dense surface layer which does not mix with deeper waters. In such a case, any leaked CO_2 would be effectively trapped below the thermocline, with increased impacts on the benthic system.

A clear result is that every leakage scenario would be unique, depending on timing, flux, location etc. As a rule of thumb, leakages of the order of 1T/d would create biologically harmful footprints measured by a few 10s of metres, leakages of the order of 1000T/d would have footprints measured in 10s of Kilometres.

Understanding the baseline

CO_2 is a natural component of seawater, CO_2 concentrations are most routinely referenced by either pH or pCO_2 (partial pressure). Over an annual cycle the acidity in seawater will vary by 0.2-1.0 pH units (typically 0.3-0.4 pH units in shelf seas, Figure 2), pCO_2 generally lies in the range 250-450 µatm. Within benthic pore waters pH may vary by over 1 pH unit over very short distances. Note that pH is a log scale and a change of 1 unit represents an order of magnitude change in effective acidity/alkalinity. This variability is due to several processes:

- The water temperature, which is much more variable over the annual cycle in relatively shallow shelf seas compared with the open ocean. Temperature affects the equilibrium state of the carbonate system (CO_2 in solution) and hence pH.

- Boundary conditions such as riverine flows and the Baltic input which have unique carbon signatures that derive from geology and land use. Locally these specific inputs can also change pH
- On seasonal scales exchange of CO_2 and O_2 with the atmosphere and oceanic water is also significant.
- The biological processes of respiration and photosynthesis which produce and take up CO_2 respectively. These processes vary both seasonally and over day-night cycles.
- Frontal systems and biological features such as blooms give rise to significant spatial discontinuities.
- In benthic systems, complex redox chemistry which exhibits large vertical gradients within the upper 20-30 cms of the sediment.

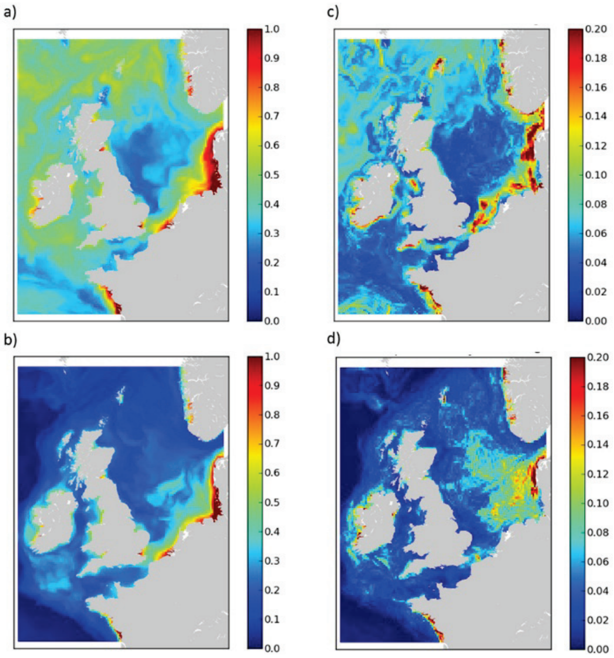

Figure 2 a, b) Annual range in daily mean pH derived from a model simulation (a surface, b, sea floor) c, d) Largest day on day change in pH recorded over a 15 year model simulation (c surface, d, sea floor).

Quantifying impact: species responses

Carbon dioxide occurs naturally in the marine environment being a product of biological activity and a key component of the carbon cycle. Consequently, marine organisms have developed a range of physiological and behavioural mechanisms to cope with life in an environment of fluctuating CO_2, pH and carbonate chemistry as we have also shown in experiments with individual species. Despite being relative insensitive to elevated CO_2, in the short-term, the experiments with the crab *Carcinus aestuarii* revealed an additive negative effect of increasing temperature and increasing CO_2 concentrations, resulting in an increased mortality at higher temperatures. In the same experiment it was observed that a sudden transfer back to control pH conditions caused additional mortality amongst the crabs that until then seemed well adapted. This suggests that sudden shifts in pH /CO_2 levels are more harmful for the organisms then a stable situation. Similar experiments with the shrimp *Palaemon elegans* showed a greater sensitivity to reduced pH, but without a relation with temperature.

The data from the RISCS experiments are in line with other studies and the generic impacts of CO_2 on marine invertebrate physiology are becoming clearer. In general, when marine invertebrate organisms are exposed to low pH/high CO_2 seawater the primary physiological effect is a decrease in the pH or an "acidosis" of the extracellular body fluids such as blood, haemolymph or ceolomic fluid. Clearly some species are physiologically better equipped to cope with elevated levels of CO_2 than others. Current understanding suggests that many of the traits that species apply to cope with high CO_2 levels will be associated with the way in which organisms use, partition and gather metabolic energy. This represents a fundamental advance in the way we appreciate the stresses associated with seawater hypercapnia and acidification. It is however clear that these organisms will be ecologically less fit than they would have been in a lower environment. This finding has significant implications for the survival of organisms during a CCS leakage event. If organisms have access to sufficient resources then they will, to some extent, be able to invest them in the physiological mechanisms needed to survive short-term exposure to high levels of CO_2 and reduced seawater pH. This means that organisms and communities could potentially be better able to survive short-term leaks than previously thought. However if leakage were to persist the increased energetic demand associated with living in a high CO_2 environment would inevitably lead to reduced growth, lower reproductive output and eventually death.

We performed a literature survey in order to determine critical CO_2 concentrations by producing a Species Sensitivity Distribution (SSD) based on available data. Basically, the SSD is the statistical distribution of species sensitivity, for a specific toxic compound for several representative species. Although the development of such a SSD for elevated CO_2 concentrations was hampered by the lack of comparable datasets of high enough quality the review revealed the clear differences in sensitivity between taxonomic groups (Figure 3). The phylum Cnidaria (including corals) were shown to be most sensitive. Calcifying organisms, such as corals and some mollusc and planktonic species, will have difficulty maintaining their external calcium carbonate skeletons under low pH. Echinodermata (mostly sea urchins) also appeared to be a sensitive phylum for the same reason. Most Mollusca (e.g., mussels and snails) also possess calcareous shells, and they were affected by a wide range of CO_2 levels. The mollusc median CO_2 effect levels were much lower than those of the Chordata, (e.g. wolf fish, salmon, Atlantic cod) which are the most tolerant of chronic elevated CO_2 conditions, whereas invertebrates were generally less tolerant of elevated CO_2 levels. Positive effects on growth in algal species (Heterokontophyta) have been recorded. This is possibly due to increased availability of CO_2 but could be the result of reduced competition or predation. Whether this effect should be considered positive or adverse for the environment as a whole is a philosophical discussion that was outside the scope of the present study. Increased primary production was observed in the RISCS mesocosm studies (see below).

Quantifying impact: community responses

A community consists of a group of populations of different species living in close interaction with each other and their environment. It is therefore tempting to assume that a community is as sensitive to an environmental stressor as the most sensitive species within it. However, this does not take into account interactions between species and with the environment. When assessing the impact of elevated CO_2 concentrations these interactions can be important. This is especially so since higher CO_2 levels can affect the availability of food for various marine species, which can have important implications for their ability to cope with the negative impact of elevated CO_2 concentrations described above. Gaining insights into the impact of higher CO_2 concentrations on marine communities and ecosystems is a key aspect of research on ocean acidification (Dupont and Pörtner, 2013). In the RISCS project such information was gathered through multi species tests.

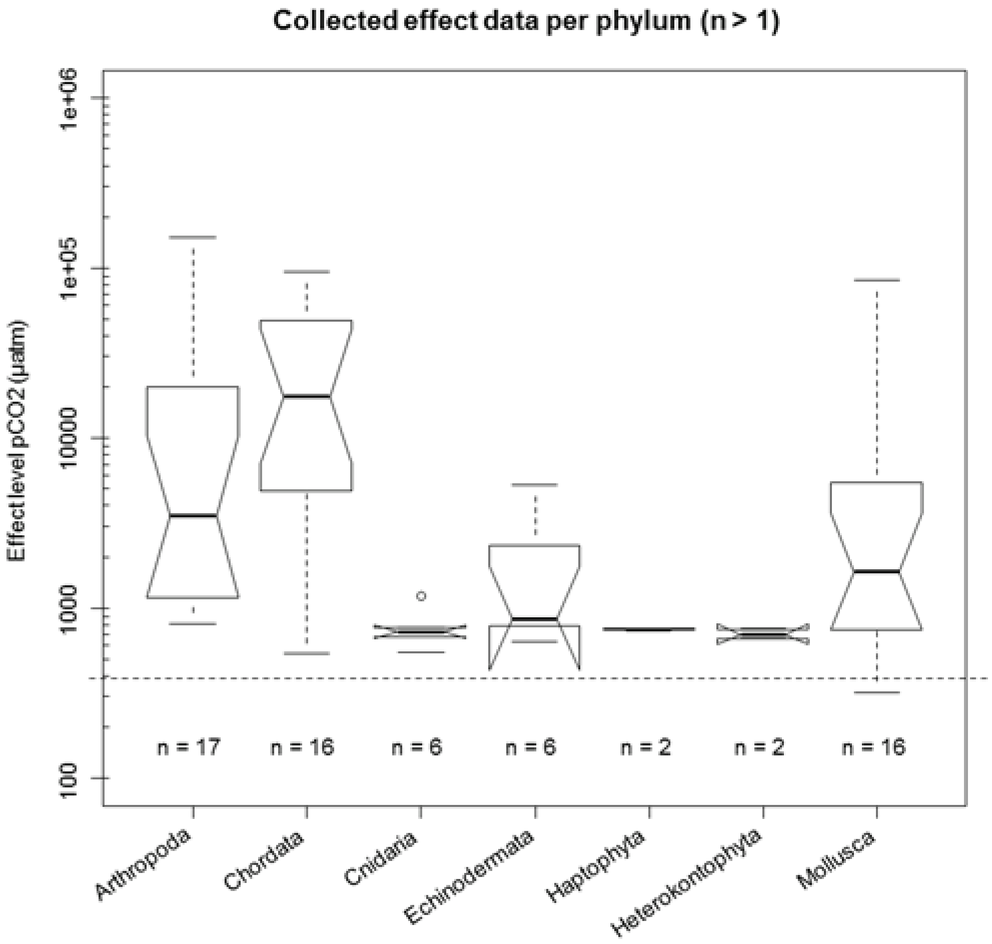

Figure 3 Boxplot of CO_2 effect levels by phylum. Boxes indicate first and third quartile, bold line indicates median. Whiskers indicate minimum and maximum (excluding outliers, which are shown as markers). Notches give a graphical indication of significant differences. Only phyla with data for more than one species are included in the plot (n = number of species). Dashed horizontal line indicates the median CO_2 level of all control experiments (381 µatm).

