Carbon Sequestration and

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The environmental science and engineering communities are engaged in a host of activities focused on elucidating and predicting the complex and interrelated environmental consequences of climate change. Concerns from the research community regarding climate change have prompted the U.S. government to explicitly acknowledge the need for climate and energy policies that can stabilize or reduce atmospheric greenhouse gas concentrations.[1,2]

Moreover, many international climate experts recently have highlighted the importance of governments to act decisively and collectively in limiting the negative impacts of climate change on ecological resources and the services they provide.[3]

While it is widely acknowledged that some effects of climate change will be unavoidable, the ability to predict the type, magnitude, and location of these impacts is fraught with uncertainty. Owing to the multifaceted and uncertain nature of climate change, effective and sustainable mitigation strategies require an interdisciplinary approach that transcends the artificial boundaries imposed by the currently established educational paradigms that support the scientific, engineering, and policy professions.

Carbon capture and sequestration (CCS) is anticipated to play a central role in climate change mitigation policies in concert with other strategies that reduce or mitigate greenhouse gas emissions.[4-6] Deployment of CCS will necessitate careful evaluation and management of potential environmental and societal impacts, liability and ownership of resources, geologic storage effectiveness, and regulatory priorities.[7]

As technologies and projects to capture, transport, and store carbon dioxide (CO_2) emissions develop, several important questions arise: For example, where will governments and private industry find the skilled workforce needed to support the implementation and evaluation of these new methods?; what expertise will be necessary for providing overall technical, regulatory, and fiscal management of carbon sequestration projects?; and how will colleges, universities, technical schools, and other educational organizations respond to the need for new interdisciplinary programs?

Beyond the obvious concerns regarding the effectiveness of CCS design, construction, implementation,

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and monitoring, parallel questions arise regarding how specific climate change mitigation technologies may impact the quality and availability of natural resources. For example, water management strategies for CCS operations require consideration of competing water demands for energy production, water supplies, and ecosystem services. In other words, concerns over the short- and long-term water quality and availability impacts of CCS are part of a larger question regarding the sustainability of specific climate mitigation practices and whether there is an adequate and sufficiently trained workforce to not only construct, operate, and monitor these practices, but is able to predict and address the myriad of potential negative impacts of a particular climate change mitigation practice on natural resource protection (see Figure 1).

This article highlights a broad suite of potential water resource impacts associated with CCS implementation. These impacts range from increased water demands associated with power generation (that support CCS operations) to water quality impacts and associated groundwater chemical changes resulting from the sequestration of large quantities of CO_2.

CCS and Water Resource Protection

As CCS deployment progresses, the resource value of water-bearing formations targeted for carbon storage must be considered in the context of projected changes in water demand and quality requirements (i.e., desalination of deep, brackish groundwater to meet agricultural or drinking water needs). The use of deep saline formations for CO_2 storage may also complicate future water resource management decisions, particularly in water-stressed regions.[8]

Future water withdrawals from formations used for carbon sequestration may have advantages due to the in-place infrastructure (i.e., groundwater wells). However, the water treatment costs associated with the removal of metals and/or organic contaminants may outweigh the benefits of future water use from these formations. To effectively resolve how water resource demands supporting CCS can be balanced with competing water resource needs requires the establishment of an interdisciplinary workforce that can reconcile and prioritize the importance of climate predictions, policy goals, and resource assessments.

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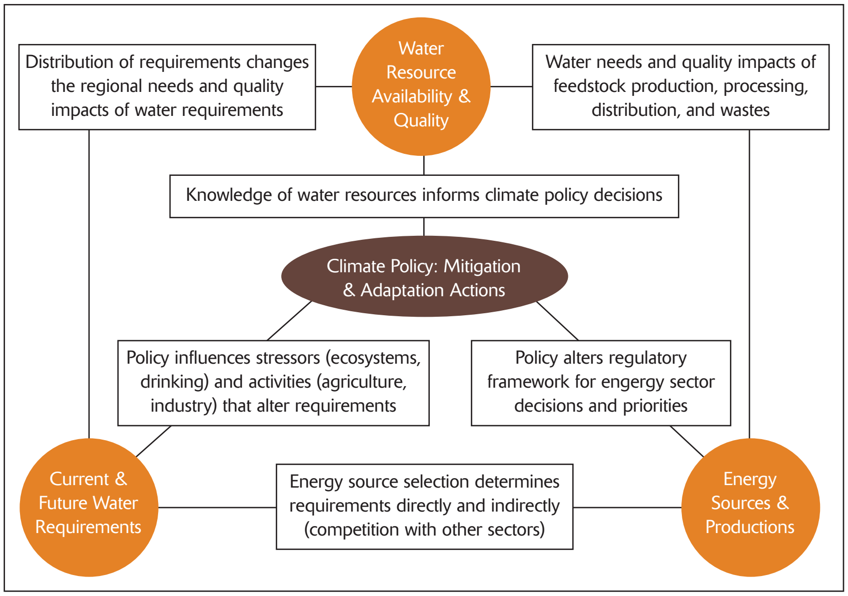

