Assessing the health risks of natural CO₂ seeps in Italy

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Industrialized societies which continue to use fossil fuel energy sources are considering adoption of Carbon Capture and Storage (CCS) technology to meet carbon emission reduction targets. Deep geological storage of CO₂ onshore faces opposition regarding potential health effects of CO₂ leakage from storage sites. There is no experience of commercial scale CCS with which to verify predicted risks of engineered storage failure. Studying risk from natural CO₂ seeps can guide assessment of potential health risks from leaking onshore CO₂ stores. Italy and Sicily are regions of intense natural CO₂ degassing from surface seeps. These seeps exhibit a variety of expressions, characteristics (e.g., temperature/flux), and location environments. Here we quantify historical fatalities from CO₂ poisoning using a database of 286 natural CO₂ seeps in Italy and Sicily. We find that risk of human death is strongly influenced by seep surface expression, local conditions (e.g., topography and wind speed), CO₂ flux, and human behavior. Risk of accidental human death from these CO₂ seeps is calculated to be 10⁻⁸ year⁻¹ to the exposed population. This value is significantly lower than that of many socially accepted risks. Seepage from future storage sites is modeled to be less than that Italian natural flux rates. With appropriate hazard management, health risks from unplanned seepage at onshore storage sites can be adequately minimized.

carbon dioxide | storage leak | public acceptance | engineered sequestration | aquifer

Several factors currently hinder upscaling of Carbon Capture and Storage (CCS) (1, 2) but one of the greatest challenges is the intrinsic uncertainty of integrity of geological storage. Uncertainty does not mean inevitable leakage from subsurface geological containment. The likelihood of surface leakage will be highly site-specific and, overall, will remain poorly calibrated until geological carbon storage has been practiced widely over decades.

Fear of surface leakage, together with a perceived lack of local benefit, is one of the prime foundations for negative public opinion towards CCS (3–6) and is driving storage operations offshore or delaying project development (e.g., Mattoon, USA; Barendrecht, Netherlands). Public acceptance can strongly influence the fate of new technologies and onshore storage will usually be the least-cost domestic option for many countries. It is therefore crucial to assess the environmental hazards from leakage of CO₂ to the surface using analogues, models, and pilot studies (7–12). Developing and implementing suitable risk-assessment procedures will enable the accuracy of current concerns to be evaluated.

Italy is a region of widespread natural CO₂ degassing from well documented surface seeps. These CO₂ seeps provide excellent analogues for assessing the health risks of CO₂ leakage from onshore storage reservoirs. Italian gas seeps have already proven a valuable tool for developing storage site assessment, monitoring techniques, and understanding and predicting CO₂ leakage pathways and fluxes (11, 13–16). This study presents a quantitative analysis of human and animal injury from Italian CO₂ seeps during recent history. The aims are to calculate the risk that natural surface seeps present and understand the factors influencing human and animal health risk from surface CO₂ seeps. Data were elicited from Googas (17), a web-based catalogue of degassing sites in Italy constructed as a national project by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), communication with Googas collaborators, fieldwork, and published scientific literature.

Results

Italian Gas Seeps. Natural CO₂ degassing is most abundant in western Italy (18–20) (Fig. 1). Here there are over 286 documented CO₂ seeps exhibiting a range of surface expressions (Fig. 2), flux, and temperatures (19, 20), see SI Text. Seeps can be found in both rural and urban regions and public access is usually unrestricted, with little or no warning signposts. Degassing sites are typically geographically related to volcanic edifices, known natural CO₂ reservoirs, and CO₂-rich aquifers.