Interaction with food availability

In the outdoor RISCS mesocosm experiments with a pelagic (planktonic) and a benthic (macro-invertebrate) community it was observed that elevated CO_2 levels can increase the production of planktonic algae (Figure 4). This improves feeding conditions for species that depend on this food source, like bivalve molluscs. As indicated above many species are able to cope with moderate changes in CO_2 concentrations/pH although with additional energy costs. Hence increased food availability should increase the potential of these species to withstand elevated CO_2 levels. Indeed, development of the flesh weight of mussels in the mesocosms was stimulated by elevated CO_2 concentrations. At the lower CO_2 exposure levels this was accompanied by increasing shell length, however at the highest CO_2 level (pH 6.9) shell growth was comparable to the control situation. This suggests that, at this highest level of acidification the mussels had problems maintaining shell growth against the erosion of the shell that occurred due to the low pH, despite the better food conditions.

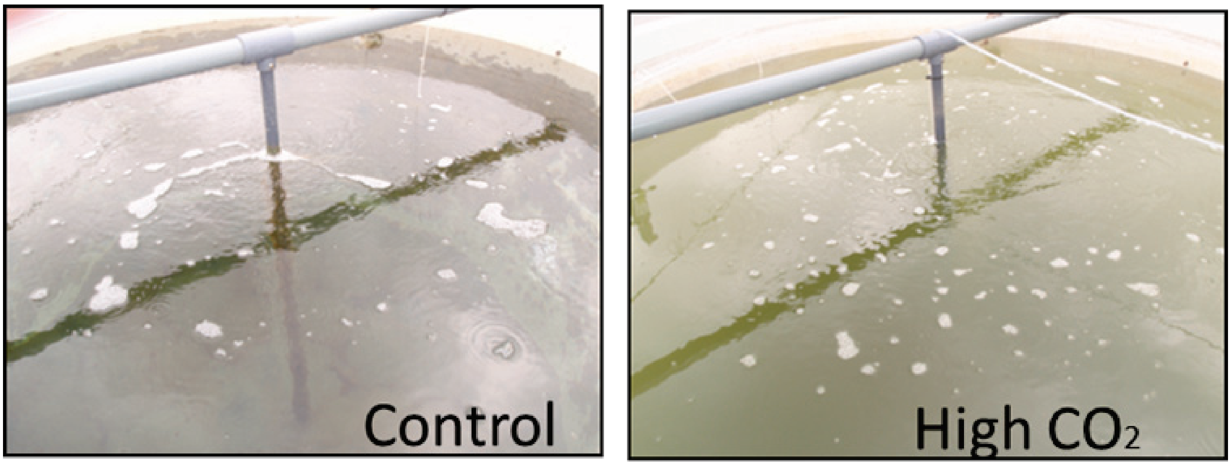

Figure 4 Comparison of the turbidity of the water in two of the RISCS mesocosms illustrates the higher algal densities in a mesocosm with elevated CO_2 concentrations (right) compared to a control (left).

Elevated CO_2 concentrations can also result in increased concentrations of benthic algae. This was seen in the different indoor mesocosms of RISCS mimicking sediment/water systems from the Mediterranean and the North Sea respectively, where elevated concentrations of benthic algae, especially diatoms, were observed at CO_2 concentrations that resulted in a pH around 7. In both studies this was a reduction with 1 pH unit compared to the controls. At higher CO_2 concentrations this stimulation disappeared.

This increased food availability is also a likely explanation for the remarkable resilience of the benthic community in mesocosms that did not show significant changes in diversity and abundance after 10 weeks exposure to a pH of 6.5 and above. These changes were only apparent at pH 6. Interesting in this respect is that the community structure in these mesocosms showed a rapid change during the first two weeks of exposure, before the bloom of the micro-organisms that appeared only after 5 weeks. The Mediterranean-type experiments, that were performed at winter (10°C) and summer (18°C) temperatures showed that development of the diatom density after the CO_2 introduction was faster at higher temperatures, indicating that under these conditions additional food to provide the energy investment necessary to cope with the negative effects of elevated CO_2 is more readily available. However, the net benefit of this is not clear, as for most species basic energy demand also increases with temperature.

In contrast to the observations in the indoor mesocosms, the development of sessile algae decreased at higher CO_2 concentrations in the larger outdoor mesocosms. The reason for this difference is not clear.

Interaction with competitors

Interaction with competitors or predators is another reason why species as part of a community can respond differently to a stressor than in a single species laboratory test. A clear example of this was observed in the zooplankton community in the outdoor RISCS mesocosms. As is normal for the North Sea the zooplankton community was dominated by copepods. In the controls (pH 8.3) and CO_2-treatments resulting in a pH reduction of up to 7.5 *Acartia tonsa* was the most dominant copepod species. At the next higher CO_2 exposure level (pH 6.8) the community underwent a drastic change; *Acartia tonsa* disappeared and the dominant species became *Eurytemora affines* another copepod that was hardly present at lower treatment levels. Apparently *Acartia tonsa* is a much better competitor than *Eurytemora affines* given undisturbed conditions. However, at pH below 7.5 *Acartia* seems no longer able to cope with the effects of the higher CO_2 concentration, leaving *Eurytemora* to take advantage of the better food conditions. This resulted in higher zooplankton abundance, although species richness declined.

Observed community changes

The benthic lander experiments performed in RISCS in a Norwegian fjord at a water depth of 350 m revealed escape behaviour when the benthic community was exposed to seawater that was acidified with CO_2 to a pH of 5.5. After 40 hours of exposure the organisms had burrowed deeper in the sediment. Changes in the macrofaunal community structure were not observed in this experiment, which is likely to be related to the relatively short exposure time. In the indoor mesocosms, containing a shell gravel community, exposure for 10 weeks to seawater with pH 6 resulted in reduced species richness of the macrofaunal community. In particular, the less abundant macrofauna species were affected. Exposure to seawater with pH 6.5 or above did not result in community changes in these experiments. This was also the case for the community of the smaller nematodes. Community structure showed some indications of being affected after two weeks of exposure, but after 10 weeks this had disappeared. The response of the shell gravel community in these mesocosm experiments was comparable to observations from similar earlier mesocosm experiments with sandy sediments that also lasted for 10 weeks (Widdicombe et al., 2009). These observations suggest that in general benthic communities are able to withstand pH values up to 6.5 for at least 10 weeks (Figure 5).

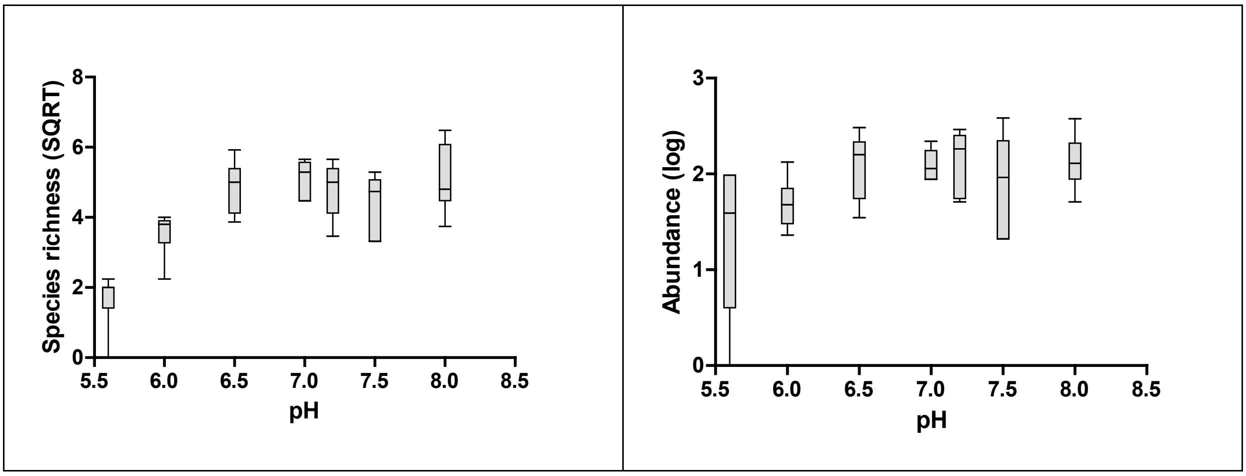

Figure 5 Impact of medium-term (10 - 20 weeks) exposure to seawater acidification on macrofaunal diversity (square root number of species) and abundance ($\log_{10}$ number of individuals) using data pooled from the study with a shell-gravel community performed within the RISCS project and that of an earlier experiment performed with a sand community (Widdicombe et al., 2009).

However, the benthic communities in the larger outdoor mesocosms, that were also exposed for 10 weeks, showed indications of reduced species richness and significant reduction of the total abundance at a higher pH of 6.8 (Figure 6). This suggests a higher sensitivity of these communities compared to those in the smaller mesocosms. The most obvious changes in the benthic community in the outdoor mesocosms at pH 6.8 were the reduction of the number of juvenile cockles (*Cerastoderma edule*, a bivalve mollusc), mudshrimps (*Corophium volutator*, a crustacean) and the meiofaunal polychaete worm *Ctenodrilus serratus*. Reproductive success of the cockles turned out to be the most sensitive feature of the mesocosm community, which is probably related to problems that the bivalve larvae experience with shell formation under acidified conditions. The mudshrimp population also developed from a limited number of individuals that were introduced at the start of the study. The reduced density could be related to reduced reproduction/survival as a direct effect of the elevated CO_2/low pH levels. Also from other studies it is recognised that early life stages are the most sensitive to the effects of acidification (Dupont et al., 2008; Kurihara, 2008). In addition, in the same mesocosms, reduced development of sessile algae was observed that serve as an important food source for the mudshrimps. As indicated earlier reduced food availability can limit the ability of organisms to cope with the physiological effects of elevated CO_2 concentrations.

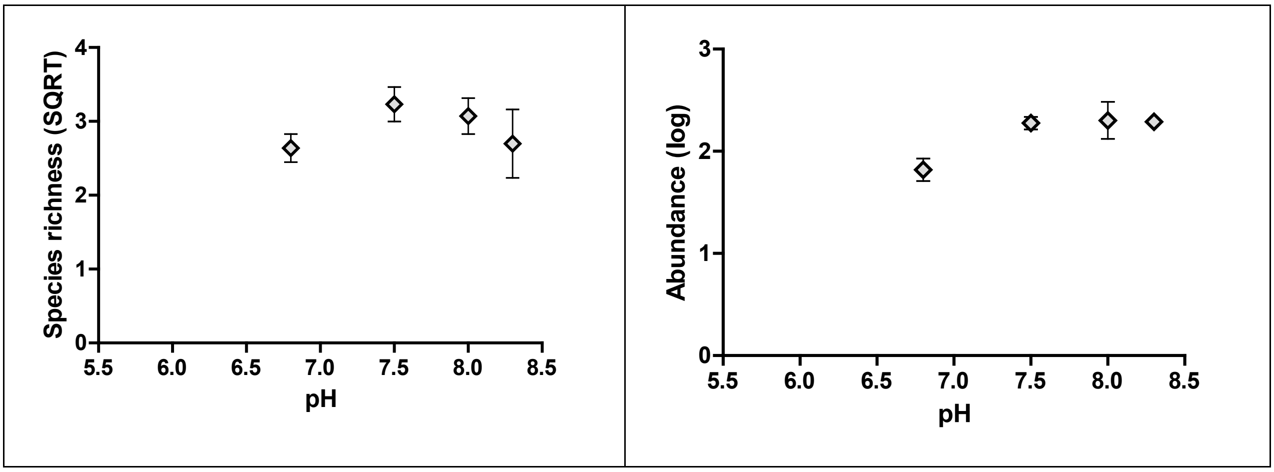

Figure 6 Impact of CO_2 induced seawater acidification on the macro faunal community (species richness and total abundance) in 5 m^3 outdoor mesocosms.

