Assessing the health risks of natural CO_2 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 CO_2 onshore faces opposition regarding potential health effects of CO_2 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 CO_2 seeps can guide assessment of potential health risks from leaking onshore CO_2 stores. Italy and Sicily are regions of intense natural CO_2 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 CO_2 poisoning using a database of 286 natural CO_2 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), CO_2 flux, and human behavior. Risk of accidental human death from these CO_2 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 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 CO_2 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 CO_2 degassing from well documented surface seeps. These CO_2 seeps provide excellent analogues for assessing the health risks of CO_2 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 CO_2 leakage pathways and fluxes (11, 13–16). This study presents a quantitative analysis of human and animal injury from Italian CO_2 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 CO_2 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 CO_2 degassing is most abundant in western Italy (18–20) (Fig. 1). Here there are over 286 documented CO_2 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 CO_2 reservoirs, and CO_2-rich aquifers.

Health Hazards of Italian CO_2 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, CO_2 is a colorless and odorless gas, which is chemically unreactive and hence undetectable by the human senses. Elevated CO_2 concentrations (1–3% air by volume, $C_{\%}v.v$) cause no physical damage but lead to rapid breathing, headaches, and tiredness. Above $3\%(C_{\%}v.v)$ incomplete gas exchange in the lungs causes CO_2 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 $5–10\%C_{\%}v.v$. At Italian gas seeps coreleased gases such as hydrogen sulphide (H_2S) also present a significant hazard. H_2S is beneficial to human health in extremely low concentrations but quickly becomes toxic above $3\times10^{-3}\%(C_{\%}v.v)$, causing irreversible tissue damage. The strong "rotten-egg" odor of H_2S 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 H_2S concentrations remain below 200 ppm. The H_2S component of analyzed Italian seeps averages $0.32\times10^{-6}\%(C_{\%}v.v)$ (19) which is well within the legal contaminant levels for geological CO_2 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

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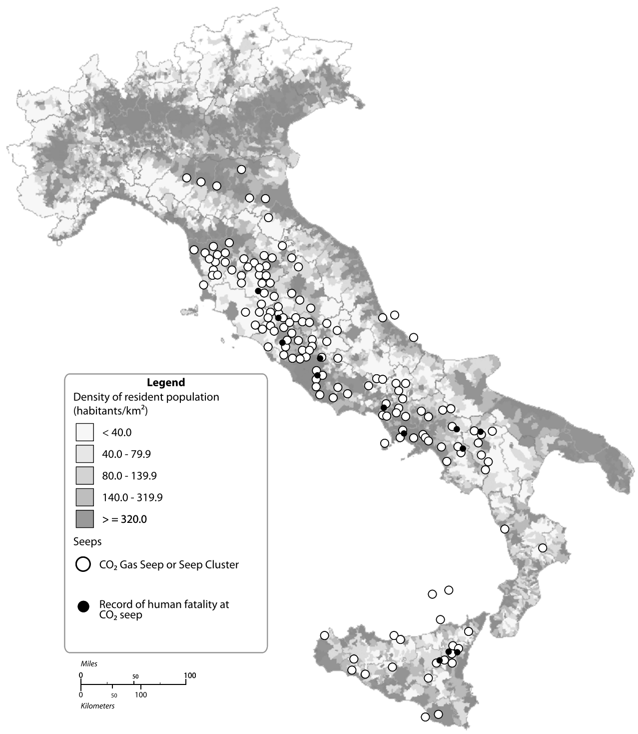

Fig. 1. Map of resident population and seep locations in Italy (2001 census, map modified from Italian Institute of Statistics). Seeps where human death has occurred over the past fifty years are in black (http://dawinci.istat.it/pl/index_eng.html) (36). Seeps concentrate in the Western sector of Italy and Sicily.

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; $\frac{2}{3}$ 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 CO_2 gases.

