Research for Deployment: Incorporating Risk, Regulation, and Liability for Carbon Capture and Sequestration

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Carbon capture and sequestration (CCS) has the potential to enable deep reductions in global carbon dioxide (CO_2) emissions, however this promise can only be fulfilled with large-scale deployment. For this to happen, CCS must be successfully embedded into a larger legal and regulatory context, and any potential risks must be effectively managed. We developed a list of outstanding research and technical questions driven by the demands of the regulatory and legal systems for the geologic sequestration (GS) component of CCS. We then looked at case studies that bound uncertainty within two of the research themes that emerge. These case studies, on surface leakage from abandoned wells and groundwater quality impacts from metals mobilization, illustrate how research can inform decision makers on issues of policy, regulatory need, and legal considerations. A central challenge is to ensure that the research program supports development of general regulatory and legal frameworks, and also the development of geological, geophysical, geochemical, and modeling methods necessary for effective GS site monitoring and verification (M&V) protocols, as well as mitigation and remediation plans. If large-scale deployment of GS is to occur in a manner that adequately protects human and ecological health and does not discourage private investment, strengthening the scientific underpinnings of regulatory and legal decision-making is crucial.

Introduction

Carbon capture and sequestration (CCS) has the potential to enable deep reductions in carbon dioxide (CO_2) emissions while still allowing for the use of inexpensive fossil fuel resources and infrastructure. [In the current literature authors use CCS to signify either carbon capture and storage, or carbon capture and sequestration. Outside of the United States, most use carbon capture and storage, influenced in part by the European Union Waste and Landfill Directives. However, in the United States, government agencies (Department of Energy, Environmental Protection Agency, and others) generally use carbon capture and sequestration. For this paper, we view these terms as synonymous and take no position on which terminology should ultimately prevail.].

CCS is conceptually simple: capture CO_2 emissions from fossil-fuel-burning sources and inject the CO_2 into deep geologic formations, thereby sequestering large volumes of buoyant CO_2 underground (geologic sequestration) and avoiding atmospheric emissions. Deep saline aquifers, depleted oil and gas formations, and coal seams could serve as geologic sequestration reservoirs. General risks from geologic sequestration (GS) arise from the large quantities of CO_2 to be injected (millions to billions of tons annually), the long sequestration times required for any climate benefit, and the fact that CO_2 will be buoyant in the subsurface. Potential hazards of GS have been identified in many different studies, (*1*−*3*), and can be broadly divided into local and global categories.

Regulation of GS will focus upon protecting public and environmental health and ensuring that GS is safe and effective. Safety roughly corresponds to management of local risks and is partially addressed by the current regulatory regime which governs U.S. underground injection activities. Effectiveness requires management of global risk of premature leakage to the atmosphere, and must be addressed by future climate policy. The current regulatory framework governing underground injection in the United States is well established and it seems highly likely that any future regulation for GS will emerge from the existing framework (*4*). The U.S. EPA, authorized by the Safe Drinking Water Act to regulate underground injection activities, is currently regulating GS pilot projects as Class V experimental wells and is discussing the development of a new well class to adequately manage future GS projects (*5*, *6*).

Legal and liability considerations and resulting financial risk will affect private firm willingness to invest in CCS deployment. Additionally, court interpretations of regulation, damages, rights, and liability will influence future investment. The current legal regime handles a host of different risks from underground injection, particularly in areas with oil and gas recovery. Extensive state administrative and case law delineate parties responsible for damage to hydrocarbon resources, creating large and legal units for resource recovery, and other potential damages (*7*).

With the first pilot- and commercial-scale GS projects underway, and a slate of additional pilot projects planned for the next few years through Phases II and III of the Department of Energy's (DOE) Carbon Sequestration Regional Partnerships, GS research has entered a new phase, with researchers beginning to carry out site-specific risk assessments and gather results pertinent to the demands of the regulatory and legal systems. While legal and regulatory considerations overlap significantly, their different needs prompt somewhat different questions, which in some cases require different research approaches. With this in mind, we developed a list of outstanding research and technical questions that will need to be addressed to establish regulatory and legal frameworks for GS. We then looked at case studies that bound uncertainty within two of the research themes that emerge: surface leakage and groundwater quality. Finally, we discuss policy implications of these case studies and suggest targeted research to support development of scientifically grounded regulatory and legal frameworks.

