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A Model-Based Strategy for Predictive Monitoring for CO_2 Conformance and Containment

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Abstract

Carbon Capture and Storage (CCS) projects in the U.S. must demonstrate secure geologic storage through rigorous monitoring aligned with Class VI permitting requirements. This study presents a predictive monitoring strategy applied to a potential storage site in Texas, designed to meet regulatory requirements while optimizing cost and operational agility. The approach leverages dynamic reservoir simulations that forecast CO_2 plume migration to automatically position three types of monitoring spots – which are subsurface areas selected for focused seismic measurements – where detecting CO_2 arrival or movement is most critical: calibration (for model tuning near injection and monitoring wells), conformance (in areas of significant plume change for model validation), and containment (along potential leakage paths such as legacy wells and faults for risk monitoring). Scaled saturation difference maps identify critical monitoring periods and locations, while average CO_2 saturation maps and plume migration velocity are used to define time-dependent alarm levels, enabling early detection and proactive risk mitigation. The results consist of a fully defined Measurement, Reporting, and Verification (MRV) plan, with monitoring locations and survey timing derived from model-based saturation changes and plume migration trends, ensuring that surveillance is focused where and when it matters most. This strategy aligns with the Environmental Protection Agency (EPA) Class VI requirements for frequent subsurface monitoring, plume validation, and risk-based site care. It also supports the MRV framework required for claiming 45Q credits by providing transparent, verifiable evidence of CO_2 behavior. The novelty lies in automating spot placement and timing using model outputs and risk assessment, reducing reliance on full-field seismic coverage. By detecting changes with focused seismic, the operational and environmental footprint of monitoring is minimized, and community acceptability is enhanced through less intrusive field operations. This enables targeted surveillance, cost-effective compliance, and long-term storage integrity essential components for successful CCS deployment under U.S. regulatory and financial frameworks.

Introduction

Traditional subsurface seismic monitoring methods inherited from the oil and gas sector are often costly and inflexible, as their large-scale surveys are not easily repeatable or adaptable to the frequent monitoring needed for CCS. Focused seismic validated through onshore applications in Canada at the Weyburn field (Brun et al., 2023; Peruch et al., 2025) and offshore in Denmark within the Greensand project (Roth et al., 2023) can address these challenges by acquiring data in limited but strategically selected subsurface areas referred to as spots. In this work, a "spot" follows the definition introduced by Morgan et al. (2020) in the context of localized ultra-light seismic monitoring: a subsurface area chosen for focused seismic measurements where detecting CO_2 arrival or movement is most critical. Once a spot is defined, focused seismic data are acquired using a dedicated source–receiver pair positioned to illuminate that specific subsurface area, enabling frequent focused measurements of CO_2-related changes with minimal operational footprint. To support the development of CO_2 storage, and in response to Class VI and 45Q expectations, a monitoring strategy guided by flow simulation forecasts, referred to as predictive monitoring, is proposed. Predictive monitoring uses dynamic reservoir model outputs to calibrate and validate plume behavior throughout the storage lifecycle, contributing to a robust Monitoring Reporting and Verification (MRV) plan.

For this case study, the methodology is applied to a potential storage site along the Texas Gulf Coast, with specific emphasis on building a monitoring plan that addresses both plume conformance and containment. A dedicated strategy is designed to monitor legacy wells and other risks, while an automated conformance spot selection workflow supports model validation during and after injection.

Theory and/or Methods

Dynamic reservoir models provide forecasts of CO_2 plume movement and are central to building an effective predictive monitoring plan. Average CO_2 saturation outputs from the numerical simulation model are used along with mapped risk elements such as legacy wells and faults.

Three types of spots support the monitoring objectives:

- **Calibration** positioned near injection and observation wells to link seismic measurements with modeled and measured pressure, temperature and CO_2 saturation. Additional calibration spots placed outside the expected plume are used to evaluate background seismic noise and to refine further the seismic measurement.
- **Conformance** automatically located based on areas showing the greatest modeled change in CO_2 saturation between successive time steps. These high change zones are calculated from scaled differences between saturation maps. Minor discrepancies between focused seismic measurements and the flow model predictions could trigger model updates, while major discrepancies might necessitate denser time-lapse acquisition, whether VSP, 2D, or 3D seismic.
- **Containment** positioned along identified risk pathways and use plume migration velocity to establish time dependent alarm levels. This ensures that containment monitoring is aligned with predicted plume arrival rather than simple distance threshold, leaving an appropriate amount of time to trigger corrective actions ahead of CO_2 suspected arrival, such as well recompletion.