The data suggest that benthic marine communities are able to withstand at least 10 weeks of exposure to elevated CO_2 concentrations at least as long as the pH does not drop below 7.5. At higher exposure levels (resulting in pH <7.5) impact may be expected, depending on local/seasonal food availability and the presence of early life stages as important factors. Recent research results indicate that at least individual species are able to adapt to elevated CO_2 concentrations when exposed for longer periods (Thomsen et al 2012; (Dupont et al., 2012).

Microbial communities

Experiments on marine microorganisms that were performed in indoor 200 L mesocosms showed that coastal bacterial community structure was not clearly altered by acidification whereas Archaea assemblage composition changed at high CO_2 levels.

On the contrary, in the 5 m^3 outdoor mesocosms, bacterioplankton community structure was highly affected by seawater acidification. This inconsistency is likely due to the secondary effect that the perturbation had on prokaryotes. In the smaller mesocosm experiments chlorophyll *a* concentrations were extremely low, whereas in the outdoor experiments phytoplankton growth was highly stimulated by CO_2 supply. Microalgae production is one of the primary energy and carbon sources for organoheterotrophic prokaryotes and is deeply involved in the shaping of bacterial communities. Organic carbon increased in the perturbed large mesocosms whereas it remained constant in the smaller mesocosms, possibly generating the differences in bacterioplankton behaviour in the two sets of experiments.

Some direct effects of CO_2 addition were observed in the mesocosm test with water and sediment from the northern Adriatic. These effects were related to degradation processes. In particular the dephosphorilation of P-esters, which in the sea is caused by the enzyme alkaline phosphatase (acting in alkaline conditions), was quickly inhibited at a pH value of 7.0. The release of orthophosphate was slowed down and the system seemed to react through a fast degradation of lipids (a potential source of organic P – Celussi & Del Negro, 2012). These results seem to be confirmed by the observation in the outdoor mesocosms that orthophospate concentrations in the water column were correlated with CO_2 levels/pH.

Experiments performed on sediments revealed only a slight influence of extra CO_2 on prokaryotic numbers and their activities (prokaryotic carbon production, degradation processes and respiration).

Monitoring strategies

Whilst in the centre of a leak the pH decrease may be greater than occurs naturally, with increasing distance from the leakage point and as the CO_2 is dispersed, the resultant changes will be similar in magnitude to those expected under normal seasonal and diurnal cycles. Therefore the challenge of detecting leakage and its impacts is to have both a detailed understanding of baseline variability and the capability to detect small leakage features against this large and variable baseline.

We have shown that monitoring may have more effectiveness by co-measuring other environmental factors such as temperature and oxygen, enabling natural signals to be recognised and differentiated from leakage. For example, if an increase in CO_2 is accompanied by an equivalent decrease in oxygen then enhanced community respiration is the likely cause; if no oxygen decrease is measured then it is far less likely that a biological process is responsible and some external source of CO_2 can be suspected. The relationship between CO_2 and oxygen concentration varies seasonally and such information could also be used to inform the interpretation of CCS monitoring data. Similarly temperature has a significant impact on pH and pCO_2 and can be used as an indicator of natural physical dynamics that affect the carbonate system.

The RISCS monitoring program at the natural leaking Panarea site, which included chemical, biological and physical measurements, showed how challenging it may be to find and delineate a seafloor CO_2 leak, due to the highly dynamic nature of the water column. Seasonal campaigns along the same transect showed different results as a function of the changing currents and level of stratification. The greatest impact, and thus the greatest possibility of discovering a leak, occurred during the campaign with the strongest water column stratification, as the leaking CO_2 was less rapidly diluted in the bottom waters. During this same campaign various chemical species were seen to correlate very closely with the dissolved CO_2 anomaly, indicating other parameters (in addition to those mentioned above) which could be used as tracers for determining if a CO_2 anomaly is due to leakage or to normal oceanographic processes. This is illustrated in Figure 7, where silica and methane show a distribution in the water column that is very similar to that of pCO_2 and pH, with the former likely associated with waters leaking with the gas and the latter being a trace component in the gas itself. The continuous pCO_2 monitoring equipment that was developed within the project showed an overall good performance, with sensors deployed in areas of active leakage showing highly variable results as a function of the ever changing mixing regime. In fact, despite the vicinity of leakage, these probes showed high values that on occasion rapidly dropped to background concentrations, caused by strong currents diluting and sweeping the dissolved CO_2 away from its original source. This indicates that early detection of leakage from sub-seabed storage sites by chemical/physical monitoring has practical challenges, and that an integrated approach is needed which involves other techniques such as current monitoring and hydroacoustic measurements. Despite the large volume of CO_2 released in the water column at this site, impact on measured biological parameters was small.

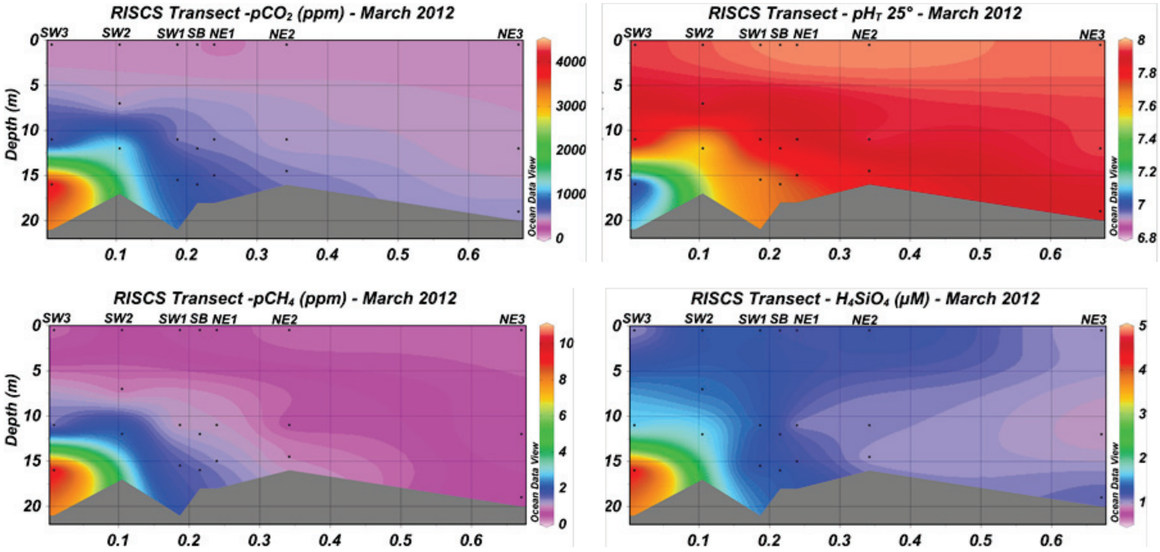

Figure 7 The spatial distribution of four measured parameters along a 700 m water column transect in March 2012 at the Panarea test site. Note that all parameters correlate well, indicating a similar origin.

For a more robust and complete interpretation of chemical and physical monitoring data a suite of additional information about water currents, sea level variations, air-sea gas fluxes, stratification, and also biological processes, like primary production, is needed. In theory site specific models will be required for integrating the collected information in such a way that non-natural patterns that could indicate CO_2 leakage can be identified. However, the question remains whether this will be practically possible on a scale that is necessary when CCS become common practice. Even if such high-level modelling is found to be impractical, modelling can at least define possible scenarios (e.g. maximum pH drops over a given area for a hypothetical leakage rate), that may indicate the level of sensitivity needed to distinguish a leakage signal from background noise, and can give important indications regarding where to sample and when to sample to maximize the effectiveness of a monitoring program.

Terrestrial

Within the RISCS project the potential impacts on terrestrial environments included consideration of impacts on Groundwater and on near surface ecosystems.

Context, rational and studied sites

Groundwater

The potential impacts on shallow potable ground water aquifers could apply in all terrestrial reference environments. Potential impacts could be twofold; firstly chemical reactions that could occur in the shallow aquifer should CO_2 leak into it and secondly the potential displacement or migration of deep brines into the aquifer as a result of pressurisation of the reservoir. Should CO_2 and brine migrate together, both processes could be combined. The potential impacts of brine displacement have not been specifically investigated in the RISCS project as the consequences of increases in salinity in ground waters are well known from other work such as saltwater intrusion studies. The dissolution of CO_2 in the aquifer waters could result in acidification, water-rock reactions, and the potential release of elements (including trace metals) into the water. Depending on many complex, interacting processes (e.g. mineral dissolution and precipitation, elemental adsorption and de-sorption, and formation of ion complexes, all of which are a function of aquifer mineralogy and water chemistry, temperature and, to a lesser extent, pressure), elements could be liberated that may (or may not) impact water quality. The extent of the impact cannot be predicted in a generic sense as it depends on site-specific characteristics.

With brine displacement, very high concentrations of various dissolved salts in a migrating brine could be mixed with the potable water that could locally reduce water quality, depending, again, on many interacting factors (e.g. the redox level of the intruding water versus that of the potable aquifer, brine leakage rate versus ground water flow rate and aquifer mineralogy). Various other site specific factors will also affect the potential impact of CO_2 and/or brine leakage, such as confined versus unconfined aquifers, aquifer depth (i.e. pressure), ground water extraction versus recharge rates, pumping well locations versus leakage location, aquifer heterogeneity (both mineralogy and permeability distribution), and the occurrence of other stressors (e.g. water production, anthropogenic contamination and saltwater intrusion).

Within this context four natural CO_2 sites were studied in the RISCS project (Figure 8): i) Florina (Greece), an industrially exploited CO_2 reservoir located in a stacked limestone-sandstone succession; ii) Latera (Italy), an extinct volcanic caldera with a high geothermal gradient where CO_2 is produced via thermo-metamorphic reactions in the underlying carbonates; iii) the San Vittorino Basin (Italy), an intra-montane basin surrounded by carbonate rocks of the central Apennine mountains where CO_2 produced by thermo-metamorphism is being emitted at surface together with ground water (i.e. flowing springs); and (iv) Montmiral (France), where natural CO_2 accumulations in sandstones (capped by clays and marls) occur at depths of over 2000 m. These sites were studied to address the potential impact of both mechanisms described above, although focus was given more to in situ water-rock reactions in the aquifers themselves. It should be emphasised that these sites of naturally occurring elevated CO_2 are not potential CO_2 storage sites, since they are not located in areas that are geologically suitable.