Regulatory and Legal System Demands for Geologic Sequestration

Effective regulatory and legal frameworks for GS must ensure that the activity is both safe and effective. Deployment will

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require development of a comprehensive risk characterization and management strategy for GS that both responds to existing requirements and addresses risks not covered by the current regulatory and legal frameworks. Risk characterization could range from providing information of evidentiary value to ensuring that regulatory regimes are neither too lax nor too stringent given the actual risk profile of the technology at a specific site. Legal and regulatory concerns regarding GS fall into five broad themes: surface leakage, groundwater quality, regional impacts, permanence, and definition of liability and responsibility. Specific research questions within each of these themes are summarized in Table 1. As individual pilot projects will be deployed in diverse geologic formations, research efforts should be targeted to understand key risks and bound uncertainties within different geologic settings and specific locations that may play an important role for CCS deployment. The following sections expand upon insights from Table 1, detailing regulatory and legal issues and associated research questions.

Surface Leakage. As injected CO_2 will be less dense than native saline fluids, buoyant flow will be important for predicting subsurface behavior. Injected CO_2 could possibly migrate to the surface through abandoned well bores, faults, and fractures, or other geologic discontinuities (*4*). Risks to public or ecologic health from CO_2 leakage to the surface (or near subsurface) are not managed under the current regulatory framework. Oldenburg and Unger define *leakage* as "movement away from the primary target formation" and *seepage* as "migration of CO_2 out of the ground" (*8*). However, we have decided to use leakage here to include emission through the ground or wells into the atmosphere. While attenuation of CO_2 migration in the subsurface will significantly reduce the likelihood of public or ecological harm, bounding the magnitude of this potential hazard is important. Understanding the mechanisms, magnitude of leakage, and steps to remedy leakage are important factors for risk assessment and risk management.

Leakage to the atmosphere could also compromise the effectiveness of any carbon management scheme, and undermines the goal of CCS. While some limited leakage may be tolerable from a climate perspective, excessive leakage will render CCS an ineffective and costly strategy for controlling anthropogenic greenhouse gas emissions (*9*, *10*).

Groundwater Quality. The U.S. EPA's Underground Injection Control (UIC) regulations, upon which future regulation of CO_2 injection for GS will likely rest, concentrate on the protection of public sources of drinking water. Scientific studies bounding the potential harm to groundwater resources from GS would allow for a better understanding of the overall relevance of this risk. Potential risks to groundwater quality arise from CO_2's buoyancy, its potential to mobilize organic or inorganic compounds in aquifers, and its potential to displace subsurface fluids on a regional scale (discussed below.) While GS reservoirs would be chosen precisely because they are not potential drinking water sources, the risks of CO_2 migrating away from the injection zone into a potable aquifer would need to be assessed. While upward migration into underground sources of drinking water is not allowed under UIC regulations, recent documented leakage in Florida's municipal wastewater injection wells has forced program modifications to allow for subsurface migration, specifically for Florida municipal injection wells and assuming that such migrations do not harm underground sources of drinking water (*11*). This experience suggests that risks of migration should be considered under future regulatory regimes governing geologic sequestration.

If mixed streams ($CO_2 + H_2S$, for example) are injected, the risk profile changes, as do both the regulatory and legal responses. As capture costs for mixed streams could be less than capturing pure CO_2, regulations must consider the altered environmental and health impacts of mixed stream injection. As the composition of these streams will differ by industrial or energy facility, and the injected stream will interact differently in different reservoirs, the problem is complex, yet crucial for deployment.