Figure 1. *Relationships between climate policy, water resource protection, and energy production.*

CCS and Water Demand

As data on geological and hydrological site characteristics are generated and compiled, a growing inventory of groundwater resources will emerge that can serve to improve our understanding of underground formations. The expansion of groundwater resources data provides an opportunity to evaluate the effectiveness of the methods by which water use, replenishment, and recharge are monitored. Enhancing the quality and quantity of information associated with geographic variations in water quality and availability taken together with a more complete knowledge of the hydraulic communication between groundwater and surface water has the potential to improve our ability to make better informed water resource management decisions.

In addition to the potential changes in water resource quality and availability, wide-scale implementation of CCS can impact the net water withdrawals needed to support power production for carbon capture, transport, and injection.[9-11] Water use for power generation may result in the translocation of water that originated in subsurface sources (including brackish formations) to surface discharge or underground injection of process wastewater drawn from surface waters. Understanding the long-term environmental and ecological implications of these decisions requires that stakeholders adopt an interdisciplinary perspective that can adequately weigh the impacts of CCS on water demand.

CCS and injection well development will also generate additional sources of waste and wastewater whose management will require the implementation of environmentally sound and cost-effective treatment approaches. Permitting of carbon injection wells must take into account the federal requirements of the Underground Injection Control (UIC) program and its mandated protection of drinking water resources.[12] Addressing the uncertainties associated with the potential impact of carbon sequestration practices on drinking water aquifer chemistry remains a vital concern for federal, state, and local public health officials.

Modeling the Potential Effects of CCS on Water Resources

Hydrological and geochemical models, based on comprehensive site characterizations, provide a framework for evaluating regional-scale flow, fate, transport, and reactive processes that affect water resources.[7-10] These assessments are an important part of selecting carbon sequestration sites and provide the environmental protection assurances needed to permit these facilities.

The injection volumes projected for geologic carbon sequestration, coupled with the depths, pressures, and the unique physical/chemical properties of CO_2 as compared to formation fluids (i.e., density, buoyancy, etc.) will necessitate the integration of site characterization, modeling, and monitoring activities in order to support defensible decisions. Ensuring effective interpretation, use, and communication of CCS field information, in turn, will require the development of an interdisciplinary workforce possessing expertise in the geological, computational, ecological, and social sciences (see Figure 2).

Under most conditions, results from CCS field and simulation studies support the utility of computational decision models.[13-15] If observed conditions deviate from model predictions (e.g., leaks or displaced formation fluids), then modeling and monitoring results can provide a systematic basis for altering injection, refining site characterization, and providing new inputs for model parameters. However, effective interpretation of simulation results for defensible decision-making necessitates that an interdisciplinary approach be adopted in which competing water resource goals are recognized and adequately considered.

Field-validated simulation models are vital to the assessment and remediation of any unintended damages from leaks of CO_2, native brines, naturallyoccurring metals, and hydrocarbons and co-injected constituents such as hydrogen sulfide and other impurities.[16-18] Over the duration of carbon storage (i.e., decades to centuries), monitoring and modeling activities can be employed to verify that water resources are being protected at a known level of confidence. As more CCS field data are collected, the development of better-informed simulation models, peer reviewed by industrial, government, and academic stakeholders, will provide greater assurance that water resource impacts associated with CCS are minimized.

