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Publication Date

2011-06-01

Geologic Carbon Sequestration as a Global Strategy to Mitigate CO$_2$ Emissions:

Sustainability and Environmental Risk

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Glossary

Carbon dioxide capture and storage (CCS) - The capture of CO$_2$ from fossil-fuel power plants and other industrial point sources and its injection through wells into deep geologic formations for permanent storage.

Consequence - An impact arising from the occurrence of an event or process. For example, the consequence of high CO$_2$ concentrations in the atmosphere is global warming.

Geologic carbon sequestration (GCS) = Geologic CO$_2$ storage (GCS) - The last step of CCS in which CO$_2$ is injected through wells into deep subsurface formations for permanent storage.

Hazard - A potential impact or consequence of an event or process. For example, high CO$_2$ emissions are a hazard to climate because CO$_2$ is a greenhouse gas.

Likelihood - The probability or degree of potential for an event or process to occur. For example, the likelihood of CO$_2$ emissions to increase is very high given population growth and worldwide increases in standard of living.

Risk - The product of likelihood and consequence of an event or process. For example, the risk

of climate change is very high because both the likelihood and the consequences are high.

Storage Resource (capacity) - Physical pore-space volume available for CO_2 storage irrespective

of economics or regulations.

Storage Reserve (capacity) - Pore-space volume available for CO_2 storage including reductions

accounting for economic, legal, environmental, and regulatory factors.

1. Definition of Subject and Its Importance

Carbon dioxide (CO_2) capture and storage (CCS) is a combination of technologies that addresses climate change by directly reducing the net CO_2 emissions arising from the use of fossil fuels as the main global primary energy source (1). In CCS as commonly envisioned, CO_2 will be captured from flue gases at point sources such as coal-fired power plants, compressed, transported by pipeline, and injected into deep geologic formations for permanent storage (i.e., geologic sequestration) (Figure 1).

The capture of CO_2 involves use of liquid sorbents, membranes, or other advanced materials that can extract CO_2 from a mixture of gases associated with power generation or other industrial processes in which CO_2 is often a minor component at relatively low pressure. Few such capture operations exist currently at more than the pilot scale. However, CO_2 occurs in many natural gas (methane, CH_4) fields at concentrations above those required for delivery to customers. Gas processing to remove CO_2 from natural gas has been carried out for decades, and at two gas fields nearly two million tonnes of captured CO_2 are re-injected annually for geologic sequestration (2, 3).

In power-plant capture, extraction of CO_2 can be done after combustion, so-called post-combustion capture, or during precombustion steps, which has the advantage of higher pressures and higher CO_2 concentrations (1). There are also direct-air capture approaches for CCS that make use of solid sorbents to capture CO_2 from ambient air rather than specifically at point sources (e.g., 4, 5). Direct-air capture has the advantage that it addresses emissions from all sources, including mobile CO_2 sources such as automobiles and trucks, but also the disadvantages of much lower CO_2 concentration and pressure.

Regardless of how CO_2 capture is accomplished, the process must be capable of providing a stream of CO_2 for compression and transport to sequestration sites. Although direct injection of CO_2 into the deep oceans has received a large amount of attention (e.g., 6), and numerous processes to accelerate uptake of atmospheric CO_2 by the oceans have been discussed (e.g., 7, 8, 9), concerns about permanence and impact to marine ecosystems are larger for ocean sequestration than for geologic sequestration (e.g., 10). This leaves geologic sequestration as the main approach under consideration for isolating from the atmosphere the vast quantities of CO_2 that will need to be captured and stored for CCS to play a role in mitigating climate change.