Health Hazards of Italian CO₂ Seeps. Here, hazard refers to a fatal outcome and risk as the likelihood of fatality according to historical records. Documentations of nonfatal events are not robust and are therefore disregarded. At the Earth’s surface, CO₂ is a colorless and odorless gas, which is chemically unreactive and hence undetectable by the human senses. Elevated CO₂ concentrations (1–3% air by volume, Cₐ/v/v) cause no physical damage but lead to rapid breathing, headaches, and tiredness. Above 3% (Cₐ/v/v) incomplete gas exchange in the lungs causes CO₂ concentration in the blood to increase hence altering the pH (21). This condition is called hypercapnia and leads to brain malfunction, loss of consciousness, and death at concentrations above 5–10% (Cₐ/v/v). At Italian gas seeps coreleased gases such as hydrogen sulphide (H₂S) also present a significant hazard. H₂S is beneficial to human health in extremely low concentrations but quickly becomes toxic above 3 × 10⁻³% (Cₐ/v/v), causing irreversible tissue damage. The strong “rotten-egg” odor of H₂S is identifiable at trace (parts per million, ppm) concentrations although human sensing of the gas rapidly decreases after exposure. Current European Union (EU) legislation would allow subsidiary gases such as sulfur species to constitute a minor component of injected flue gas (22) and pipeline corrosion is not a concern if H₂S concentrations remain below 200 ppm. The H₂S component of analyzed Italian seeps averages 0.32 × 10⁻⁶% (Cₐ/v/v) (19) which is well within the legal contaminant levels for geological CO₂ storage.

Italian gas seeps have claimed 19 human and hundreds of animal lives over the past fifty years (17, 20). The greatest human mortality in one incident in this period was the death of three adults at Mefite D’Ansanto in the 1990’s (7, 17). Many animal...
fatalities of all sizes and numbers are recorded, from hundreds of toads (Galleria drenante Acquasecca) to fields of cows (Colli Albani) to lone foxes (Mefite D’Ansanto).

Factors Influencing Risk at Italian Gas Seeps. Seep classification. Historically all seep classifications except springs and fumaroles present serious health hazard to animals (Fig. 2). A third of all known seeps are responsible for animal fatalities.

Only thirteen seeps are responsible for loss of human life, the majority of which are dry seep types (diffuse and vent). Dual-system seeps, where two seep types occur in one location, are particularly high risk; they have claimed animal lives (Fig. 2). Dual seeps are commonly diffuse classification coexisting with vent or bubbling-water types. There are no recorded human fatalities at fumaroles, which may be for two reasons: (i) Fumaroles have distinct surface expressions and high temperatures (>90°C) which signal to humans and animals to be cautious; (ii) Fumaroles are found close to volcanic edifices or geothermal fields which are sparsely populated, sparsely vegetated, and hence less visited by humans, and more exposed to wind, which disperses CO₂ gases.

Seep flux. Italian seeps most commonly degass between 10–100 tonnes CO₂ per day (Fig. 3). Monitoring studies over several years have not detected temporal variances that challenge the flux classifications assigned to measured seeps (23). Italian gas seeps do not show intermittent geyser-style emissions, although characteristics such as water content are known to show minor variation at some gas seeps (24). The influence of gas-flux and other seep characteristics are therefore considered to be constant factors affecting seep hazard.

Seep type affects the relationship between risk of death and CO₂ gas-flux. Risk positively correlates with gas-flux at dry seeps (r² = 0.9 and 0.6 for vent and diffuse seeps respectively). In contrast, at wet seeps the correlation if any, is much weaker; similar numbers of deaths have occurred at both low flux and high flux seeps.

Seep temperature. All measured seep temperatures are cool enough such that both CO₂ and H₂S are denser than air at atmospheric pressures, which can lead to gas pooling in sheltered locations. Seeps with emergent temperatures warmer than 34 °C record no injury to humans or animals, implying that low-temperature seeps present the greatest risk of fatalities. The increased health risk at low-temperature seeps is important because low-temperature dry seeps are analogous to CO₂ leakage from...
engineered storage sites. The observed relationship between cool temperature and greater risk could be attributed to the relative abundance of cooler seeps and their coincident high flux, or simply that elevated temperatures invoke precautionary behavior taken by animals and humans in the same way as hypothesized for fumaroles.

**Local topography.** Gas pooling from topographic effects can account for high risk but low flux wet seeps. For example, Santa Maria De Luco (Potenza) is a low flux seep in a sparsely populated rural region. Although located in pasture fields, discrete metre-scale topographical depressions allow CO$_2$ to accumulate to dangerous concentrations (17). Gas pooling in this manner will be more rapidly accomplished by higher flux emissions but is certainly achievable by any seep located in the correct environmental conditions. Density-driven accumulations can flow like a river. The paths of these gas-rivers are visible as gray scars on the landscape (7, 25) where the CO$_2$ and H$_2$S gas mixtures modify or kill the local vegetation (13, 26, 27). Abnormal vegetation is common at gas seeps and might assist gas hazard recognition if the animal or human is aware of such phenomena.