Figure 8 Locations of groundwater sites studied in the RISCS project.

Near surface Ecosystems

The potential impacts of CO_2 leakage on near surface ecosystems will depend on the characteristics of the land above the site including the geology, soil type, topography, climate and land use. They will also be influenced by the weather conditions, both preceding and prevailing, when leakage reaches the soil or escapes into the atmosphere. Factors such as soil moisture, permeability and cracking of dry soils will all influence the flux and concentrations of CO_2 in the soil. Preferential pathways through the soil are likely to lead to locally higher CO_2 concentrations where the impact of the leakage is potentially greatest. Lower permeability layers, or high moisture contents in the near surface, may impede gas escape and lead to a build up of CO_2 in the soil.

The flux of gas through the soil, and hence its concentration, are affected by the soil and air temperature, air pressure and wind speed and direction as well as soil moisture. These factors vary seasonally and with the passage of weather systems. The natural level and flux of CO_2 in the soil is also governed by these parameters and shows strong seasonal variability with maxima during the growing season when biological activity (respiration and photosynthesis) is greatest and minima in the winter. Thus the timing of leakage in this annual cycle can be important in determining the background level of CO_2 to which any leaked gas is added. During winter, frozen ground or snow cover can also affect soil gas contents and fluxes. Waterlogged ground may be common at this time of year, and in spring, especially where a thaw follows a hard winter, and can greatly impede CO_2 escape.

The timing of leakage will also be important in relation to the development stage reached by plants; young tender plants are likely to be affected more than mature specimens and the effects are likely to be greatest during the growing season compared with the more dormant winter months, at least in more temperate climes. In southern Europe, hot dry summer conditions can lead to dieback in pasture vegetation and so the addition of CO_2 might have little impact on plants which have died back due to drought, though could create larger impacts in plants that are becoming stressed through drought but yet to fully die back.

The RISCS project has included the study of impacts on both crops (arable and pasture) and soil microbes in both cool temperate and warmer Mediterranean terrestrial environments. Research encompassed both controlled injection experiments at sites in the UK and Norway, laboratory experiments in Norway and observations at sites of natural leakage in the Florina Basin in northern Greece. This has allowed a comparison of the impacts of newly introduced CO_2 in previously unaffected sites with sites where the ecosystem has had a long time (years to thousands of years) to adapt to the presence of high concentrations of CO_2.

In Norway, four experimental plots (6m x 3m) were set up in an agricultural area. Gas was injected at rates ranging between 1 and 2 $l.min^{-1}$ during the growing season at 85 cm depth at one side of the plot. Here the idea was to create a gradient along the plots so effects of differing exposure could be assessed in crops (oats). In addition labelled CO_2 ($\delta^{13}C$ of -46.2‰) was used to enable isotopic tracking of the injected gas. The lab experiments consisted of growing winter wheat and oats under manipulated soil atmosphere conditions to test 1) whether the effects of high CO_2 content on plant growth were due to CO_2 toxicity or hypoxic conditions resulting from O_2 replacement by CO_2 and 2) whether species differ in their tolerance.

At the ASGARD site in UK CO_2 was injected between 50 and 60 cm depth at a rate of 1 $l.min^{-1}$ in the centre of (2.5 x 2.5 m) plots. Pristine pasture sites, grass/clover mix, wheat and beetroot, as well as spring and autumn sown barley and oilseed rape, were tested over a three year period. All the experiments were fully replicated with four gassed plots and four controls for each plant type, allowing statistical testing of the significance of any responses to soil CO_2.

In the Florina Basin in northern Greece soil gas and flux surveys were used to select a CO_2 vent for study. The botanical and microbiological effects of differing exposure to soil gas CO_2 were then examined on a 30 m long transect, running from the vent centre, with high levels of CO_2, to an area with normal low concentrations of the gas.

Modelling

Numerical models of leakage impacts can be used to help develop understanding of possible impacts from CO_2 leakage by testing theoretical representations of key processes against experimental outputs and predicting impacts in environments other than those investigated experimentally. The goals of the modelling were therefore twofold:

- to develop a terrestrial systems model, based on previously published theory and experimental results, and the laboratory and field experimental results, particularly those obtained at ASGARD and Grimsrud and;
- to apply this systems model to explore the potential impacts of CO_2 leakage in a range of reference environments and impact scenarios developed in Task 1.

Summary of results

Groundwater

Research at the four sites (Figure 8) where natural CO_2 has been leaking or accumulating over geological time periods, focussed on different aspects: the Latera and San Vittorino sites were examined at a very small scale to determine the spatial evolution of impact, the influence on different aquifer mineralogies, and possible differences between CO_2 + brine and CO_2-only leakage types; the Florina site was studied at the basin scale to look at potential regional effects and how impacts may vary in time as a result of different seasonal recharge rates; and the Montmiral site was examined to compare deep reservoir brine chemistry and isotopes with that in potable ground water aquifers to study mixing processes, focussing on the potential for leakage of the brine upwards via faults or the deep boreholes drilled in the area.

Analyses of natural CO_2-rich systems are extremely useful for determining how CO_2 migrates and reacts with ground water and aquifer rocks in the sub surface, and the nature of the impacts when it leaks towards the surface. Although they do represent sites that have been exposed to naturally occurring emissions for very long time periods, and thus are quite unlike what might be expected from a potential CCS leak (which might be stopped shortly after its discovery), these sites help to fill the gap between short term laboratory experiments and theoretical modelling efforts. In particular, they allow the complex issues of scale, leakage pathways, heterogeneity, and interacting - and often competing - chemical reactions to be examined.

The distribution of leakage effects will strongly depend on factors such as leakage style (point or area), gas and/or brine leakage rate, ground water flow rate, the presence of confined versus unconfined aquifers, and the aquifer mineralogy and chemistry. For example, the carbonate-dominated aquifer materials buffered the pH decrease at San Vittorino to a minimum pH of 6 (Figure 9), compared to the less-reactive silicate mineralogy of sediments at Latera, where pH values down to 3.8 were observed. Furthermore, the composition of the gas stream can influence the nature of the impact, as the effect of pure CO_2 is different from CO_2 which contains reduced acid gases like H_2S. For example, at Latera the presence of H_2S likely contributed to an additional lowering of the pH beyond that explained just by aquifer buffering capacity.

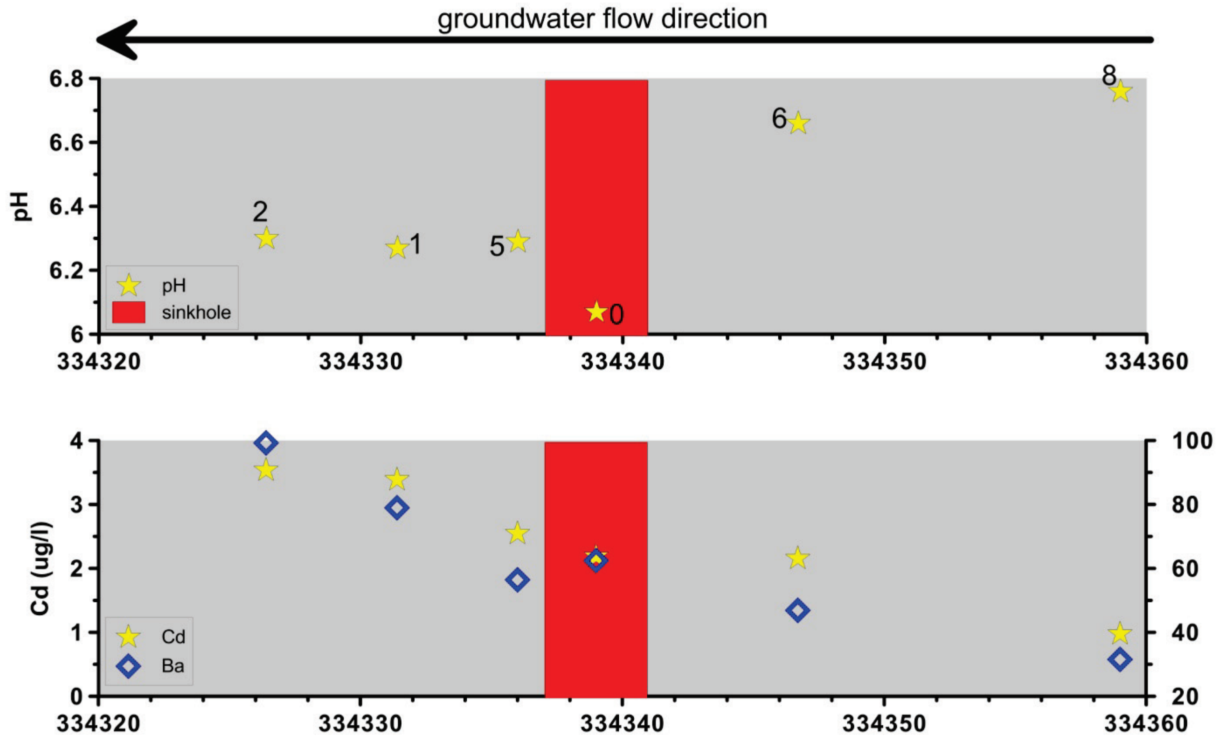

Figure 9 Results of ground water CO_2 impacts, San Vittorino, Italy. The lower pH from CO_2 leakage at the sinkhole is associated with a rise in Cd and Ba. Cd gets close to drinking water limits (3-5 µg/l) but Ba is well below (700-2000 µg/l).

Ground water flow direction and strength can strongly influence the shape of the impacted zone. For example at the San Vittorino site, although some impact was observed up gradient it was much reduced compared to that occurring down gradient (Figure 9). Brine displacement may induce anoxic conditions (i.e. where no free oxygen is present dissolved in the water) in an oxic aquifer.

The potential in situ release of trace metals will depend on aquifer mineralogy, with these elements occurring either as trace constituents of minerals that may be highly soluble (e.g. the carbonate minerals at San Vittorino) or as a potentially significant component of mineral phases that form a trace proportion of the rock that may be less soluble (e.g. arsenic in arsenopyrite, as is potentially occurring in the volcanic rocks at the Latera site).

Changes in chemical composition of the water along a flow path, and / or variations in mineralogy of the rocks through which flow occurs, can alter the attenuation of trace metal migration which is controlled by secondary precipitation of certain minerals in which the trace metals are included; or by adsorption onto mineral surfaces, such as clays or organic matter. Increases in the acidity of the water can cause the release of trace metals to the point that precipitation of new minerals begins.