The extra expense involved in capturing, transporting, and injecting CO_2 in the CCS process can be expressed in terms of an energy penalty, i.e., the amount of energy that must be expended above business-as-usual fossil-fuel energy use. Estimates of the energy penalty for CCS vary over a wide range depending on combustion process, age of facility, distance to geologic storage site, etc., but are likely around 40% (1, 11). Whether stated in terms of dollars or energy penalty, the largest expense in CCS is capture (which also includes compression), currently projected to account for more than 60% of the cost of CCS (12).
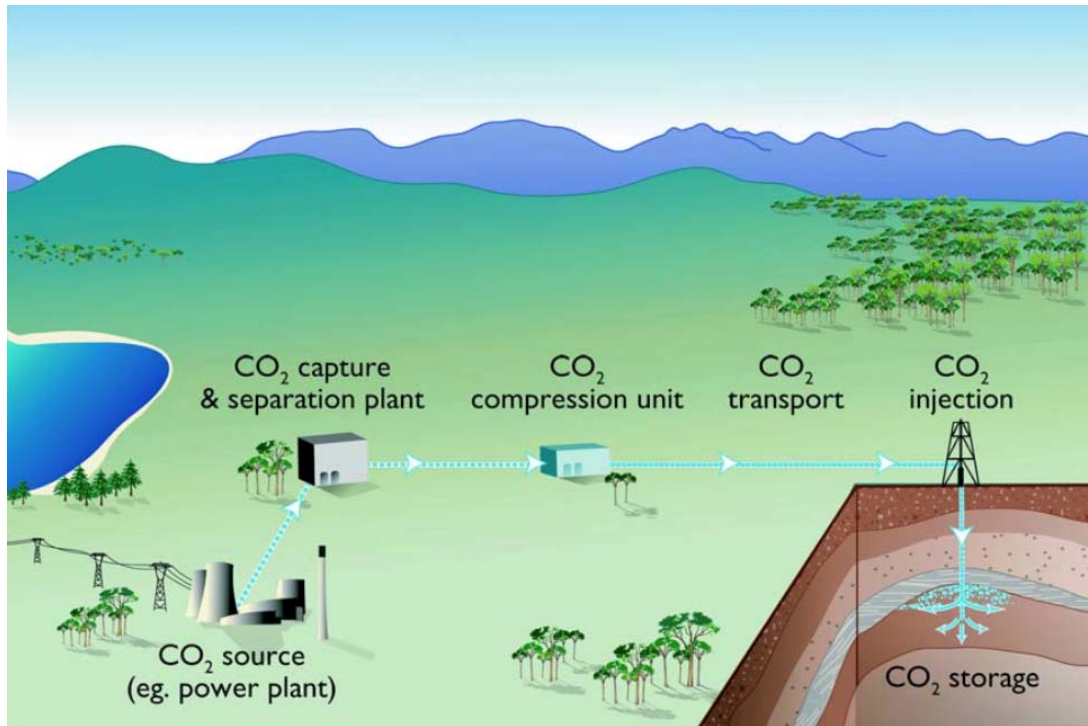
Figure 1. Schematic of the Carbon dioxide Capture and Storage (CCS) process (CO2CRC, http://www.co2crc.com.au/aboutccs/).

2. Introduction

Fossil fuels are abundant, inexpensive to produce, and are easily converted to usable energy by combustion as demonstrated by mankind's dependence on fossil fuels for over 80% of its primary energy supply (13). This reliance on fossil fuels comes with the cost of carbon dioxide (CO_2) emissions that exceed the rate at which CO_2 can be absorbed by terrestrial and oceanic systems worldwide resulting in increases in atmospheric CO_2 concentration as recorded by direct measurements over more than five decades (14). Carbon dioxide is the main greenhouse gas linked to global warming and associated climate change, the impacts of which are currently being observed around the world, and projections of which include alarming consequences such as water and food shortages, sea level rise, and social disruptions associated

with resource scarcity (15). The current situation of a world that derives the bulk of its energy from fossil fuel in a manner that directly causes climate change equates to an energy-climate crisis.

Although governments around the world have only recently begun to consider policies to avoid the direst projections of climate change and its impacts, sustainable approaches to addressing the crisis are available. The common thread of feasible strategies to the energy-climate crisis is the simultaneous use of multiple approaches based on available technologies (e.g., 16). Efficiency improvements (e.g., in building energy use), increased use of natural gas relative to coal, and increased development of renewables such as solar, wind, and geothermal, along with nuclear energy, are all available options that will reduce net CO_2 emissions. While improvements in efficiency can be made rapidly and will pay for themselves, the slower pace of change and greater monetary costs associated with increased use of renewables and nuclear energy suggests an additional approach is needed to help bridge the time period between the present and a future when low-carbon energy is considered cheap enough to replace fossil fuels. Carbon dioxide capture and storage (CCS) is one such bridging technology (1).

CCS has been the focus of an increasing amount of research over the last 15-20 years and is the subject of a comprehensive IPCC report that thoroughly covers the subject (1). CCS is currently being carried out in several countries around the world in conjunction with natural gas extraction (e.g., 2, 3) and enhanced oil recovery (17). Despite this progress, widespread deployment of CCS remains the subject of research and future plans rather than present action on the scale needed to mitigate emissions from the perspective of climate change. The reasons for delay in deploying CCS more widely are concerns about cost (18), regulatory and legal uncertainty (19), and potential environmental impacts (21).

This chapter discusses the long-term (decadal) sustainability and environmental hazards associated with the geologic CO_2 storage (GCS) component of large-scale CCS (e.g., 20). Discussion here barely touches on capture and transport of CO_2 which will occur above ground and which are similar to existing engineering, chemical processing, and pipeline transport activities and are therefore easier to evaluate with respect to risk assessment and feasibility. The focus of this chapter is on the more uncertain part of CCS, namely geologic storage. The primary concern for sustainability of GCS is whether there is sufficient capacity in sedimentary basins worldwide to contain the large of amounts of CO_2 needed to address climate change. But there is also a link between sustainability and environmental impacts. Specifically, if GCS is found to cause unacceptable impacts that are considered worse than its climate-change mitigation benefits, the approach will not be widely adopted. Hence, GCS has elements of sustainability insofar as capacity of the subsurface for CO_2 is concerned, and also in terms of whether the associated environmental risks are acceptable or not to the public.