Legal considerations for groundwater quality impacts will be influenced by the varying groundwater rights regimes in place across the country (*7*), and will focus on human and ecological health and associated liability concerns. Establishment of causal relationships between CO_2 injection and groundwater harm, and attribution and partition of damage between multiple actors injecting the same reservoir will be important. Understanding the potential for CO_2 to mobilize organic and inorganic compounds, effects of mixed injection streams, potential mechanisms for CO_2 to migrate to drinking water aquifers, and the steps to remedy any harm to groundwater are key considerations for potential risk assessment and eventual risk management.

Regional Impacts. A one gigawatt coal-fired power plant produces 5−10 million tons of CO_2 annually. Pruess et al. simulate injecting nine million tons of CO_2 into a 100 m thick geological formation for a 30-year plant lifetime, estimating the resulting subsurface "pool" of CO_2 at roughly 120 km^2, with bouancy flow increasing the areal extent by a factor of 1.4 (*3*, *12*). In the field, actual linear dimensions will be dependent on reservoir geometry. Alterations in the subsurface pressures may be detectable over thousands of km^2, again depending upon subsurface structure and hydrogeology. Current regulations and practices are not yet sufficient for managing the potential risks posed by GS deployed on this scale. Potential risks due to large-scale CO_2 injection include induced seismicity (*13*), basin-scale displacement of subsurface fluids, and increased risk of surface leakage, because over such large areas subsurface heterogeneities in the confining layer are likely and more potentially leaky wells may be present.

Current underground injection regulations do not directly address issues of fluid displacement. With increased demand for groundwater resources throughout the country, especially in the Southwest and West, understanding the implications of GS damage to groundwater resources (for drinking water as well as for agriculture) caused by regional scale displacement of brines or hydrocarbons could become increasingly important.

Legal precedent treating damage to hydrocarbons from fluids injected for oil and gas recovery is potentially applicable to regional scale risks from GS. There are also administrative mechanisms to create large and legal fields of operation for underground resource recovery activities (*7*). "Unitization" of individual oil and gas interests creates large scale units, suitable for optimizing field management and reducing liability from the injection of CO_2 (*14*). No such units for non-hydrocarbon-related projects yet exist and unitization in certain jurisdictions is notoriously difficult (*7*, *14*). Such a mechanism might shield an operator from claims of "geophysical trespass" that would otherwise necessitate contractual agreements with each and every land and mineral owner to be in place even before a site is surveyed.

Research to characterize and model risks of regional impacts requires large-scale pilot projects to assess probability of induced seismicity, displacement of subsurface fluids on a regional scale, and development of project management techniques that protect regional groundwater and hydrocarbon resources.

Permanence. From a climate perspective, the effectiveness of CCS depends on CO_2 remaining sequestered for a very long time, on the order of 100's to 1000's of years. Will 500, 1000, or 10 000 years be required? Such policy decisions affect technology choice, monitoring and verification (M&V),