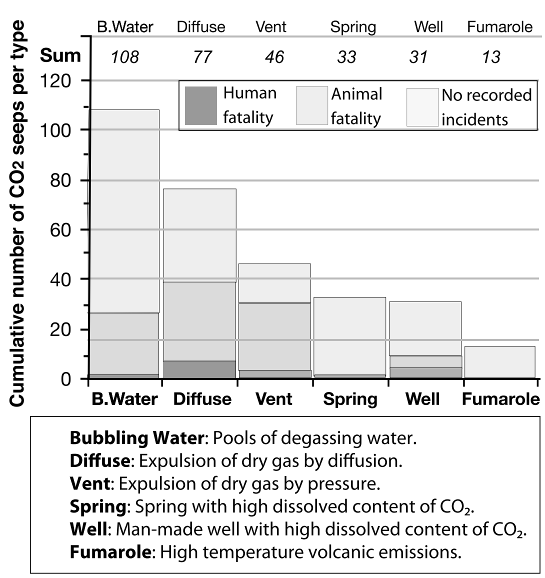

Fig. 2. Record of health incidents according to seep type from the past fifty years. There are six different seep types classified according to surface expression. Dual-system seeps are treated as two separate occurrences here. The number of fatalities relate to seep type rather than relative abundance; the most dangerous seeps being diffuse and vent (dry seeps). Only fumaroles record no fatal injury to humans.

Seep flux. Italian seeps most commonly degass between 10–100 tonnes CO_2 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 CO_2 gas-flux. Risk positively correlates with gas-flux at dry seeps ($r^2 = 0.9$ 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 CO_2 and H_2S 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 CO_2 leakage from

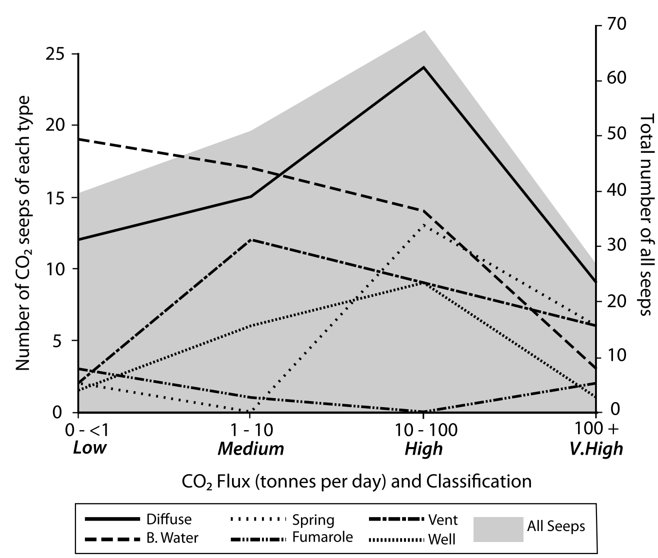

Fig. 3. Flux data for 169 of the 286 CO_2 seeps in Italy. Flux is measured by the CO_2 t/d and class as "low" (<1 t/d); "medium" (1–10t/d); and "very high" (>100 t/d). These data are represented above according to seep type (lines) on the left axis and total number of seeps in each flux class on the right axis (block gray). High flux seeps are most common, however it is expected that these seeps have been preferentially studied.

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_2S 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 2.8×10^{-8} risk of fatality from CO_2 seeps per annum. Table 1 places this value alongside socially 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 × 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_2S, H_2, 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 megatonnes 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

Event	Risk/yr
Killed in car accident (It, 2006)	1.8×10^{-4}
Struck by lightning (USA)	2.3×10^{-5}
Accidental domestic death from CO poisoning (United Kingdom)	9.2×10^{-7}
Winning the lottery jackpot (United Kindgom)	7.1×10^{-8}
CO_2 poisoning at seeps (western sector of central and southern Italy and Sicily)	2.8×10^{-8}

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.

Summary

While CO_2 degassing sites are indeed capable of causing death, the frequency of these incidents is extremely rare. According to 20 y of recent historical records from 286 seep locations in Italy, the risk that gas seeps present to the population is orders of magnitude lower than many other natural or socially accepted hazards. The risk of death from CO_2 poisoning to the population is extremely low at 2.8×10^{-8} y^{-1}.

Seep characteristics (type, temperature, and flux), as well as the surrounding environment and human behavior all have strong effects on the risk that each seep presents. Cool and dry seeps pose greater risk than hot or wet seeps. Risk from wet seeps poorly correlates with seep flux, unlike dry seeps which show a strong positive relationship. Simple human behavior which maintains breathing height above ground and avoids regions of low topography greatly reduces the risk of death.

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_2 storage operations. Therefore, in the event of onshore CO_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_2 leaks to the surface, the risk of death is extremely low. Hence the current public concern regarding death by CO_2 leakage from onshore storage sites appears overamplified.

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