3. Carbon Dioxide (CO_2) Capture and Storage (CCS): How Does it Work?

In order to understand the main environmental hazards and sustainability issues associated with GCS, the basic principles of CCS must be understood. First, CO_2 gas compresses into a relatively high-density form at the pressures and temperatures encountered below approximately 1 km in the earth's crust. In this dense form, called its *supercritical* form because it is neither strictly liquid nor strictly gas, a larger amount of CO_2 can be stored per unit volume than if CO_2 is stored as a gas at shallower levels in the crust. The density of CO_2 at depths greater than 1 km in the crust ranges from around 600 kg/m^3 to 850 kg/m^3 depending on the geothermal gradient. The maximum depths targeted for GCS are typically in the range of 1-4 km, with the maximum depth dictated by the economics of deep wells and the decreasing

permeability of deep sedimentary rock. The density of CO_2 is nearly constant at these depths as the effects on CO_2 density of increasing temperature approximately compensate for increasing pressure in typical sedimentary basins (21). Although CO_2 is very dense at depth relative to its gaseous form at the ground surface and can therefore be volumetrically sequestered very efficiently in the deep subsurface, it will always be buoyant relative to the native fluids (saline groundwater or brine) in the subsurface and tend to rise up through them if a flow path is available.

Second, global tectonics have created sedimentary basins on all of the continents in which sediment deposition over geologic time scales has produced thick sequences of sedimentary rock capable of storing CO_2 (22). There is a vast amount of pore space in these sedimentary rocks arising from the imperfect packing of individual rock grains and incomplete cement filling of the space (pores) between the grains. Significant space can also sometimes arise from pervasive fracturing of the rock. In addition, sedimentary rocks commonly exist in alternating sequences of sandstones (relatively coarse-grained, with high porosity and permeability) and shales (fine-grained, with low permeability) making a configuration in which some sedimentary layers are porous and permeable and others are relatively impermeable. The fine-grained and low-permeability formations are the cap rocks that provide the upper seal for the high-porosity and permeability reservoirs into which CO_2 can be injected in the process of GCS.

Four different primary trapping mechanisms are recognized to occur in the deep subsurface to permanently sequester CO_2 (20). These include:

1. Structural and stratigraphic trapping, which occurs when buoyant CO_2 flows up and becomes trapped against fine-grained and very low-permeability overlying cap rock often in dome-shaped structures. This is the same mechanism that traps oil and natural gas.

2. Residual gas trapping, the process in which CO_2 bubbles are left trapped in the pores of the rock as CO_2 and water flows through the reservoir (e.g., by buoyancy forces) and water in-fills the pores previously occupied by CO_2. This is the same process that occurs in oil reservoirs as water replaces oil and prevents full recovery motivating various enhanced oil recovery approaches.

3. Solubility trapping, the process in which CO_2 dissolves into the saline water or brine in the reservoir rock. This same process of CO_2 dissolution occurs to create both natural and man-made carbonated beverages.

4. Mineral trapping, which occurs as CO_2 dissolved in the native water reacts with minerals and other dissolved constituents to form new carbonate minerals. This is analogous to the precipitation of travertine that forms in some hot (and cold) spring waters after discharge.

CO$_2$ injected into the deep subsurface will tend to be trapped by all four of these mechanisms in proportions that vary over time. For example, mineral trapping depends on dissolution (e.g., 23) and precipitation of mineral phases that can take on the order of 100's to 1,000's of years (24, 25). Considered together, the fractions of trapping by residual gas and solubility and mineral precipitation processes tend to increase over time, while the fraction of CO_2 trapped by structural and stratigraphic trapping decreases (20). As sequestered CO_2 progresses over time through the sequence of structural and stratigraphic, residual gas, solubility,

and mineral trapping mechanisms, CO_2 storage is considered to become more permanent over time (20).

One process that has similarities to GCS is natural gas storage, carried out at over 450 sites in the U.S. (26). In this process, methane (CH_4) produced from natural gas reservoirs in one location is re-injected into depleted natural gas reservoirs or aquifer storage reservoirs for temporary storage until market demand (e.g., a cold or hot spell) exceeds supply at which time extra gas is produced from the storage reservoir. In the U.S., the amount of natural gas stored is much smaller than the amount of CO_2 that is produced from fossil-fuel power plants (approximately six times less CH_4 by volume (7.5 Tcf = 1.4×10^8 tonnes (27)) is stored overall than there is CO_2 produced at fossil-fuel power plants (47 Tcf = 2.4×10^9 tonnes) per year). Furthermore, the natural gas storage industry uses the same reservoir for decades of injection and production cycles, whereas the GCS industry would need to continuously develop new reservoirs. So while the processes are very similar and much can be learned from the natural gas storage industry, the scale of the GCS industry will need to be much larger (e.g., 28, 29) in order for it to have an effect on climate change mitigation.