TABLE 1. Research Areas Driven by Regulatory and Legal Demands for CCS

Research Theme	Regulatory Issues	Legal Issues	Specific research questions
Surface leakage	• Human health • Ecosystem health • Climate change mitigation effectiveness	• Liability for harm to public or environmental health from surface leakage • Breach of contract under climate management regime	• Amount of CO_2 that could leak out from active or abandoned wells under a range of conditions • Amount of CO_2 that could leak due to subsurface faulting and other geologic discontinuities • Identification and management of active and abandoned wells • Remediation technologies to stop leakage from wells and faults • CO_2 dispersion and uptake in the near surface environment
Groundwater quality	• Drinking water safety • Drinking water aesthetics • Irrigation water quality • UIC regulations are likely framework for public water sources • If no drinking water standards are violated, unclear what UIC role would be	• Differing groundwater rights regimes • Establishment of causal relationship between CO_2 injection and groundwater harm • Potential tort liability from groundwater harm • Attribution and partition of damage from multiple-actors injecting into the same reservoir • Use of groundwater as drinking water source will influence liability	• Potential for CO_2 to mobilize organic and inorganic compounds in aquifers • Potential change of groundwater taste, color or smell • Brine displacement from large-scale GS adversely impacting groundwater • Potential pathways for injected CO_2 to migrate to aquifers, transport within aquifers • Effects of mixed injection streams • Groundwater remediation options
Regional impacts	• Regional groundwater resource protection • Regional hydrocarbon resource protection • Managing risk of induced seismicity • Current regulatory framework does not address displacement of subsurface fluids on a regional scale	• Current legal regime geared toward oil and gas recovery and storage operations • Liability for geophysical trespass varies across jurisdictions • Develop mechanisms to "unitize" CO_2 reservoirs • Liability for induced seismicity	• Large-scale testing needed to study potential regional impacts • Potential for large volumes of CO_2 to displace subsurface fluids on a regional scale • Potential for GS projects to cause induced seismicity • GIS mapping of surrounding resources, affected populations • Technologies to detect regional subsurface migration • GS project management techniques to avoid and remediate regional displacement of groundwater and hydrocarbon resources
Permanence	• Minimum time required for sequestration • Maximum allowable leakage rate • Monitoring requirements for completed GS projects • Regulatory mechanisms to transform EOR projects into geologic sequestration projects	• Partitioning of long-term liability, with possible public assumption of some liability • Timing of liability transfer • Determination of insurance needs during different project stages • Liability for remediation • Ownership of CO_2 sequestration credits	• Change of sequestration security over time • Materials function and behavior with long-term CO_2 exposure in subsurface conditions (cement, steel casing, etc.) • Development of monitoring regimes to ensure project safety
Definition of liability and responsibility	• Development of M&V protocols • GS project siting guidelines	• Ownership of injected CO_2 • Establishment of causal relationship between CO_2 injection and groundwater harm or regional effects • Attribution and partition of damage between multiple-actors injecting the same reservoir • Liability for remediation	• Ability to monitor and verify location of injected CO_2 • Modeling coupled with sampling for validation • Identification of novel risks, such as effects of mixed injection streams • Site remediation techniques

and ultimate regulatory regime. Important concerns include the evolution of risk profile over time, which would affect site selection and operational requirements for large volume projects.

The partitioning of long-term liability is also crucial. Given long sequestration time requirements, the comparatively short lifespan of private companies, and the fact that insurance policy contracts range only 0–30 years, fully private systems for long-term liability are likely to be unsuitable for managing risks from CCS. Over the long term, it appears likely that some type of public assumption of liability will be necessary to spur private firm investment in the technology. Prediction of changes in the risk profile of sequestered CO_2 over time and the identification of adequate monitoring and verification strategies to manage risk emerge as necessary research areas.

Given the potential for commercial profitability, most initial sequestration sites will be affiliated with enhanced oil recovery (EOR) projects, and eventually transformed into GS sites. These two activities exist within separate legal regimes; identifying what site operations and managerial actions are crucial for transforming EOR operations into effective GS operations is important.

Definition of Liability and Responsibility. Future legal considerations focus upon the novel features of GS, primarily the large volumes of CO_2 injected and the long storage times required. For private firms, this unique liability portrait is crucial and could impede commercial technology deployment.

Establishing causal linkages of damage from GS in court may prove challenging, as could attribution and partition of damage between multiple actors injecting into the same reservoir. Risk characterization and bounding analysis of demonstration and research projects should provide understanding of underlying physical mechanisms and system constraints. This scientific and technical base is crucial for both understanding and managing liability. The potential liability of an operator for damages due to surface leakage of injected CO_2 will need to be well delineated, and uncertain areas will need to be highlighted. Identifying technologies or mechanisms for mitigating damage and enabling site remediation is key, as is quantifying potential liabilities for damage to hydrocarbon resources or potable water supplies. Estimating damages from potential seismic events, where no liability litigation currently exists, is speculative at this point. Development of techniques to monitor and verify the location of injected CO_2, as well as modeling coupled with sampling for validation will be crucial to support the legal framework necessary for deployment.

Bounding Uncertainty: Case Studies

This section presents case studies that attempt to bound uncertainty within two of the research themes presented above: surface leakage due to abandoned wells, and groundwater quality impacts from metals mobilization.