**Human population and behavior.** Incidents of human fatality are greatest in the most populated areas where exposure to the gas hazard can be assumed to be greatest but some deaths have occurred in sparsely populated regions (Fig. 1). Where fatality occurred in a rural area the victim was commonly engaged in an activity placing them close to the ground; either the victim was breathing close to the surface (swimmers; low-lying hunters) or lower than the surrounding surface (in a ditch or basement). The increased risk when breathing close to the ground is illustrated by the greater than 6:1 proportion of animal to human fatalities (Fig. 2). Hence the height or behavior of animals and humans influences their risk of death where even slight density pooling occurs.

**Quantifying Risk from Italian Gas Seeps.** Between 1990 and 2010, a time period considered to represent the fullest record, there were a total of 11 accidental fatalities at Italian CO$_2$ seeps. To quantify risk we consider regional resident populations in the western sector of central and southern Italy and Sicily, see SI Text. These 20 million (M) people were exposed to unfenced, unsigned, open-access seeps during this 20-year period.

These deaths equate to $2.8 \times 10^{-8}$ risk of fatality from CO$_2$ seeps per annum. Table 1 places this value along with the regionally accepted hazards and events for context. CO$_2$ poisoning at Italian gas seeps is markedly lower risk in comparison to most low-probability events, with 1 in 36 million chance of death per annum for exposed populations.

In risk analysis the expression Risk = Probability \times Consequence is commonly applied. Death by CO$_2$ poisoning is a “critical” consequence. However, the probability of death occurring is so small in this case that risk would usually classify as “low.”

**Discussion**

Natural analogues can provide an understanding of important processes which are otherwise unfeasible or unethical to test, but their comparability to engineered scenarios does have limitations. Large quantities of natural CO$_2$ in Italy originate from volcanic, mantle, and biogenic sources (28), rather than a single injector source. Italian gas seeps include trace components (H$_2$, S, light hydrocarbons) that industrial flue gas may not constitute. Only a proportion of the seeps considered in this study arise from reservoirs analogous to CO$_2$ stores. These seeps reflect established fluid migration pathways from carbonate reservoirs in a tectonically complex region rather than new emerging pathways from reservoirs more geologically suitable for CO$_2$ storage.

The purpose of CCS is to undertake storage in deeply buried geological reservoirs for “long” periods of time. In the context of reversing anthropogenic forcings, long refers to many (perhaps hundreds of) thousands of years (29). Such time scales are difficult to reconcile with legislative and commercial operations, and thus long typically means 1,000 y in the context of human planning. The EU CCS Directive (12) expects a CO$_2$ storage site to operate under zero, or very small and predictable, leakage. There is, as yet, no standardized value for tolerable seepage, and this will be specific to any storage site. As a minimum standard of performance, the IPCC 2005 (30) suggested retention of at least 99% stored CO$_2$ during a 1,000 y period. In this manner, leakage of 10–100 tonnes per day (t/d)—a common flux at Italian seeps—would be deemed a reasonable leakage (0.1–1%) from a storage facility injecting 3.6 Mt per year. Modeled leakage rates from storage to surface, based on well established knowledge of complex fluid flows, are typically several orders of magnitude lower than that from Italian gas seeps (31, 32).

In the unfortunate case of surface leakage of CO$_2$ from an engineered site risk management procedures will be implemented. It is expected that public access to any surface leak site would be restricted unlike described Italian natural analogues. Furthermore, local communities would be informed of the dangers of CO$_2$ gas seeps, hazardous behaviors around seeps, and how to recognize a seep. Under EU legislation (22) if any “significant irregularities” in the storage operation are experienced, injection would have to immediately cease, strict remediation procedures would have to be followed, and the operator would be penalized. Consequent pressure decrease is predicted to reduce or cease leakage flux. In addition the seep quantity, spread and affected population is likely to be much reduced in the case of leaking onshore CO$_2$ stores. As such, risk calculations here can only overestimate the risk of death by CO$_2$ poisoning from leaking onshore scenarios.

CCS offers rapid remediation of CO$_2$ emissions. While CCS development and deployment is delayed, many megaran tonnes of CO$_2$ are being released into the atmosphere without abatement. Anthropogenic CO$_2$ release is contributing to a process which will have catastrophic effects on human lives across the globe (33–35). Without decarbonization by CCS and other methods, risk of death from climate change will be much greater than that from breached engineered CO$_2$ stores.