4. Opportunity and Capacity

As mentioned above, sedimentary basins in the U.S. and around the world are the primary targets for large-scale GCS (22, 1). Shown in Figure 2 are sedimentary basins (blue) in the U.S. and Canada with hydrocarbon-producing regions shown in red. As shown, there are large areas of the U.S. and Canada that are potential sinks for CO_2. Most of the opportunity is in sedimentary basins on the continent, but offshore opportunities are also being pursued (e.g., 30). Economics and regulatory and environmental considerations will govern the extent to which

offshore options are viable. Current efforts in North America are mostly aimed at onshore GCS

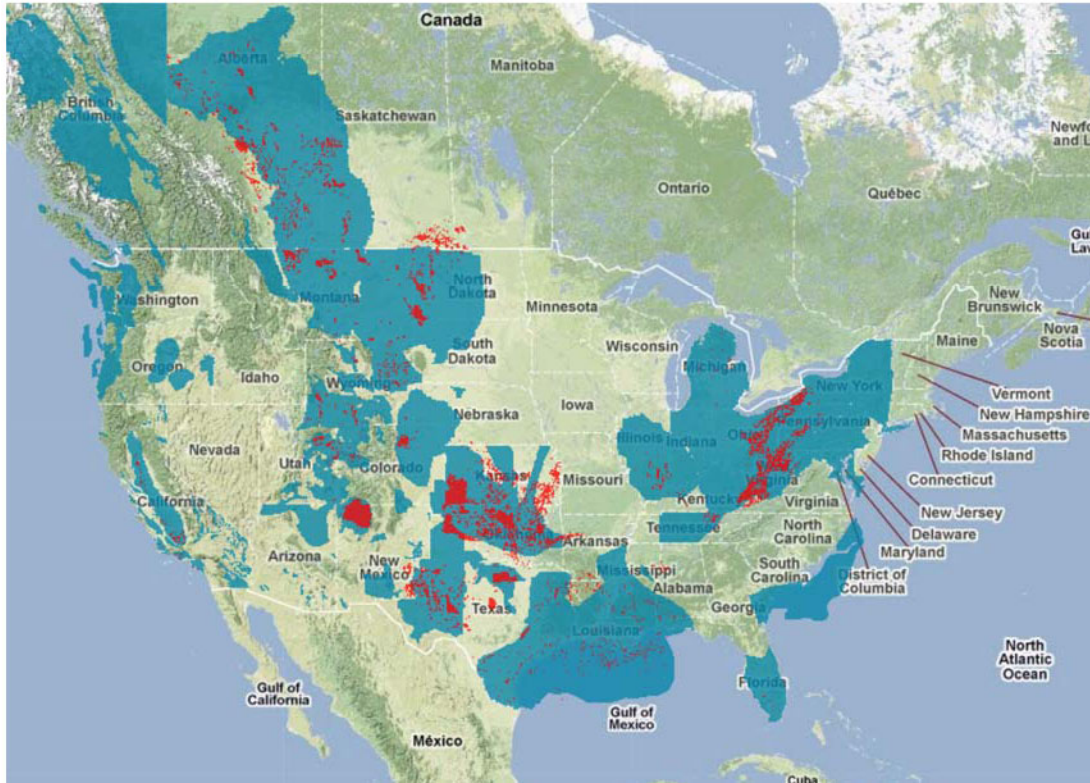opportunities, while in Europe primarily off-shore opportunities are pursued.

Figure 2. Sedimentary basins (blue) in the U.S. and Canada considered good targets for potential geologic storage of CO_2, with oil and gas producing regions shown in red (31).

Sustainability and feasibility of GCS are largely dependent on capacity. Evaluations

have shown there is more than enough capacity to store point-source CO_2 emissions for hundreds

of years or more (e.g., 1). However, large capacity is a necessary but not sufficient condition for

GCS feasibility. First, large capacity does not equate to adequate injectivity, i.e., there may be

large porosity in some formations that have low permeability or are highly compartmentalized

which would require more wells to inject CO_2 than the economics of a project could support. Second, capacity may not be available in close proximity to large CO_2 sources necessitating long pipeline transport distances and associated extra costs (32). Some of this transport cost can be accommodated under reasonable projections of CO_2 storage economics, but clearly the closer the sink is to the source, the better. Finally, this discussion points out that there are two different types of capacity, namely, resource and reserve capacity (e.g., 33). Most evaluations to date have focused on resource capacity, i.e., the total amount of pore space available regardless of where it is located or what it takes to access it. As described in the glossary, reserve capacity is the more practical measure of capacity, because it includes not only economics but also policy, environmental, and regulatory restrictions and limitations on capacity. By this definition, reserve capacity is a fraction of resource capacity, and reserve capacity can change over time as economics or regulations change.

Although different methods to estimate capacity have led to wide variations in capacity estimates over various regions (e.g., 34), there is no doubt that there is an enormous amount of resource capacity available. In short, resource capacity does not at present appear to limit the long-term (decadal) sustainability of GCS. On the other hand, resource capacity is not the only measure of feasibility. One must take into account potential environmental impacts associated with GCS such as the possibility of groundwater contamination and induced seismicity, since the environmental risks and costs may be unacceptable to the public.