Together, these three types create a structured, model-driven monitoring strategy that supports conformance verification and containment assurance. For each selected spot, focused seismic monitoring is carried out using optimal source and receiver locations designed to repeatedly sample the subsurface area, allowing CO_2-related changes to be tracked with a light operational footprint (Morgan et al, 2020). In practice, the roles of calibration, conformance, and containment spots may overlap, and focused seismic measurements will not match model forecasts exactly. As with any seismic monitoring tool, interpretation biases can arise, and these are reduced by calibrating seismic responses against pressure and temperature variations recorded at injection and monitoring wells. Spot locations are updated only when model revisions justify it, ensuring repeatability while allowing the workflow to adapt to meaningful plume deviations.

Results

Successive CO_2 saturation maps, such as those shown in Figures 1a and 1b, provide the basis for determining conformance spots. The scaled saturation difference map (Figure 2) identifies regions where the plume is expected to expand or undergo significant change before the next time step. This map is calculated as a smoothed difference between two successive average saturation maps 1a and 1b, multiplied by the saturation of map 1a.

The scaled saturation difference map highlights new cells encountered by CO_2 (Gestin et al., 2025) representing high-sensitivity monitoring zones with a detection threshold estimated at 10%. Conformance spots automatically positioned in these zones enable early detection of deviations between modeled and observed plume movement, enhancing the reliability of model validation.

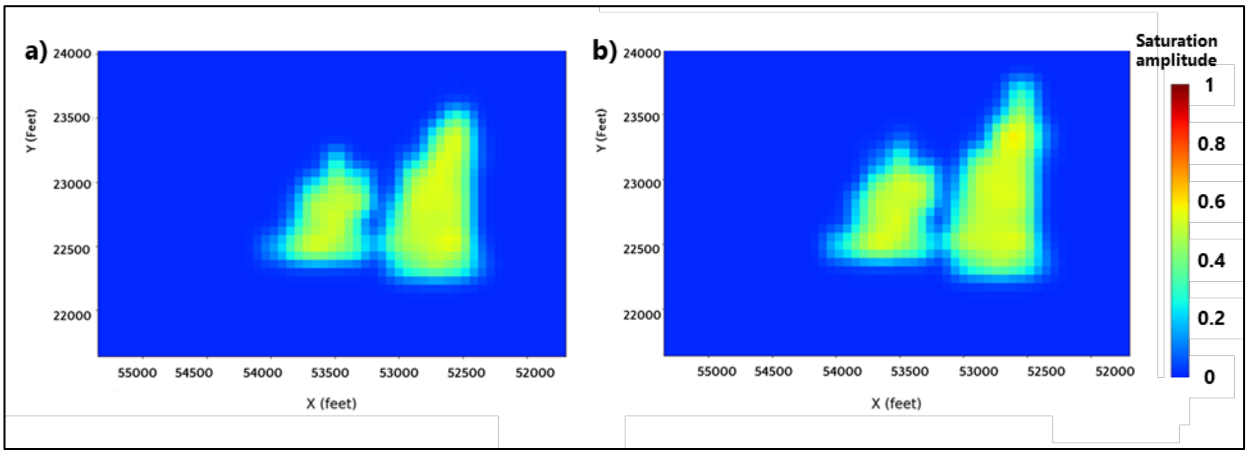


Figure 1: Average CO_2 saturation maps after 4.5 years (a) and 5 years (b) of simulated injection, illustrating plume growth over time.

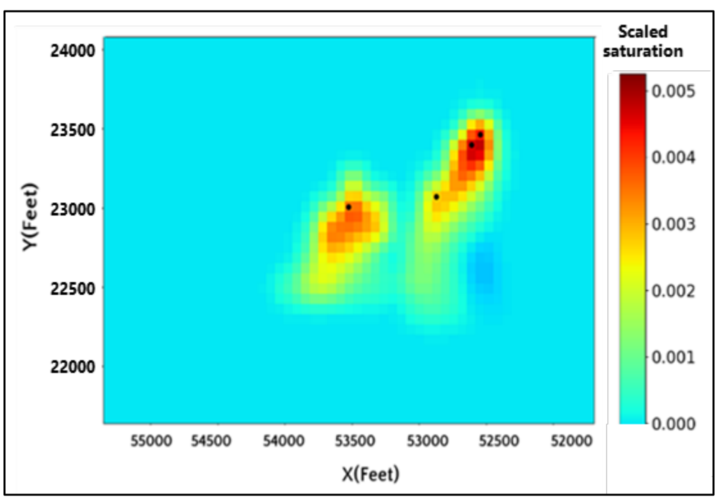


Figure 2: Scaled saturation difference map showing the areas of highest modeled change between successive time steps, with conformance spots shown as black dots. These spots are located where plume evolution is most critical for monitoring.

Containment monitoring requires a complementary approach. Instead of relying solely on the distance between the plume and a risk element, the workflow incorporates plume migration velocity to define three containment levels (Figure 3). This ensures enough time to trigger and complete potential remediation actions. Level one corresponds to two years before predicted arrival at the risk feature, level two to one year, and level three to locations immediately adjacent to the risk element for monitoring lateral and potential vertical migration. This approach provides structured early warning capabilities.