At both San Vittorino and Florina, increased Fe concentrations can be detected in ground waters due to increasing CO_2 concentration and reduced pH values. Elevated concentrations of Mn were also observed at Florina. However, since Fe, Mn and other substances can also have elevated values in natural waters, changes in concentrations should be compared with variations in other indicators of elevated CO_2, as described above.

At Florina no significant negative ground water impacts from elevated CO_2 concentrations were observed. There is no correlation between CO_2 concentration and dissolved metal concentrations, although a correlation between dissolved CO_2 and pH can be observed.

At Florina, the ascent of $CO_{2,}$ and of the ground water with it, is not continuous but periodic. CO_2 concentrations vary substantially within the basin, reflecting the spatially and temporally variable flux of gas from depth. Hence, leakage may also be similarly spatially variable and episodic in rate.

The zone of potential impact above the deep Montmiral CO_2 reservoir does not show any conclusive and unambiguous signs of deep CO_2 leakage. This study shows that heavy deep CO_2 is not required to explain the observed chemical and isotope data. The shallow groundwaters are chemically rather homogenous except for some waters polluted by agricultural activities and a small subset of samples with much higher cation ratios (magnesium and strontium vs. calcium) and enrichment in ^{13}C. Water-rock interactions are dominated by the evolution of the carbonate system in contact with a biogenic CO_2 soil reservoir. The enrichments observed in several samples can be explained by residence time and incongruent Mg-calcite or dolomite dissolution without needing to invoke mixing with deep geogenic CO_2. Whilst deep CO_2 could indeed be expected to isotopically enrich DIC it would enhance congruent dissolution without changing the cation ratios. Lack of interaction with gaseous CO_2 of deep origin is also confirmed by the isotopic composition of the shallow waters

Some observations can be made regarding monitoring, which for the purposes of monitoring groundwater impact we can divide into the broad categories of hydrogeochemistry, geophysics, and near-surface gas geochemistry.

Hydrogeochemistry implies the sampling of existing groundwater wells or the installation of fit-for-purpose piezometers. As shown here, there will potentially be a significant difference in the types of parameters that should be monitored based on : i) whether the leak is gas only, water / brine only, or both phases together; ii) the leakage rate; and iii) the ph-Eh buffering capacity of the impacted aquifer. For example if brine is leaking one would expect high Cl^- concentrations; considering that this species is conservative and flows essentially at the groundwater flow rate, it could be a potential early warning parameter compared to more attenuated (and more harmful) elements like As or Pb. In addition, as Cl^- contributes to free ion concentrations, conductivity could be used as a simple, robust monitoring tool. Finally, depending on background aquifer conditions, Eh measurements would also be useful. If instead only CO_2 gas is leaking, Cl^- will likely not increase much, Eh may not change significantly, while increases in other major elements will depend on aquifer mineralogy and related dissolution kinetics; on the other hand trace metal concentrations may increase due to the more rapid desorption processes. Considering that trace element measurements are prone to sample contamination and expensive, in this case pH and dissolved CO_2 would be good parameters to monitor, as would DIC; as pointed out by some authors conductivity may not be a good indicator in this case as DIC at lower pH values will be primarily in the neutral form H_2CO_3, which does not contribute to conductivity. The advantage of using pH and pCO_2, as opposed to DIC, is that sensors can be installed for continuous in situ monitoring, and together with temperature these parameters can be used to calculate carbonate alkalinity. Implicit in all of this is the need for an accurate characterisation of the baseline conditions, both spatially to define aquifer heterogeneity and temporally to address potential seasonal variability, for correct identification of a leakage signal.

In terms of geophysics, again the leak type will influence the types of methods chosen. For example, a brine leakage would best be monitored for using electrical resistivity tomography (ERT) to look for zones of increased conductivity. Clearly a method like this cannot be used to constantly cover very large areas, however it could be used in areas of suspected leakage to delineate the impacted zone. Instead for a gas only leakage scenario, if the impacted aquifer is confined methods such as shallow seismic and again ERT could be used to define CO_2 accumulations that mark the source of the groundwater impact.

Finally, near surface gas geochemistry methods can be used in gas-only leakage cases to, once again, define the original leakage point or area. This information would then be used to focus more detailed groundwater studies.

Near surface ecosystems

Plant response to increased CO_2 soil gas concentrations is rapid. The threshold for observing responses appears to be at about 10% soil gas concentration at shallow depth (20-30 cm). Between 15-20% CO_2 at this depth, results indicate that broad-leafed plants become stressed within 7-14 days of exposure during the growing season and then die after a few weeks of continued exposure. However, plants with root systems that are well developed before exposure may be more resilient to subsequent increased CO_2 concentrations. For example, autumn-sown crops which were then exposed to CO_2 leakage in the following spring were less susceptible as were more established plants in laboratory experiments.

Although CO_2 leakages have the potential to cause large decreases in yields from crops with short growing periods, such decreases are likely to have little economic impact because leakages are most likely to take place over very small areas. Indeed, impacts may not be detected until harvest. The impact from CO_2 must also be viewed in the context of other environmental stressors (e.g. weather extremes, disease and pests) which are likely to have greater overall impacts on crop yield. For well-established pasture, the impacts of CO_2 leakage on yields for animal feed may also be minimal, because of the small area impacted.

In pasture and grass/clover mixtures, grasses were more tolerant of CO_2 than clover and most broad-leafed plants. However at higher CO_2 concentrations (>30-40% at 20-30 cm), at sites of natural CO_2 leakage, a specific broad-leafed indicator species, *Polygonum*, is the only plant present, whilst at the highest CO_2 levels (where concentrations can approach 100%) there is bare soil with no plant growth.

Table 3 Summary of CO_2 impacts on crops from ASGARD, UK field experiments, an example of a maritime temperate environment. Negative impacts (down arrows) were restricted to small areas.

	Oilseed rape (Spring)	Oilseed rape (Autumn)	Barley (Spring)	Barley (Autumn)	Beetroot
Plant / Stem no.	↔	↔	↓	↓	↔
Height	↓	↔	↓	↓	
Stem dry weight	↓	↔	↓	↓	
Pod / Grain no.	↓	↓	↓	↓	
Leaf dry weight	↓				↓

Microbial responses to increased CO_2 concentrations above ~20% at 20 cm are rapid with an increased activity rate as shown at ASGARD. Long term changes in the microbial community were only seen at Florina and other European sites where there has been long-term natural leakage of CO_2. Such community adaptation was not seen at ASGARD when plots were subjected to lower levels of CO_2 (~10% at 20 cm) over a period of 24 months. Thus monitoring of the microbial population would provide early indications of increasing CO_2 on soil ecosystems and could also indicate where there has been long-term undetected exposure.

The RISCS project was not able to determine the significance of impacts of elevated CO_2 on soil fertility. This is because, in order to obtain a broad understanding of the impacts of elevated CO_2 in the near-surface, the top 15 cm of soils, which is particularly important for fertility, were excluded in the studies. As impacts on plants with roots in the zone were observed, it is likely the microbes present will also be affected. This is a potential area of future research.

Experiments conducted at the Grimsrud field site and associated laboratory experiments simulated the impacts of a CO_2 leak on oats. Results showed that at the soil surface, the geometry of the leak seemed to be strongly related to the soil structure. Plant growth reduction, yellowing, purple discolouration, and reduced chlorophyll and canopy water contents were observed at the end of the growing season, where both soil and atmosphere were enriched in CO_2. The simulated leak had a strong impact on the soil CO_2 concentration but almost none on the atmospheric concentrations, suggesting that most of the impacts observed on plant development were due to high CO_2 concentration in the soil. In the canopy CO_2 seemed to be dispersed readily, even by gentle breezes, although there can be CO_2 build up under very still conditions. Such low air flow was more prevalent at night and especially just prior to sunrise.

The laboratory study performed in controlled conditions assessed the effect of high soil CO_2 concentrations on growth and photosynthesis parameters of different agricultural plant species. Results showed that plant growth and photosynthetic performance decrease with increasing root CO_2 concentration. The reduced plant growth and photosynthetic performance under high root CO_2 concentration is caused both by the direct toxicity of CO_2 and an indirect low soil O_2 concentration, resulting from replacement of O_2 in the soil air by CO_2. Differences in the tolerance to elevated root CO_2 concentration between oats and wheat could not be observed in the experiments. The sensitivity of plants to high root CO_2 concentration appears to depend on the size and/or physiological condition of the plants at the start of gas exposure.

Modelling

Systems models aim to represent all the important processes throughout the system that is being studied, but usually in a simplified form compared to detailed models for particular processes or parts of the system (Figure 10, left). The systems model developed for terrestrial environments in the RISCS project represents near-surface processes (Figure 10, right).

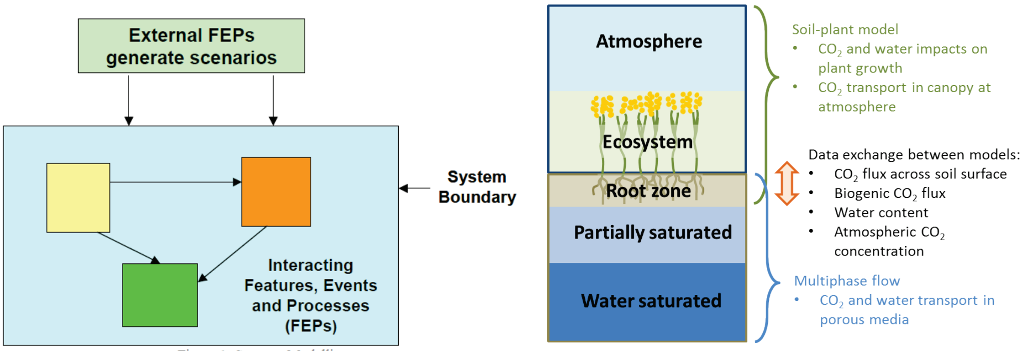

Figure 10 Schematic illustration of the systems model (left) and terrestrial ecosystems- model (right).

The systems model developed for RISCS consists of two main components (Figure 10, right):

- The multi-phase flow model (MPF) represents the flow of multiple fluids (air, CO_2 and water) through a porous medium, the sub-surface component of the system.
- The soil-plant model (SPM) represents different plant components, the air and CO_2 in the canopy and wider atmosphere, and their interaction by metabolic processes (Figure 11).

This systems model was implemented using Quintessa's general-purpose QPAC software, together with specialist modules designed to simulate multi-phase flow and vegetation. The model can be spatially discretised in 1D, 2D or 3D using Cartesian or cylindrical type geometries with different materials, and all inputs can be time dependent or coupled to other system properties, allowing the model to be used to represent spatially heterogeneous 1D, 2D or 3D physical geometries.