5. Potential impacts

The injection of large quantities of CO_2 into the deep subsurface through wells is clearly a large perturbation to the local natural system in terms of changing the composition and

pressure of the native fluids. Specifically, CO_2 will partially dissolve into the native saline groundwater or brine while also pushing these native fluids outward away from the well as a relatively fast-moving pressure wave. The deep fluid injection process is very well known and practiced widely for injection of various fluids today (35, 26, 19) —and the reverse, production of fluids through wells such as oil, gas, and groundwater are similarly practiced widely under regulatory frameworks aimed at protecting against adverse consequences. Nevertheless, the novelty of CCS associated with the large volume of CO_2 that needs to be injected motivates discussion of what can go wrong and what general impacts are possible. This discussion will serve to evaluate which impacts are the most likely and which have the greatest consequences. This in turn will allow focus to be placed on the highest environmental risks so they can be avoided altogether, or assessed and mitigated if unavoidable.

Broadly, impacts of CCS can be broken down into those occurring at depth with no discharge of CO_2 into the atmosphere (i.e., the CO_2 storage objective is achieved even as other consequences occur), and those that involve CO_2 discharging into the atmosphere. Presented in Table 1 are potential impacts of geologic CO_2 storage broken down into these two broad categories.

Table 1. Shallow (top part of table) and deep (bottom part of table, shaded) processes and potential impacts of GCS (Oldenburg, 2007).

Category	Scenario	Significance	References
CO_2 enters the atmosphere	Root zone impacts	Profound, visible impact on plants, trees, crops	(36, 37)
	Migration in to vadose zone	May include root zone and entry into buildings	(38)
	Bubbling through surface water	Alters water quality (e.g., lowering pH)	(39)
	Accumulation in topographic lows	Very hazardous due to possibility of asphyxiation	(40, 38)
	Seepage into basements and homes	Very hazardous due to possibility of asphyxiation	(41)
	Ground plumes	Very hazardous due to possibility of asphyxiation	(40, 42, 43)
CO_2 may or may not enter atmosphere	Intrusion of CO_2 into potable water	Lowers pH, dissolves minerals potentially releasing heavy metals	(44, 45)
	Intrusion of CO_2 into hydrocarbon, mineral, or geothermal resources	Lowers value of natural gas or mineral resources such as potash	
	Displacement of saline groundwater or brine into potable water by regional pressurization	Saline water intrusion into potable water degrades water quality	(45, 46, 47)
	Induced seismicity	CO_2 injection pressure may cause felt earthquakes	(48, 49)

While the impacts arising from CO_2 leaking upward into the vadose zone, root zone, surface water, and out of the ground may be very serious, such occurrences all require a conduit or flow pathway from the deep injection zone to the near-surface environment, such as an improperly abandoned well or conductive fault. Any GCS project that had moderate to high potential for the leakage scenarios in the upper part of Table 1 would presumably not be

undertaken assuming effective risk management, insurance, and regulatory processes are in place. Furthermore, theoretical studies aimed at finding ways that CO_2 could be catastrophically released from CO_2 storage sites leading to the most serious impacts at the ground surface have found self-limiting fluid interference behaviors rather than run-away behaviors (50). Finally, the impacts described in the upper part of Table 1 are associated with failures of GCS in that CO_2 will enter the atmosphere negating the sequestration objective. Assuming an adequate monitoring program is in place, these leakage events would be relatively obvious and appropriate changes in operations and remedial actions could be carried out.

In the exceptional case of the occurrence of an uncontrolled CO_2 leak from a well into the atmosphere, the main consequence of concern is asphyxiation of workers or bystanders. Documented CO_2 well blowouts associated with oil production indicate the asphyxiation hazard is low for blowouts occurring in open environments (e.g., 51, 52). Modeling studies of open-air scenarios have also found that the area of asphyxiation hazard around a blowout is small because dispersion acts to rapidly decrease concentrations (53).

In contrast to a well blowout or the scenarios in the upper part of Table 1, it may be much more difficult to detect the onset and development of the scenarios listed in the lower part of the table in order to take early action to limit impacts. Although the scenarios listed in the lower part of Table 1 do not involve CO_2 entering the atmosphere and thus do not involve outright failure of GCS, the intrusion of CO_2 or saline groundwater or brine into groundwater resources and injection-induced seismicity are considered the main hazards associated with GCS that are likely enough to warrant risk assessment and related regulatory measures in order to minimize the likelihood of their occurrence and their consequences. These two categories of risk, described in

more detail below, must be assessed and managed as part of widespread, long-term, and sustainable GCS deployment.

6. Potential impacts to potable groundwater

CO_2 that leaks upward out of the storage region through wells (e.g., 54, 55), or faults and fractures (56), can potentially enter potable groundwater resources as shown schematically in Figure 3a. Degradation of the groundwater quality is possible through indirect contamination. As CO_2 dissolves into groundwater, it partitions into species comprising dissolved inorganic carbon (DIC) as $CO_2(aq)$, HCO_3^-, and CO_3^{2-}, resulting in a decrease in the solution pH. At the same time, alkalinity is controlled by HCO_3^- and CO_3^{2-}, which can increase upon CO_2 dissolution. Control over the geochemical changes in the water is provided by the composition and mineralogy of the mineral grains, coatings, and cements present in the rock. For example, a carbonate mineral in the rock such as calcite ($CaCO_3$) will dissolve by the reaction $CO_2 + H_2O + CaCO_3 = Ca^{2+} + 2HCO_3^-$, resulting in the doubling of dissolved inorganic carbon (DIC) (i.e., one mole of CO_2 reacts to produce two moles of HCO_3^-) and a release of Ca^{2+} to solution. Similar reactions are possible involving alteration of biotite, plagioclase and alkali feldspar, and other common minerals in sedimentary rocks (e.g., 25).