Potential Surface Leakage from Abandoned Wells. Leakage from wells remains a pressing element of risk. Many workers have identified mechanisms and conditions for leakage (*2*, *15*, *16*). Anecdotal evidence is conflicting. For example, EOR operators insist that all wells leak some amount, and yet they have seen no demonstrable or substantial leakage from long-lived EOR fields (e.g., Klusman, *17*, *18*). Simple constraints on the potential magnitude of leakage could help clarify potential risks for many stakeholders. Three cases are discussed below.

Case 1: Crystal Geyser, UT. Although there is very little current literature on CO_2 leakage, two cases stand out. One is Crystal Geyser near Green River, UT (*19*). Here, a 1936 oil exploration well penetrated a saline formation naturally charged with dissolved CO_2 at 215 m depth. Since that time, the well has erupted CO_2-rich brines and emitted CO_2 into the atmosphere, releasing gas as a point-source plume. This provides a direct analog to well failure from CO_2 that accumulates in shallow formations, and a possible analog to well failure at the edge of a large plume or in places where substantial water still affects the system. Because the well has no plug and an open borehole to depth, it can be considered a reasonable constraint on maximum leakage rate for these situations (*20*).

Researchers collected atmospheric samples from several eruptions (*20*) and a long time-series of eruptions (*21*). This information suggests a range of eruption volumes from ~3–10 tons CO_2 per eruption, roughly ~11 000 t/yr. Importantly, the CO_2 concentrations near the well averaged 6000–7000 parts per million (ppm) during these eruptions, just 50 m from the well averaged well below 3000 ppm, and never exceeded 21 500 ppm. These levels are well below the limits at which acute human health effects are documented (15 000 ppm), and far below levels that cause rapid loss of consciousness or immediate death (50 000–100 000 ppm) (*1*). In addition, plume modeling of events at this scale indicated dispersion ~100 m from the well site to ~100 ppm above background.

This case suggest that leaks from abandoned wells in saline formations may not present an acute risk to human health under most conditions. However, modeling of atmospheric release of CO_2, such as that done for Crystal Geyser, can help identify the conditions under which eruptions could create concentrations of CO_2 that are of concern (*22*).

Case 2: Sheep Mt. Drill Well. Another possible scenario for well failure is that either an injection well or abandoned well might fail when a large volume of pure CO_2 is in a dry reservoir. This condition is similar to the naturally occurring CO_2 provinces in the United States, Europe, and Australia (*23*). Interestingly, the Sheep Mountain CO_2 Dome in Southern Colorado (*24*) experienced failure of a production well in 1982 (*25*). Seven years after initial production, well 4-15-H blew out and was uncontrolled for 17 days. Five attempts were needed to control and close the well. Flow rates were estimated between 7000 and 11 000 t CO_2/day, with integrated leakage of ~200 000 t (roughly 7 days CO_2 output from a 1 GW coal-fired power plant). Interestingly, CO_2 vented not only from the well but also through soil and rock fractures near the well.

The 4-15-H well failure provides useful constraints on leakage rate, risk, and potential magnitude. First, and most importantly, no one was killed or seriously injured, despite large volumes of CO_2 leakage. In part, this was because the sloped terrain and local weather provided rapid atmospheric mixing, even for such a high discharge rate of CO_2. Second, the failure was immediately recognized as dry ice accumulated on the casing and blew off the well in chunks (*25*). Third, the rates of flow were 70–1000 times greater than those in the Crystal Geyser case, providing a reasonable upper limit of leakage from a single well. Fourth, the well was finally controlled and closed, with no documented subsequent leakage.

Importantly, it is not clear what conditions or circumstances would lead to this style of failure in a commercial GS operation. To date, there are no published steady-state models of this event, nor any dynamic models that lead to well venting of this magnitude. However, it can be concluded that proper siting, monitoring, and operations can prevent substantial harm from emission rates of this magnitude.

Case 3: Potential Leakage over a Large Area with Many Wells. Study of several individual wells does not readily advise the risk associated with significant numbers of wells over a large area. Semianalytical approaches allow for Monte Carlo simulation of possible leakage scenarios (*26*), which can characterize hundreds or thousands of scenarios quickly.