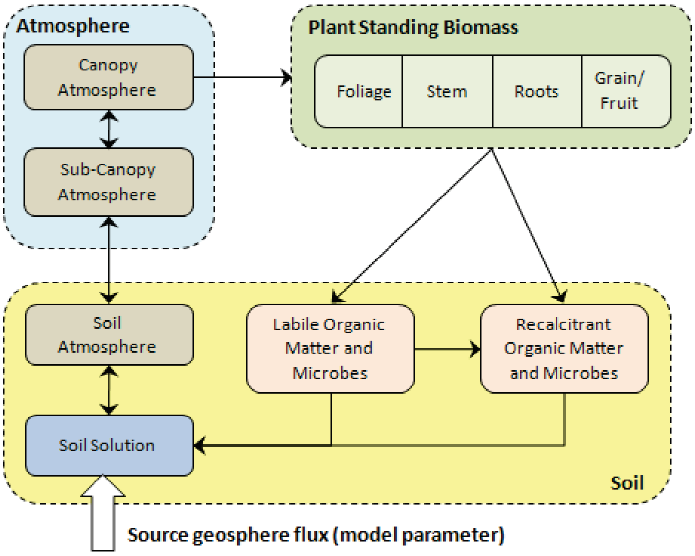

Figure 11 Simplified representation of the soil plant model. The model represents metabolic processes that control the cycling of carbon between different parts of the system and both CO_2 toxicity and fertilisation effects.

The terrestrial systems model was tested by application to two sets of field experimental data obtained during WP3 of the RISCS project: one dataset obtained from ASGARD, near Nottingham, UK; and one obtained from Grimsrud in southern Norway. The models were able to reproduce the impacts of CO_2 on plant growth at the sites and some suitable parameters for the investigated vegetation types were identified. The work also demonstrated that the model can be adapted readily to different crops. Example results are shown in Figure 12.

The ASGARD models considered a number of different crop types (barely and oilseed) as well as a grass/clover pasture. A further different crop type (oats) was considered in the Grimsrud Farm models. At both ASGARD and Grimsrud Farm, the observed soil concentrations are much lower than predicted given the known injection rate and the fluxes coming out of the ground. This can be explained by the majority of the CO_2 moving from the injection point to the ground surface in discrete pathways, reducing the diffusion of CO_2 into the matrix pore space. At both sites, observations show that injection of CO_2 can decrease the growth of crops, but the effect is small in all experiments. None of the data indicate that crops growth was stopped by the elevated levels of CO_2 and the model results suggest that growth could actually be enhanced by CO_2.

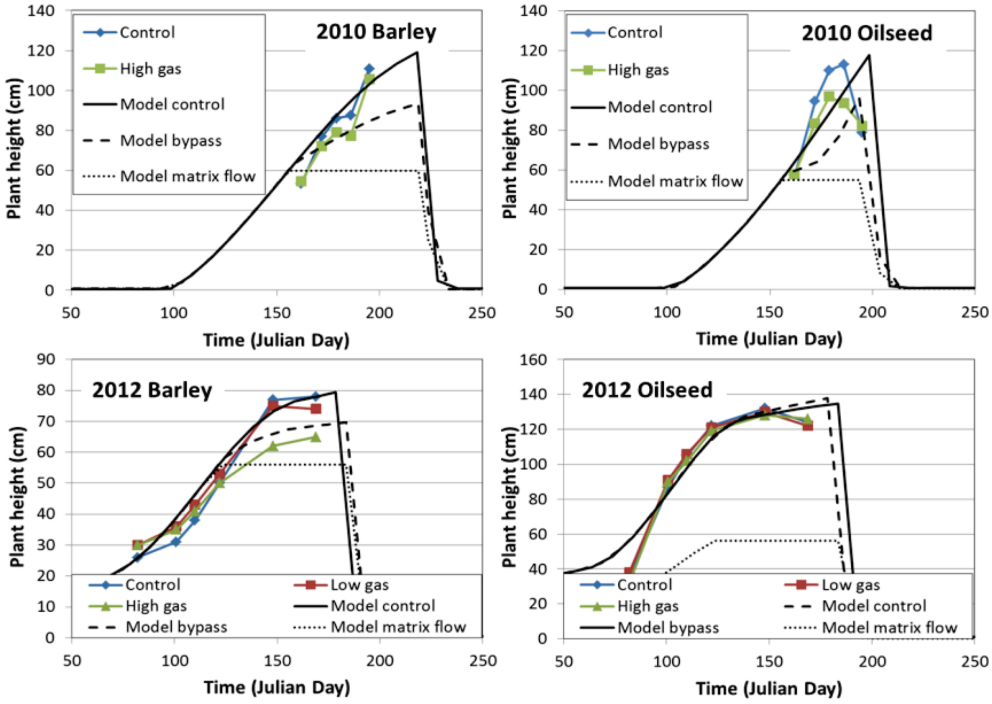

Figure 12 Example output showing how the systems model matches the plant height data obtained from the ASGARD site during the RISCS project.

After development and testing using the results of the terrestrial field experiments, the terrestrial systems model was applied to explore various terrestrial impact scenarios developed in WP1:

- Direct release to the atmosphere;
- Localised release to soils leading to high CO_2 concentration;
- Localised release to soils leading to low CO_2 concentration;
- Diffuse release to soils;
- Localised release to aquifers.

Example outputs from simulations to investigate localized release to soils are shown in Figure 4.

The impacts of CO_2 on plants depend more on attained CO_2 concentrations than CO_2 fluxes, so a good understanding of how fluxes relate to concentrations in different parts of the soil-plant system is essential to predict impacts. High-flux CO_2 releases to the atmosphere are likely to cause little or no impact due to rapid mixing with air, which produces low canopy CO_2 concentrations. High atmospheric CO_2 concentrations will occur only where there is ponding in topographic hollows or where there is no movement of the ambient air caused by leakage. High flux releases to the base of the soil may bypass the soil zone via relatively permeable pathways such as fractures, reducing the impact on plants. Even where leakages to the soil zone cause some impact to plants, this could restricted to within 10 m of the leakage site and it is questionable whether the impact will be observable; leakages to an aquifer are likely to results in a drop in pH in the formation water and possibly a build-up of gas above the water table.

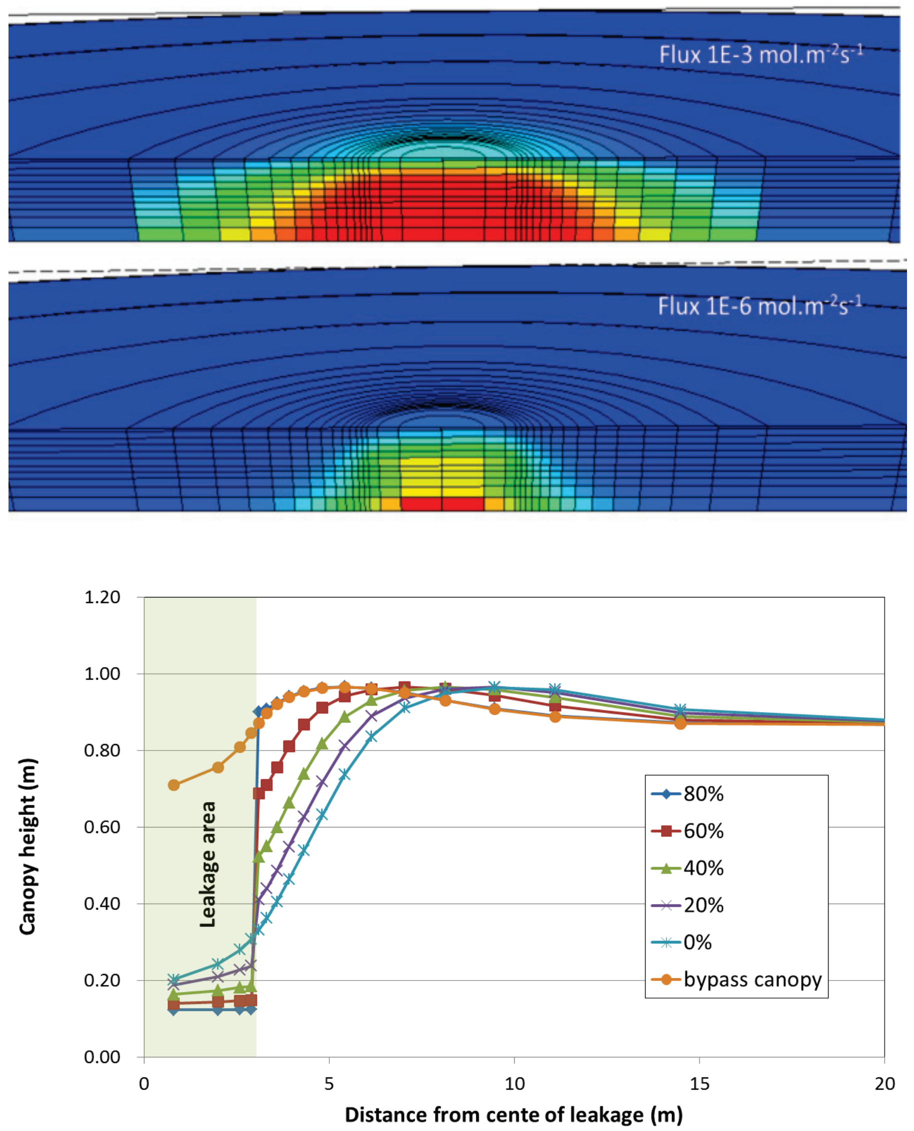

Figure 13 Top - CO_2 concentration in the soil zone for two leakage fluxes (red corresponds to 8E5 ppmv for the upper image but 1E4 ppmv for the lower image). Bottom - Canopy height after 5.27 years, for cases with 0 – 80% bypass flow and a case in which the 80% bypass flow also bypasses the canopy. Flux into the model's base was 1E-3 mol.m^{-2}.s^{-1}.

The systems model has demonstrated that understanding of processes controlling near-ground surface CO_2 migration and accumulation, and the metabolism of common European crop types and pasture vegetation, is sufficient to simulate CO_2 leakage impacts on these vegetation types. The actual impacts at a particular site will depend upon many different site-specific parameter values, so the model cannot be used predictively in the absence of site-specific information. However, the work has demonstrated the feasibility of predicting bounding impacts to vegetation from different leakage scenarios at a particular terrestrial storage site, provided that these site-specific data are obtained. A key insight is that higher leakage fluxes do not necessarily lead to bigger impacts. Even relatively high leakage fluxes may produce little or no observable impacts as a result of CO_2 flow bypassing the soil zone. This possibility will need to be considered when designing monitoring plans that incorporate observations of vegetation health and growth.

Monitoring

Although, hyperspectral monitoring can be used to estimate the health of vegetation it might not be able to differentiate effects due to CO_2 leakage from that caused by other stressors. Hyperspectral indices such as NDVI705 and the agricultural stress index proved to be particularly useful for the detection of CO_2 leaks through plant stress in Norway.

Studies at the RISCS sites have shown that bio-indicators may be useful to determining the location of leakages. For example, *Polygonum* spp was a useful plant indicator of CO_2 vent zones at Florina (Figure 14) and seen in previous studies near the Laacher See in Germany. Leguminous plants, such as beans and clover, are also potential indicator species being more sensitive to elevated CO_2 concentrations than other plants such as grasses.