CO_2 or saline groundwater and brine leakage into groundwater aquifers will also give rise to impacts on microbiological communities (57). Although cell density declines by 3-6 orders of magnitude from the ground surface to 4 km depth, microbes at the depths of potable groundwater can be affected if CO_2 or brine intrudes into this region. The alteration of minerals such as feldspars by acidic groundwater can release iron which can stimulate Fe^{3+}-reducing communities

and result in methanogenesis. Clearly, microbial processes can affect geochemistry and vice versa.

Assuming the reaction kinetics allow it, geochemical reactions can further alter pH, DIC, isotopic composition, and trace element concentrations in solution. For example, trace elements in the minerals, in coatings, or in ion exchange sites in clays (including heavy metals such as lead) may be released into groundwater as biogeochemical conditions change with associated degradation of groundwater quality (58, 44). Observations of such effects have been made during CO_2 injection experiments at field sites (e.g., 59, 60) and in the laboratory (61). Recent work has further assessed the potential for such reactions by examining actual groundwater compositions and aquifer mineralogy from across the U.S., and found that increases in the concentration of As and Pb could be a concern if widespread CO_2 leakage into groundwater resources were to occur (45). Buffering reactions may serve to moderate pH decline and may serve to diminish groundwater degradation as observed in a natural analog study in New Mexico (62). In summary, it is recognized that impacts of CO_2 leakage on potable groundwater may be significant and costly if they occur, and therefore careful monitoring, GCS operations, and site selection (e.g., 63) are essential to reduce groundwater contamination risk.

Another hazard to groundwater resources is the potential intrusion of displaced saline groundwater or brine or CO_2-charged water into potable groundwater as shown in Figure 3b. In addition to the above biogeochemical impacts arising from the CO_2 itself, there is the first-order degradation arising from the presence of dissolved solids (e.g., NaCl, $CaCl_2$, KCl) in the saline groundwater or brine along with whatever trace elements it may contain. Potable groundwater in the U.S. is defined on the basis of total dissolved solids (TDS) content equal to 10,000 mg/L or less. Injection into deep aquifers is regulated in the U.S. by the Environmental Protection

Agency (EPA) under the Underground Injection Control (UIC) program to protect potable groundwater from degradation (e.g., 64, 35). The hazard arising from GCS is that deep saline water or brine pressurized by CO_2 injection may tend to migrate upward into potable groundwater aquifers, thereby increasing TDS and degrading the resource.

The main reason that saline groundwater or brine intrusion arising from GCS is such a concern is that pressure increases associated with CO_2 injection can occur at great distances (~10-100 km) from the injection site (65, 46, 47, 66). So while characterization of a given site may have demonstrated that CO_2 will be contained within a well-defined CO_2 storage region, there will generally be a large region of pressure increase in the formation that may not have been characterized to the same degree because of the large distance from the injection site. Because of this, it is possible that the cap rock may not be continuous over these large distances, or may not have the same integrity as the region targeted for CO_2 storage. Nevertheless, in order for upward saline groundwater or brine intrusion to occur, there must be a driving force in addition to the conduit or pathway (e.g., improperly abandoned well, or fault or fracture zone). Although pressure rise is high near the CO_2 injection wells, it falls off rapidly away from the injection wells. In addition, dense brines with high TDS require overpressures to be driven upward into potable groundwater through wells or other conduit (e.g., conductive fault) due to their high density and resistance to flow (67). Furthermore, once in the potable aquifer, the higher density of the brine will tend to limit the extent of its mixing with potable groundwater (68).
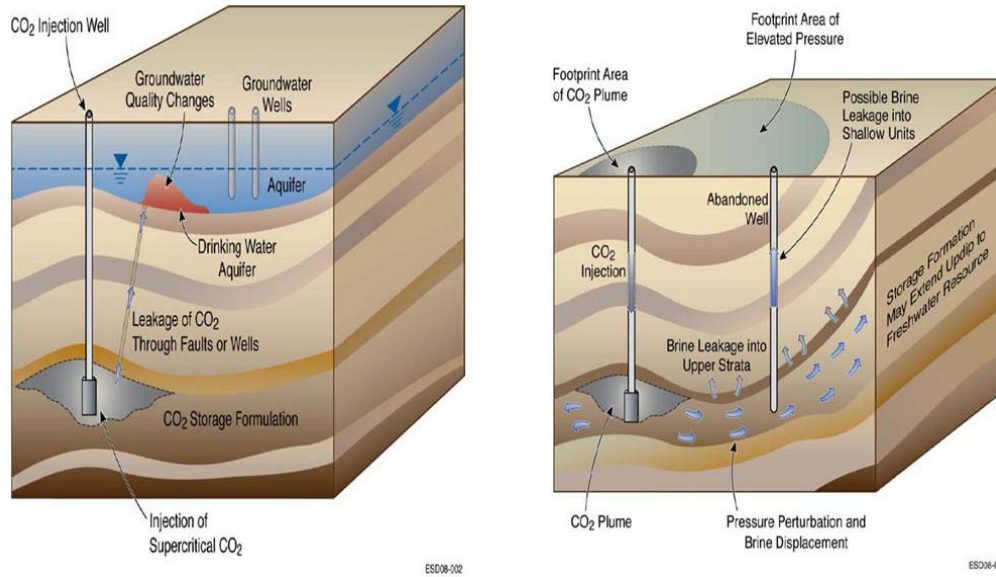
Figure 3. Potential groundwater impact scenarios. Left-hand figure from (45), right-hand figure from (47).