TABLE 2. Some Key Freshwater Aquifers ((s) = Silicilastic; (c) = Carbonate)

Basin/region	Key aquifers	Geological note
Appalachian Basin (ORV)	Glacial deposits (s), Devonian-Ordovician carbonates (e.g., Grant Lake Fm.)	Some shallow, Pleistocene; others Paleozoic with complex structure equivalent to saline formations
Illinois Basin	Glacial deposits (e.g., Mahomet) (s), Patoka, Shelburn (s, c)	Some shallow, Pleistocene; others Paleozoic with complex structure equivalent to saline formations
Gulf Coast	Gulf Coast Aquifer (e.g., Oakville Sandstone, Fleming Fm.) (s)	Complex, tiered, faulted strata of varying thickness and continuity
Great Plains/ North Texas	Ogallala (s), Edwards (c)	The Ogallala is largest potable aquifer in North America.
Central Rockies	Dakota (s), Madison (c)	These freshwater aquifers locally are saline units and oil reservoirs

This requires two pieces of information. The first is an understanding of well location, count, and vintage. In general, this information is readily available. The second is a leakage probability density function (PDF). It is likely that leakage PDFs are bimodal, consisting of many low risk wells (good integrity) and some higher risk wells (poor integrity). PDF distributions may be assumed (*26*) or determined empirically; currently no empirical data sets exist for this kind of approach (*27*).

Studies have focused on areas of high well density like the Alberta basin and used the well performance information as a semianalytical solution base. PDFs for well transmissivity are assumed. These studies indicate it is likely that a small number of high transmissivity wells will dominate the leakage pattern (*28*). If so, then those wells must be reworked and recompleted for effective storage. However, one cannot guess today which well set will perform poorly, and there is no standardized or required method for monitoring abandoned or orphaned wells to identify leak occurrence.

Potential Groundwater Quality Impacts from Metals Mobilization. Groundwater merits special attention because it is a precious resource, and it is subject to current regulation. While there are several ways in which large-scale injection or leakage might affect water supplies, most attention has focused on CO_2–brine–rock interactions. While processes in this system could affect both organic and inorganic geochemistry of aquifers, only the mobilization of inorganic compounds, chiefly metals, through dissolution and transport will be considered here.

South Liberty (Frio) Pilot, TX. In 2004, a DOE pilot field experiment in South Liberty, TX injected ~1800 t of CO_2 into the Frio saline formation (*29*). This injection was designed to validate simulations of CO_2 transport and fate in one of the largest saline formations in the United States. A monitoring well located ~100 ft. from the injection well collected direct fluid samples using a U-tube apparatus (*30*). This tool and others detected arrival of a CO_2 plume in the monitoring well 7 days after injection.

Of note, a substantial amount of dissolved metal was recovered in the U-tube (*31*). Initially, workers thought that the well casing was reacting to carbonic acid in the reservoir. However, laboratory studies and geochemical analyses confirmed that a substantial fraction of the metals were the product of mineral dissolution, specifically the oxide and hydroxide coatings of mineral grains that represent <2% of the rock volume (*31*). The rapidity of mobilization and the high concentrations suggested strongly that carbonic acid formed from dissolved CO_2 in formation brines might quickly and dramatically alter groundwater chemistry.

The Frio was the first saline formation analyzed in this way. Ultimately, this result is not unexpected, yet it is not clear whether this effect of metal mobilization is common or significant at depth. It is also not clear what fraction of metals would be transported with CO_2 should it leak to other formations. However, it raised the concern that should CO_2 leak into a shallow freshwater aquifer, there could be consequences that could negatively affect groundwater quality, potentially impacting public health and acceptance of CCS deployment.

Carbonate and Siliclastic Systems. To a first order, both injection targets and shallow aquifers can be divided into siliciclastic or carbonate systems. This division reflects the primary composition of the reservoir rocks. Carbonate systems chiefly comprise calcite, aragonite, dolomite, and other carbonate minerals that form limestones and dolostones, whereas siliciclastic systems chiefly comprise fragments of quartz, feldspar, and other siliceous minerals that form sandstones, siltstones, and shales.