Figure 14 *Polygonum aviculare* is tolerant of high natural CO_2 levels near Florina, Greece.

Field trials undertaken in Norway have indicated that isotopic monitoring can characterise the three-dimensional extent of the leak within the soil-atmosphere continuum, including the assimilation of leaking CO_2 by vegetation. In these experiments, isotopic analyses improved the detection and monitoring of the simulated leakage of geological CO_2, enabled the proportion of the flux that was due to injected CO_2 to be estimated and the characterisation of different zones of CO_2 transfer in soil. However, this was dependent on a clear isotopic contrast between the injected CO_2 and local biogenic CO_2. This is not the case, for example, when the CO_2 is derived from the combustion of coal, which is formed from ancient plant material.

Potential impact

The main findings of RISCS were intended to be most directly relevant to policy makers, regulators and operators involved in geological CO_2 storage. They will assist in the formulation of decisions on the deployment of CCS in general and more specifically help in the selection, licensing and monitoring of CO_2 storage sites. In addition they will inform the general debate on the potential environmental impacts of CO_2 storage and allow this to be set in the context of the broader effects of climate changes and other stresses on marine and terrestrial ecosystems.

RISCS will directly and positively impact on the following areas of CO_2 storage safety:

- The project will significantly increase knowledge of the potential environmental impacts of leaks from CO_2 storage, for several key groups.
- The RISCS consortium increased the number of research organisations investigating aspects of CO_2 storage to the benefit of the whole community. Links to international research at CO_2CRC, Montana State University and University of Regina also greatly benefitted international collaboration in this area.
- External links with other projects in Europe (e.g. other FP7 project such as ECO2, SiteChar, MUSTANG and national projects such as QICS in the UK, CIPRES in France and CATO2 in the Netherlands) and worldwide (ZERT in the USA and Ginninderra Farm in Australia) has further fostered a wider appreciation of RISCS results and helped to develop firmer conclusions through pooling with the results of these projects.
- Strong integrated involvement in the project by representatives of several industries, such as energy suppliers (Vattenfall, Eon, ENEL, RWE) and oil and gas companies (Statoil) should promote uptake and exploitation of the findings from RISCS. Specifically, RISCS has provided previously unavailable data and methodologies that will help industry to formulate Environmental Impact Assessments, design appropriate monitoring and formulate mitigation plans. Indirectly RISCS results will improve site selection and characterisation, and enhance dialogue between industry and regulators.
- The strong integrated involvement of the Environmental NGO, ZERO and social scientists among the research partners has helped to ensure that key findings from RISCS were communicated to a range of stakeholders and will help to inform the public on these sensitive issues. By sharing such knowledge, public confidence in CO_2 storage should be improved.

The RISCS Guide was specifically conceived to have a direct impact on the development, implementation and approval of environmental impact assessments for regulatory bodies at the European and Member State level, by providing:

- Accessible, authoritative information on a range of focussed and relevant topics to improve regulator capability and capacity in this rapidly evolving and growing area.

- Definitions of credible leakage scenarios, realistic impacts and ranges of CO_2 leakage rates that are necessary to cause significant impacts both qualitatively and quantitatively, wherever possible.
- Proven methodologies for assessing the degree of environmental impact with case studies.
- An improved knowledge base to enable improved decision-making when developing strategic policies for leasing storage sites, assessing risks of CO_2 storage and granting storage licences.

RISCS will improve the safety of CO_2 storage. This will be achieved by:

Increasing the understanding of key (quantified) parameters that influence leakage and the consequences of such leaks on near-surface ecosystems

Addressing important questions which regulators and industry are increasingly being challenged on:

1. How much CO_2 is needed to cause significant impact?
2. What is a significant impact?
3. When would a leak be most/least harmful?
4. How long would a leak have to last to cause significant impact?
5. Where would leaks cause most/least impacts?
6. How quickly could an impact be attenuated?

The project has been structured to maximise the benefits of the research for a wide audience with vested interests. The principal steps undertaken to achieve the aforementioned impacts include:

Development of the Guide through a series of versions, each being built up from the emerging results of RISCS and other research internationally, and also through critical internal and external review. The precise scope and content of the Guide was defined through internal discussion within the RISCS consortium, and discussion and feedback from the RISCS Advisory Board. This was then tested and reviewed via external workshops, with feedback being incorporated into the next version. The final version of Guide will be widely disseminated to the target stakeholder groups and made freely available to all interested parties through the website.

The improved knowledge base has had a direct beneficial impact on the Features, Events and Processes (FEP) database developed by Quintessa and available as an open-access tool to help audit the identification of largely geotechnical risks during project development. The FEP database has been updated to take account of the knowledge acquired during the project in areas of ecosystem impacts. This will be of benefit to all those involved in designing and developing risk assessment methods, protocols and undertaking risk assessments for CO_2 storage projects.

Dissemination activities

Presentations

Presentations made during the project and planned in 2014 are listed in Appendix 1. Opportunities may be taken to disseminate the results at other meetings beyond 2014.

The Guide will be distributed to key stakeholders and will be available to all through the RISCS website.

Publications

Papers published to date and those in preparation are listed below. Other papers have been proposed but are not yet in preparation.

Published or in press

Blackford, J C, Torres, R, Cazanave, P and Artioli, Y. 2013. Modelling Dispersion of CO_2 Plumes in Sea Water as an Aid to Monitoring and Understanding Ecological Impact. *Energy Procedia*, Vol. 37, 3379-3386.

Bond, A E, Metcalfe, R, Maul, P R, Suckling, P, Thatcher, K, Walke, R, Smith, K, Rasse, D, Steven, M and Jones, D. 2013. Systems Analysis of Field and Laboratory Experiments Considering Impacts of CO2 Leakage in Terrestrial Systems. *Energy Procedia*, Vol. 37, 3394-3402.

Bøe, C M 2013. Potential impacts of abrupt in situ CO_2 acidification on microbial abundance and community structure in deep-sea sediments MSc Thesis University of Bergen

de Vries, P, Tamis, J E, Foekema, E M, Klok, C and Murk, A J. 2013. Towards quantitative ecological risk assessment of elevated carbon dioxide levels in the marine environment. *Marine Pollution Bulletin*, Vol. 73, 516-523.

Klok, C, Wijsman, J W M, Kaag, K and Foekema, E. In press. Effects of CO_2 enrichment on cockle shell growth interpreted with a Dynamic Energy Budget model. *Journal of Sea Research* http://dx.doi.org/10.1016/j.seares.2014.01.011..

Lions, J, Humez, P, Pauwels, H, Kloppmann, W and Czernichowski-Lauriol, I. In press Tracking leakage from a natural CO2 reservoir (Montmiral, France) through the chemistry and isotope signatures of shallow groundwater. *Greenhouse Gases: Science and Technology* http://dx.doi.org/10.1002/ghg.1381

Moni, A C and Rasse, D P. 2013. Simulated CO_2 Leakage Experiment in Terrestrial Environment: Monitoring and Detecting the Effect on a Cover Crop Using 13C Analysis. *Energy Procedia*, Vol. 37, 3479-3485.

Moni, A C and Rasse, D P. (accepted with minor revision). Detection of simulated leaks from geologically stored CO_2 with ^{13}C monitoring. *International Journal of Greenhouse gas control*.

Paulley, A, Metcalfe, R, Egan, M, Maul, P R, Limer, L and Grimstad, A A. 2013. Hypothetical Impact Scenarios for CO2 Leakage from Storage Sites. *Energy Procedia*, Vol. 37, 3495-3502.

Smith, K L, Steven, M D, Jones, D G, West, J M, Coombs, P, Green, K A, Barlow, T S, Breward, N, Gwosdz, S, Krüger, M, Beaubien, S E, Annunziatellis, A, Graziani, S and Lombardi, S. 2013. Environmental impacts of CO_2 leakage: recent results from the ASGARD facility, UK. *Energy Procedia*, Vol. 37, 791-799.

Ziogou, F, Gemeni, V, Koukouzas, N, de Angelis, D, Libertini, S, Beaubien, S E, Lombardi, S, West, J M, Jones, D G, Coombs, P, Barlow, T S, Gwosdz, S and Krüger, M. 2013.

Potential Environmental Impacts of CO2 Leakage from the Study of Natural Analogue Sites in Europe. *Energy Procedia*, Vol. 37, 3521-3528.

In preparation

Celussi, M, Franzo, A, Del Negro, P, De Vittor, C. In prep. Effect of CO_2-induced pH decrease on biogeochemical properties at a shallow coastal marine site (northern Adriatic Sea): a mesocosm study.

Franzo, A, Celussi, M, Cibic T, Del Negro P, De Vittor, C. In prep. Effect of CO_2-induced pH decrease on shallow benthic microbial communities at a coastal marine site (northern Adriatic Sea): a mesocosm study.

Crispi, G and Pacciaroni, M . In prep. Scenarios of *Posidonia oceanica* and trophic web changes in the Mediterranean.

Gwosdz, S . In prep. “Impacts of high CO_2 concentrations on near surface microbial communities at natural and artificial sites” Unpublished PhD thesis, University of Hannover.

Lorenzon, S, D’Antoni, S and Ferrero, E A. In prep. Physiological and immunological responses of the intertidal crab Carcinus aestuarii (Crustacea, Decapoda) exposed to variation of water pH and temperature.

Queirós, AM, Taylor, P, Cowles, A, Reynolds, A, Stahl, H, Widdicombe, S. In prep. Assessing marine sedimentary pH profiling for ocean acidification and carbon capture and storage research. Marine Ecology Progress Series.

West, J M, Jones, D G, Annunziatellis, A, Barlow, T S, Beaubien, S E, Bond, A, Breward, N, Coombs, P, Angelis, D d, Gardner, A, Gemeni, V, Graziani, S, Green, K A, Gregory, S, Gwosdz, S, Hannis, S, Kirk, K, Koukouzas, N, Krüger, M, Libertini, S, Lister, T R, Lombardi, S, Metcalfe, R, Pearce, J M, Smith, K L, Steven, M D, Thatcher, K and Ziogou, F. In Prep. Comparison of the impacts of elevated CO_2 soil gas concentrations on selected European terrestrial environments. *International Journal of Greenhouse Gas Control*.