### Table 1. Comparison of risk of fatality from CO$_2$ seeps in Italy alongside other hazards and events that many societies are exposed to

<table>
<thead>
<tr>
<th>Event</th>
<th>Risk/yr</th>
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<tbody>
<tr>
<td>Killed in car accident (It, 2006)</td>
<td>$1.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>Struck by lightning (USA)</td>
<td>$2.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Accidental domestic death from CO poisoning (UK)</td>
<td>$9.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>Winning the lottery jackpot (UK)</td>
<td>$7.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>CO$_2$ poisoning at seeps (western sector of central and southern Italy and Sicily)</td>
<td>$2.8 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Many members of society choose to accept these risks so as to, for example, enjoy the benefits of travelling by car. United Kingdom national lottery statistics represents a positive risk that people are familiar with, and many United Kingdom citizens choose to take despite low-returns.

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The factors we identify to influence health risk at Italian gas seeps are readily assessable and can be managed to achieve a reduced-risk environment at these sites or seeps which might arise in the event of leakage from CO\textsubscript{2} storage operations. Therefore, in the event of onshore CO\textsubscript{2} leakage from engineered storage operations the ensuing health risk to the local population would be significantly lower than that from Italian gas seeps. CCS cannot operate with zero risk. We have shown here that even if all containment fails and stored CO\textsubscript{2} leaks to the surface, the risk of death is extremely low. Hence the current public concern regarding death by CO\textsubscript{2} leakage from onshore storage sites appears overamplified.

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Supplementary Methodology. Information from all known seeps were compiled into a database, simplified, and analyzed (see Table S1). Many documented seeps lack precise information other than location, type, and safety. For example, 41% of all seep locations described in historic documents lack any detailed information regarding the number of fatalities or injuries. We assume that these fatalities and injuries are low in number or were not recorded. In the case of the Fossa del Bue, Pozzo Contrada Pescheria (1 death), and S. Maria De Luco, Cava dei Selci vignette, no death information related to these seeps is currently available in any source. Further, it is assumed that the fatality cannot have occurred in the Fossa del Bue, Pozzo Contrada Pescheria, or in published literature. For these seeps, no date of death information either in the Googas database, regional population cartography from the 2009 databases (6), or the Carbon Monoxide Gas Safety Society database (8), and the number of residential dwellings in 2009 source from the Department of National Statistics (9) find a similar risk factor when the risk factor was averaged for all seeps. Additionally, the risk factors presented in Table 1 were all calculated by a similar, simple approach.

The annual death rate from CO poisoning sourced from the Department of Health campaign from 2008 (7) and verified by the Carbon Monoxide Gas Safety Society database (8), and the number of residential dwellings in 2009 source from the Department of National Statistics (9). The risk of being struck by lightning in the USA was taken from published sources (10). National Lottery statistics can be derived from probability calculations:

- In the United Kingdom National Lottery, players pick six numbers from the range of integers between 1 and 49. When the lottery draw takes place, six numbers are drawn and to win the Jackpot all six numbers must be accurately predicted by the player. There are 49!/(6!*(49-6)!) combinations of six numbers which can be drawn. The calculation equates to 1 in 13,983,816 (approximately 1 in 14 million) chance of winning the right combination.

Regional population cartography from the 2001 census (3), car accident deaths (4) in Italy in 2006, and Italian resident population in the same year (5) source from the Italian National Institute of Statistics. Risk calculations included regional populations from the 2009 databases (6). CO2 seeps locate in only the western sector of central and southern mainland Italy. Human population is evenly weighted between the west and the east in both the Central region and the Southern region, therefore 50% of the population for each (11.8 M × 0.5 and 14.2 M × 0.5) were summed with the population of insular Italy (32.5 M) to represent the population exposed to CO2 hazard (20 M). We favor this simple approach because we do not have information to which communities encounter CO2 seeps. Risk calculations which considered only the population within 5 km radius of a CO2 seep (from the population density per commune, 2001 census) find a similar risk factor when the risk factor was averaged for all seeps. Additionally, the risk factors presented in Table 1 were all calculated by a similar, simple approach.


Other Supporting Information Files
Table S1 (DOC)