This compositional difference greatly affects the response of carbon acid. Silicate minerals react slowly with CO_2, which means that there is little change in porosity and permeability over the duration of injection; however, the brines with dissolved CO_2 will remain acidic. In contrast, carbonate rocks react quickly with CO_2 and could change permeability and porosity quickly; however, the rapid kinetics will result in rapid increase of brine pH and buffering of the brine–CO_2 system, reducing reactivity over time. Because of these competing effects, it is not clear which fundamental rock composition is more prone to leakage or to mobilizations of metals, and little work has focused on direct comparison of these two primary aquifer compositions.

Key U.S. Freshwater Aquifer Settings. Given the distribution of CO_2 point sources and potential GS reservoirs, it is likely that CO_2 storage will be concentrated in a small number of basins. To understand and appraise the potential for metal mobilization in shallow aquifers, it would be helpful to understand the composition and acid-reaction response near the surface of these basins. Table 2 provides a subset of key shallow aquifers in these basins and some issues around their geology.

Importantly, some of these aquifers (e.g., Mahomet) have naturally elevated levels of arsenic locally (*32*). It is not clear how introduction of CO_2 through leakage might affect the chemistry of such waters, for example increasing concentrations of metals in portions of the aquifer beyond accepted levels. These questions could be constrained and circumscribed by limited scientific investigation.

Discussion

Policy Implications of Case Studies. The case studies on surface leakage from abandoned wells and groundwater quality impacts from metals mobilization illustrate how research can inform decision makers on issues of policy, regulatory need, and legal considerations. They show that some wells may present a substantial risk that should be addressed. In the absence of more scientific or technical information, it is NOT clear that metals present a large risk;

however, little is known about the potential liberation of metal species and the concentrations and flux rates of CO_2 that might present such a risk. Saline aquifers are chosen as sequestration units precisely because they are not used for drinking or irrigation, so *in situ* CO_2-induced changes to groundwater quality present limited risk, but these results raise two important questions which warrant further study. First, if metals are mobilized what is their fate in saline formations? Second, if CO_2 were to leak from a saline sequestration formation into a drinking water aquifer, would it mobilize metals (or other constituents) and harm groundwater quality? These specific cases have the following policy implications.

Pre-injection Requirements Should be More Stringent than Under the Current UIC Program. Regulatory agencies request operators to assemble an atlas of wells within the likely injection footprint, but this could be expanded to include aeromagnetic surveys of potential sites (*33*) and recompletion of problem wells or wells beyond a certain age. Preinjection studies might also include sampling and analysis of overlying groundwater aquifers to establish baseline natural concentrations of hazardous metals (e.g., arsenic, cadmium).

Site Monitoring and Remediation Plans Should be More Extensive. Site MMV and remediation protocols might encompass not just surface leakage and the injection target, but also local groundwater aquifers.

Establish Minimal Requirements for Monitoring of Wells. This may be as limited as occasional field surveys of risky wells or as involved as permanent monitoring stations on each well head. Cost and technology options will greatly affect how this concern is managed.

Construct Public Access Data Sets on Wells. Federal or State bodies could begin to gather and analyze drilling and completion records on wells to rank and assess the risk of wells within targeted regions. They could also begin to create a comprehensive and easily searchable census that confirms well location and condition. While this information exists in the state regulatory agencies, the format is not consistent within or across different states. Access is difficult and time-consuming (*34*). It is worth noting that very old, orphaned wells may be poorly documented, and as such this task may prove daunting.

This paper does not make recommendations for any specific measure. Rather, it attempts to illustrate how even limited study and information can help inform key decisions, and that current levels of information are not sufficient to drive more stringent requirements.

Targeted Research Suggested by Case Studies. To improve upon current knowledge and aid development of legal and regulatory frameworks, several studies would be highly relevant.

A Census of Well Conditions. Field work to confirm depth and status of plug, continuity of casing, and cement bonding would help advise the need for well treatment. This information might serve as a basis for leakage PDFs.