7. Induced seismicity

The phenomenon of induced seismicity due to fluid injection has been recognized for approximately 50 years starting with the well-known example of injected fluid waste disposal at the Rocky Mountain Arsenal in Colorado (69, 70, 71). Induced seismicity is well understood from experience in the fields of injection for deep disposal of liquid waste, and injection for geothermal energy extraction (72, 48, 49). Induced seismicity is caused by the reduction in effective stress that accompanies an increase in pore pressure. The potential for induced seismicity is determined by the Mohr-Coulomb criterion which quantifies the amount of normal stress beyond that provided by fluid pressure that is needed before shear failure occurs (i.e., reactivation of existing faults or slippage along fractures). The Mohr-Coulomb criterion is given by the relation $\tau = C + \mu\,(\sigma_n - p)$ where τ is the shear strength of the rock, C is the Coulomb criterion, μ is the coefficient of internal friction, σ_n is the normal stress, and p is the fluid

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pressure (e.g., 73). When the right-hand side (normal stress) is smaller than the left-hand side (shear strength), the rock is likely to slip along fracture planes of optimal orientation, which releases seismic energy (i.e., causes an earthquake). The Mohr-Coulomb equation shows that injection pressure reduces the effective normal stress in the rock, hence the tendency for injection to cause slippage along existing faults and fractures as shown in Figure 4a.

A simple graphical representation of pressures as a function of depth helps elucidate the processes active near an injection well. Shown in Figure 4b are the variations with depth of hydrostatic pressure, so-called fracture pressure (or commonly frac pressure), and lithostatic pressure. As shown, fluid pressure at an injection well must be larger than hydrostatic pressure in order for injection to occur. However, if the pressure exceeds the frac pressure at a given depth, the injection process will tend to fracture the formation. By the Mohr-Coulomb criterion, seismicity can be induced at injection pressures below the frac pressure as effective stress decreases and existing faults are reactivated. Either the generation of new fractures, or slippage along existing faults and fractures, is manifest as induced seismicity.

It is important to note that while the word *earthquake* evokes fear and a certain image of destruction in most people's minds, the term encompasses a wide range of magnitudes, from microseismic earthquakes that cannot be felt by humans, to great earthquakes that imperil life and damage structures. Earthquakes tend to follow a logarithmic frequency distribution such that very small earthquakes are orders of magnitude more frequent than very large earthquakes (74). Experience from water injection into geothermal systems shows that the majority of induced seismicity is microseismicity, with felt earthquakes much rarer, and moderate to large earthquakes rarer still (48). Despite the fact that large earthquakes are not expected to be

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induced by CO_2 injection in carefully chosen sites (75), the hazard of induced seismicity is looming large at present in the area of public acceptance of GCS.