Educational Strategies To Support CCS Workforce Needs

Given that CCS is anticipated to be among the earliest and more rapidly deployed responses to climate change, an interdisciplinary and professional workforce is urgently needed to address the multifaceted challenges associated with this climate change mitigation strategy. The starting point for determining the educational and training requirements needed to support CCS, as well as the protection of water resources, is to identify and document the surface and geological characteristics of potential carbon sequestration sites that could influence regional water quality and/or availability demands.[11-14]

In the United States, the Department of Energy has initiated seven Regional Carbon Sequestration Partnerships (RCSPs) that are located across North America, in which the effectiveness of geologic sequestration of CO_2 is being investigated.[8,9] Within these research projects, CO_2 is being injected into saline formations, depleted oil and gas reservoirs, unmineable coal seams, and basalt to evaluate carbon storage effectiveness and generate data that will inform future CCS projects at larger scales.

The overarching goal of the RCSPs is to develop "best practice" approaches for geologic carbon sequestration and to provide a technical framework for future climate change research activities through facilitating collaboration between various government, universities, and industry partners. Unfortunately, neither climate change mitigation technical training nor workforce capacity building is an explicit goal of the RCSP activities.

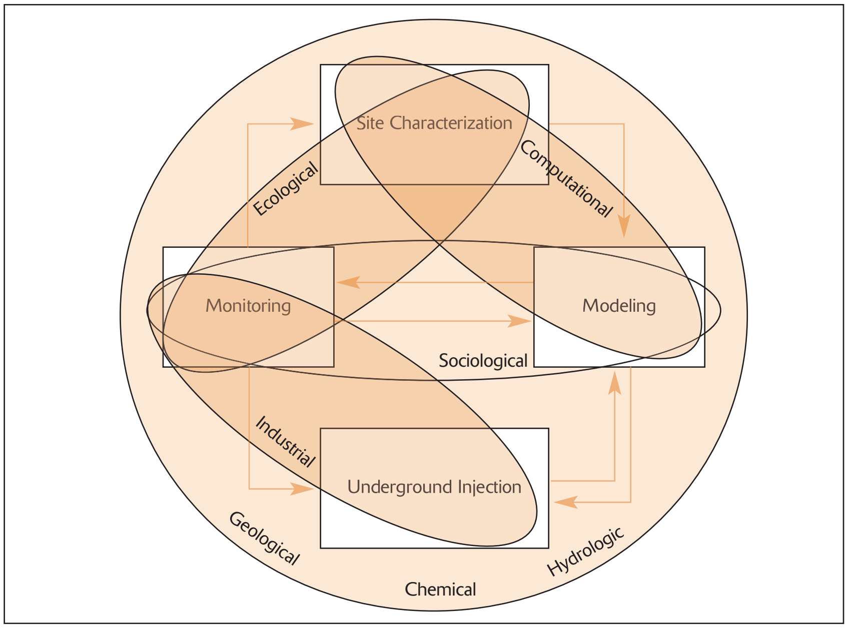

Figure 2. Ideal CCS process integrating site characterization, modeling, and monitoring.

However, given that the long-term sustainability of CCS requires effective technical capacity building, expanding the role of the RCSPs to include "practical" training of undergraduate, graduate, and post-doctoral graduate students is warranted. By leveraging existing academic resources, the RCSPs provide an ideal environment for fostering greater interdisciplinary collaboration across physical and social sciences together with the effective development of future professors, teachers, and instructors of climate change mitigation practices.

Similarly, the RCSP program framework could consider establishing small "think tanks" consisting of academic, industrial, and government experts whose overarching tasks would include identification and prioritization of major scientific, regulatory, and technical data gaps associated with full-scale implementation of CCS. The work of such groups would support scientific and regulatory agencies in developing future CCS research priorities and implementation strategies.

Despite the absence of a fully integrated and accredited climate change mitigation educational and training program, in its current form, the RCSP initiative and its field demonstration results can be utilized as a baseline for compiling and documenting the specific workforce needs of climate change stakeholders, including those required by industry, regulatory, environmental advocacy, and academic organizations. Meeting current and future climate change workforce needs will require an educational approach that begins with retraining of current workers and moves toward the development of interdisciplinary curricula in climate science and mitigation technologies that incorporate key components from basic science, engineering, social science, and policy programs. **em**

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