Improved Simulation Capabilities for Wells. Reactive transport models help identify and quantify features, events, and processes that affect well-bore integrity (*35*). While new studies continue to expand the capabilities of simulators (*36*–*38*), current models do not yet fully render all key processes and features in the subsurface, and it may take many years before such tools are commercially available.

New Monitoring and Mitigation Technologies for Wells. New tools to detect CO_2 leakage from wells would enable better field management and reduce liability concerns. These tools may involve new sensors operating at the surface or down hole, and may include components of data transmission and integration.

Additional Research Needs. Commercial- and pilot-scale GS projects currently underway or planned can contribute valuable data related to surface leakage, groundwater quality, and permanence, and help define liability and responsibility. A central challenge is to ensure the research program supports both development of general regulatory and legal frameworks and the geological, geophysical, geochemical, and modeling methods necessary for effective GS site monitoring and verification (M&V) protocols, as well as mitigation and remediation plans.

While some of these research areas are the focus of DOE, international, and industrial studies (e.g., the Carbon Capture Project 2), the tremendous need for information in this arena points to an accelerated research program (*39*). Importantly, this is likely to require exchange of responsibilities and information between different governmental branches (e.g., DOE, EPA, Department of Interior) and different sectors (public, industrial, NGOs). Accelerating this critical exchange between decision makers and among stakeholders is key for future CCS deployment.

It is worth noting that the small-scale pilot studies and isolated commercial projects currently planned or underway (e.g., Frio) provide insight and value, yet they cannot be expected to address potential regional impacts. This gap in the research program has the potential to hamper development of truly comprehensive GS risk assessments, and delay deployment.

Moving Toward Site-Specific Risk Assessment. Local risks predominate in deployment decisions, making project siting arguably the most important factor affecting the risk profile. Each site is also embedded within a unique network of local, state, and federal regulatory and legal requirements, so project location will also determine the regulatory and legal regimes that will govern the project. Each site-specific risk analysis must be grounded in a comprehensive understanding of local geology and geochemistry, as well as a thorough survey of local well densities and completion histories. Additional information, covering oil field unitization, location of potable water supplies, abandoned wells, and remediation plans, must be collected alongside data on local and regional geology. The risk profile and subsequent analysis will vary significantly across sedimentary basins, reservoir classes and compositions, and structural configurations. Ongoing research, including the experiences of the DOE's GS pilot projects with carrying out site-specific risk assessments, will help create "best-practice" manuals for regulators and potential GS project operators and sharpen their understanding of what will be required for comprehensive, site-specific, GS risk assessment.

Embedding Scientific Risk Analysis within the Larger Policy Framework. The goal of this paper is to outline where intersections between overarching policy concerns and GS research would be most fruitful to support CCS deployment. Regulatory and legal demands provide a formal framework for integrating potential GS risks, crucial for future deployment. For deployment beyond isolated pilot project scale, these frameworks will provide predictability, both for adequately managing risks and ensuring stability for investment necessary for technology diffusion. Risk analysis for GS should concentrate on providing scientifically grounded information to help bound uncertainty of policy decisions.

From the perspective of a future climate policy regime, GS is essentially a contract where the operator agrees to sequester CO_2 underground for a specified time period. Once the contract is formed, it will be policed, the performance will be assessed, and any breach of contract will be remedied. As a comprehensive climate policy is yet to be determined, uncertainties on the treatment of leakage and role of site remediation for GS exist. Thus, the mechanisms and magnitude of potential leakage coupled with technologies to remediate a site are key considerations. Additionally, identifying institutional incentives or disincentives for monitoring

and remediation of leakage will be important for eventual policy and programmatic design.

We hope that by embedding scientific risk analysis within the larger policy framework, the research undertaken will be targeted toward supporting difficult and ultimately political decisions. If large-scale deployment of CCS is to occur in a manner that adequately protects human and ecological health and does not discourage private investment, strengthening the scientific underpinnings of regulatory and legal decision-making is crucial.

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