Aside from the hazard of ground acceleration at the surface, induced seismicity also creates the possibility that a cap rock seal could fracture or a fault could become permeable giving rise to a leakage pathway for CO_2 (e.g., 76, 73). This is a well-recognized failure mode, and injection regulations are aimed at preventing fracturing from happening. However, induced seismicity of critically stressed rocks on pre-existing faults and fractures is still possible even when the frac pressure is not exceeded. The extent to which the risk of induced seismicity, objectively considered to be a small risk, outweighs the benefits in terms of risk reduction of climate change that CCS affords, is one of the questions that must be addressed by the public and decision-makers to guide their acceptance of CCS.
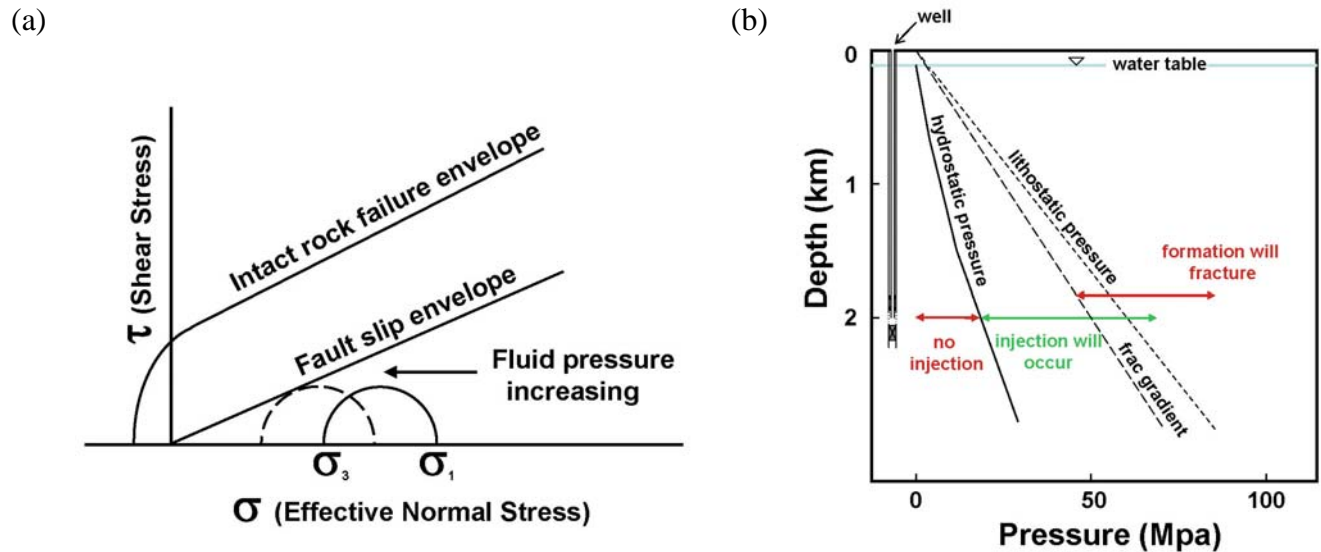
(a)

(b)

Figure 4. Mohr Circle representation of fault slip (induced seismicity) as fluid pressure increases, and (b) pressure-depth depiction showing hydrostatic, frac, and lithostatic pressure gradients.

8. Future Directions

As the discussion here suggests, one approach that can aid in addressing the energy-climate crisis is CCS. There are significant costs to CCS, primarily associated with capture, and CCS also brings with it recognized environmental risks the most uncertain of which are associated with the geologic storage component of the process. The main risks in GCS are threat to potable groundwater and induced seismicity, two areas of active research. Despite the need for greater understanding of these hazards, mitigation measures are available today. For example, if contamination of groundwater were to occur, the water could be treated, or alternate sources could be found if treatment is found impractical (63). As for induced seismicity, the hazard can be reduced by reducing injection pressure (e.g., through use of more wells for a given CO_2 source), carrying out pressure management through saline groundwater or brine extraction, by careful site selection that avoids heavily faulted and tectonically active areas, and by establishing and enforcing building codes.

The path forward for demonstrating and deploying CCS, as a sustainable part of the portfolio of energy production and use changes that are needed to mitigate the energy-climate crisis, can be described as follows. First, testing and demonstration projects (e.g., 77, 78) that include CO_2 capture from anthropogenic sources need to expand rapidly and by many factors so that the technology can be perfected in different regions and geologic settings. These multiple demonstration projects will show how GCS works, and if GCS continues to perform as envisioned, additional CCS deployments can be added over time. Second, research on capture and alternative combustion approaches that enable more efficient capture should be accelerated. Third, a large program of site characterization and capacity studies (e.g., 79) should be undertaken so that the well-known large basin-scale sites are understood and operational plans

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can be put in place quickly at the time when large-scale capture facilities come on line and anthropogenic CO_2 streams become available for sequestration. Fourth, research on injection, trapping, migration, long-term fate, leakage impacts, mitigation, monitoring, and modeling should be continued so that GCS can be optimized and related technologies can be commercialized and deployed in a cost-effective manner. Fifth, governments at all levels should promulgate regulatory and economic policies that answer the current questions and uncertainty faced by businesses who foresee the broad outlines of a carbon-constrained future but do not yet have the clear ground rules (e.g., policies on carbon pricing, injection regulations, and legal frameworks) provided by government that are necessary for making the large capital investments required for CCS.

The decision to take on the costs and risks of GCS, with the accompanying promise of contributing to reductions in the extent of climate change, should be made based on an objective comparison against the climate and environmental risks of carrying on business as usual with fossil-fuel use and unabated CO_2 emissions. The public and decision-makers should keep in mind that the environmental risks of CCS are local to the basin where GCS is carried out, whereas the projected impacts of climate change are global-to-regional in scale and are expected to have profound consequences for the social, physical, and natural systems on Earth. Support for GCS technology will come in the form of policy decisions about carbon pricing, injection regulations, and legal frameworks that encourage commercial applications of CCS. The decision about whether to adopt these policies will ultimately fall on the public or its representatives. The risks to the Earth's environment and social systems of doing nothing about the energy-climate crisis must be communicated effectively to the public and the decision makers so that they can

make an informed decision about acceptable risks and costs of the various options available for

avoiding the worst impacts of climate change.

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Acknowledgements