Website

The RISCS website will be maintained for at least 2 years after the end of the project and links will be provided to new outputs

Address of the website

http://www.riscs-co2.eu/

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Appendix 1 List of presentations

Date	**Meeting**	**Location**	**Presentation**	**Presenter**
6-8 May 2010	IEAGHG Monitoring Network	Natchez, Texas, USA	General overview	Sarah Hannis, BGS
10-11 May 2010	CO_2GeoNet Open Forum	Venice, Italy	General overview	Dave Jones, BGS
17-18 May 2010	IEAGHG Risk Assessment Network	Denver, Colorado, USA	Short overview	Ameena Camps, IEAGHG
13 Sept 2010	Environmental Monitoring for CCS	Copenhagen, Denmark	General overview	Dave Jones, BGS
14-15 Sept 2010	UK CCS Consortium	Leeds, England, UK	General overview	Karen Kirk, BGS
2-4 Nov 2010	IEAGHG Workshop: Natural releases of CO_2	Maria Laach, Germany	General overview	Dave Jones, BGS
03-06 April 2011	Annual Conference of the Association for General and Applied Microbiology, 2011	Karlsruhe, Germany	Effects of elevated CO_2 on microbial communities in near surface environments	Simone Gwosdz, BGR
6-8 May 2011	CTSC conference	Le Havre, France	General overview	Karen Kirk, BGS
9-11 May 2011	CO_2GeoNet Open Forum	San Servolo Island, Venice, Italy	Assessing impacts in terrestrial environments - results from the RISCS project	Dave Jones, BGS
9-11 May 2011	CO_2GeoNet Open Forum	San Servolo Island, Venice, Italy	Assessing impacts in marine environments - results from the RISCS project	Cinzia De Vittor, OGS
9-11 May 2011	CO2GeoNet Open Forum	San Servolo Island, Venice, Italy	Building a guide for impacts appraisal: proposals and suggestions	Jonathan Pearce, BGS & Samuela Vercelli, Sapienza
May 2012	China University of Mining and Technology	Beijing	RISCS overview and ASGARD studies	Mike Steven, UNOTT
24-26 May 2011	CO2Net annual seminar	London, UK	General overview & early project results	Karen Kirk, BGS

14-16 June 2011	Sixth Trondheim CCS conference	Trondheim, Norway	Definition of Hypothetical Impact Scenarios for CO2 Storage Sites: An Input to the RISCS Project	Richard Metcalfe, Quintessa
14-16 June 2011	Sixth Trondheim CCS conference	Trondheim, Norway	RISCS: Research into Impacts and Safety in CO2 Storage – an overview of the project and early progress	Richard Metcalfe, Quintessa (produced by Dave Jones, BGS)
14-16 June 2011	Sixth Trondheim CCS conference	Trondheim, Norway	Influence of CO_2 detectability thresholds and remediation response time on surface leakage rate	Alv-Arne Grimstad, Sintef
21-23 June 2011	IEAGHG Risk Assessment Network	Pau, France	Microbiological impact and implications for groundwater quality	Julie West, BGS
28 August - 2 Sept 2011	SAME 12 The 12th Symposium forAquatic Microbial Ecology	Germany, Rostock–Warnemünde	CO_2 induced pH decrease: effect on planktonic microbes	Mauro Celussi, OGS
1-3 Sept 2011	EAGE / SEG Summer Research Workshop	Trieste, Italy	Effects of CO2 induced pH decrease on shallow benthic microbial communities	Franzo Annalisa and others, OGS
8-11 Nov 2011	EAGE Sustainable Earth Sciences	Valencia, Spain	Assessing Impacts of CO_2 Leakage on the Ecosystem - An Overview and Early Results from the RISCS Project	Dave Jones, BGS
03-07 Dec2011	AGU 2011 Fall Meeting	San Francisco, California, USA	Effects of elevated CO2 on microbial communities in near surface environments	Simone Gwosdz, BGR
5-9 Dec2011	AGU Fall Meeting	San Francisco, USA	Effects of elevated CO_2 on microbial communities in near surface environments	Dave Jones, BGS
9-10 Nov 2011	CO2: CCS and CCU in Germany, The Netherlands, Norway, Poland, and Scotland	Rheinterrasse Düsseldorf	RISCS – Short Presentation	Tore Torp, Statoil
01Mar 2012	SiteChar Stakeholders Conference	Paris, France	RISCS contributions to storage permit process - GIA	Jonathan Pearce, BGS
18-21 March 2012	Annual Conference of the Association for General and Applied Microbiology, 2012	Tübingen, Germany	Effects of elevated CO2 concentrations on microbial ecosystem at the artificial test site ASGARD, England	Simone Gwosdz, BGR
16-19 April 2012	CO2GeoNet Open forum	San Servolo, Italy	RISCS update	Dave Jones, BGS
19 Apr 2012	IEA Regulators Network meeting	IEA, Paris	Overview of risks for CO_2 storage	Jonathan Pearce, BGS

14 Jul 2012	European Science Open Forum	Dublin, Ireland	RISCS and CGS Europe event	Samuela Vercelli, Sapieza
17-19 July 2012	IEAGHG Leakage Impacts Workshop	Montana, USA	RISCS overview	Dave Jones, Jonathan Pearce, BGS
19-24 August 2012	ISME, 2012	Copenhagen, Denmark	Seeping volcanic CO2 and its effects on freshwater environments	Simone Gwosdz, BGR
01-03 Oct 2012	GeoHannover, 2012	Hannover, Germany	Volcanic CO2 seeps and their influence on freshwater environments	Simone Gwosdz, BGR
18-22 Nov 2012	GHGT-11	Kyoto, Japan	Systems analysis of field and laboratory experiments considering impacts of CO2 leakage in terrestrial systems	Alex Bond, Quintessa
18-22 Nov 2012	GHGT-11	Kyoto, Japan	Potential environmental impacts of CO2 leakage from the study of natural analogue sites in Europe	Fotini Ziogou, CERTH
18-22 Nov2012	GHGT-11	Kyoto, Japan	Simulated CO2 leakage experiment in terrestrial environment: Monitoring and detecting the effect on a cover crop using 13C analyses (Poster)	Christophe Moni, Bioforsk
18-22 Nov 2012	GHGT-11	Kyoto, Japan	Environmental impacts of CO2 leakage: recent results from the ASGARD facility, UK (Poster)	Karon Smith, UNOTT
18-22 Nov 2012	GHGT-11	Kyoto, Japan	Hypothetical Impact Scenarios for CO2 Leakage from Storage Sites.	Alan Paulley, Quintessa
18-22 Nov 2012	GHGT-11	Kyoto, Japan	Modelling dispersion of CO2 plumes in sea water as an aid to monitoring and understanding ecological impact.	Jerry Blackford, PML
24 January 2013	Zero Emissions Platfrom Taskforce Technology	Hoofddorp, Netherlands	RISCS Guide to potential impacts of leakage form CO2 Storage.	Jonathan Pearce, BGS
10-13 March 2013	Annual Conference of the Association for General and Applied Microbiology, 2013	Bremen, Germany	Natural CO2 vents affect freshwater environment	Simone Gwosdz, BGR
7-12 April 2013	EGU General Assembly	Vienna, Austria	Method for tracing simulated CO2 leak in terrestrial environment with a 13CO2 tracer	Christophe Moni, Bioforsk

7-12 April 2013	EGU General Assembly	Vienna, Austria	Damage evaluation for crops exposed to a simulated leakage of geologically stored CO2 using hyperspectral imaging technology	Christophe Moni, Bioforsk
9-11 April 2013	CO2GeoNet Open Forum	Venice, Italy	What is the likely extent of ecosystem impacts should a CO2 storage site leak? Findings from the RISCS project	Dave Jones, BGS
4-6 June 2013	The 7th Trondheim Conference	Trondheim, Norway	Impacts of elevated CO2 concentrations on CO2-adapted and non-adapted environments	Simone Gwosdz, BGR
4-6 June 2013	The 7th Trondheim Conference	Trondheim, Norway	Comparison of the impacts of elevated CO2 soil gas concentrations on selected European terrestrial environments	Julie West, BGS
10-13 June 2013	IEAGHG Joint Modelling and Risk Assessment Networks meeting	Trondheim, Norway	'Modelling Scenarios for Low-Probability CO2 Leakage - Approaches and Applications'	Richard Metcalfe, Quintessa
19-20 June 2013	International Forum on Transportation of CO2 by Pipeline 2013	Gateshead, UK	COOLTRANS - Environmental impacts of CO2 leakage into the soil environment.	Janice Lake, UNOTT
26/06/2013	CCS seminar (Athens)	Athens, Greece	Pilot and demo CO2 Geological Storage Projects worldwide -Research activities of CERTH on CO2 Geological Storage	Nikolaos Koukouzas, CERTH
21-25 July 2013	The 5th Congress of European Microbiologists (FEMS 2013)	Leipzig, Germany	Long-term monitoring of the microbial communities in agricultural soils continuously gassed with CO2	Simone Gwosdz, BGR
25-30 August 2013	Goldschmidt 2013	Florence, Italy	Effects of volcanic CO2 vents on a freshwater environment, the Laacher See	Simone Gwosdz, BGR
26-30 August 2013	IEAGHG Combined Monitoring and Environmental Research of CO2 Storage	Canberra, Australia	Synthesis of RISCS and project comparison	Dave Jones, BGS
26-30 August 2013	IEAGHG Combined Monitoring and Environmental Research of CO2 Storage	Canberra, Australia	Biological impacts of CCS leakage, monitoring opportunities	Steve Widdicombe, PML

26-30 August 2013	IEAGHG Combined Monitoring and Environmental Research of CO2 Storage	Canberra, Australia	Marine baselines - natural variability	Jerry Blackford, PML
29 Nov 2013	RISCS Final Conference	Rueil-Malmaison, France	Various	Various
9-10 January 2014	Tekna CO2 Conference 2014	Trondheim, Norway	RISCS project - what happens if CO2 leaks: a guide to the consequences, choice of storage sites, monitoring and remediation	Camilla Skriung Svendsen, ZERO
23-25 April 2014	Fourth EAGE CO2 Geological Storage Workshop Demonstrating storage integrity and building confidence in CCS	Stavanger, Norway	Groundwater changes caused by flow through naturally occurring gas (±water) leakage points.	Stan Beaubien, Sapienza
23-25 April 2014	Fourth EAGE CO2 Geological Storage Workshop Demonstrating storage integrity and building confidence in CCS	Stavanger, Norway	Use of the Panarea natural test laboratory for offshore CO2 leakage monitoring and impact studies	Stan Beaubien, Sapienza
27 April to 2 May 2014	EGU General Assembly 2014	Vienna, Austria	Direct interaction with the public: making it a "serious game" with role playing	Samuela Vercelli, Sapienza
2-3 April 2014	UKCCSRC Annual Meeting	Cambridge, UK	Potential environmental impacts of CO2 leakage: results from the ASGARD facility	Mike Steven, UNOTT
5-9 October 2014	GHGT12	Austin, Texas, USA	Baseline variability in onshore near surface gases and implications for monitoring at CO2 storage sites	Dave Jones,BGS
5-9 October 2014	GHGT12	Austin, Texas, USA	A Guide for assessing the potential impacts on ecosystems of leakage from CO2 storage sites	Jonathan Pearce , BGS
5-9 October 2014	GHGT12	Austin, Texas, USA	What would you like to know regarding the potential impact of CO2 geological storage?": results from the RISCS project's stakeholders' questionnaire	Samuela Vercelli, Sapienza