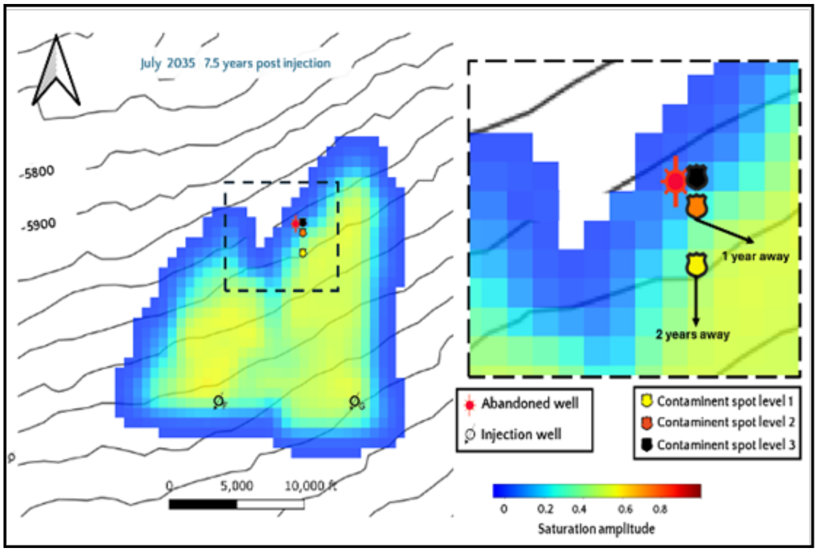
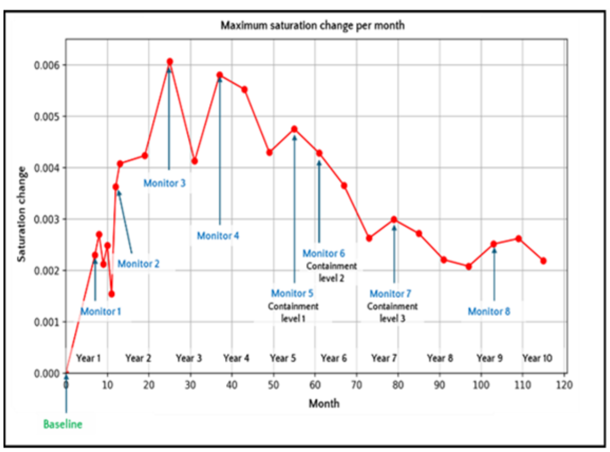


Figure 3: Illustration of containment monitoring showing three containment levels overlaid on a saturation map after 7.5 years of simulated injection. The underlying map depicts the top reservoir depth, highlighting risk elements and containment spot locations.

Baseline and monitoring survey times are selected by analyzing time steps associated with the highest maximum changes in CO_2 saturation (Figure 4). These intervals represent periods when plume movement is most dynamic, ensuring that monitoring efforts are focused on the most informative moments in the simulation timeline.



Survey	Years after injection
Baseline	0
Monitor 1	0.5
Monitor 2	1
Monitor 3	2
Monitor 4	3
Monitor 5	5.5
Monitor 6	6
Monitor 7	7
Monitor 8	9.5

Figure 4: Monitoring schedule derived from maximum change in saturation per month used to identify baseline and follow-up monitoring survey periods aligned with key plume evolution stages.

The predictive monitoring strategy ensures that focused monitoring seismic is used where it provides the greatest value. Denser time lapse seismic acquisition such as VSP, 2D seismic or 3D seismic is only recommended when differences between model predictions and focused seismic measurement cannot be adequately explained through model update. This reduces the need for full-field coverage while maintaining monitoring robustness.

Conclusions

Predictive monitoring provides a structured, model-driven approach that addresses the main MRV challenges of CCS projects by focusing on plume conformance and containment. By integrating dynamic model forecasts with focused seismic acquisition, the approach delivers early detection of deviations in plume behavior and supports proactive risk management. As with any seismic monitoring tool, interpretation biases can arise, but they are reduced by calibrating focused seismic responses with gauges data from injection and monitoring wells. Onshore data quality can also be affected by low fold, ambient noise, and coupling variations, which are addressed through optimized source placement, small receiver antennae to improve filtering, and temporal stacking to strengthen signal to noise ratio and repeatability. If needed, denser seismic acquisition is triggered only when predictive monitoring indicates insufficient confidence in the model forecast. The strategy meets EPA Class VI requirements for frequent subsurface monitoring and supports the documentation required for 45Q credit eligibility. Its targeted acquisition footprint reduces operational intensity and enhances long-term storage integrity monitoring.

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