Plains CO_2 Reduction (PCOR) Partnership
Energy & Environmental Research Center (EERC)

A QUANTITATIVE APPROACH FOR DEMONSTRATING PLUME STABILIZATION UNDER CCS POLICY FRAMEWORKS

Plains CO_2 Reduction (PCOR) Partnership
White Paper

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A QUANTITATIVE APPROACH FOR DEMONSTRATING PLUME STABILIZATION UNDER CCS POLICY FRAMEWORKS

EXECUTIVE SUMMARY

Carbon capture and storage (CCS) is the process whereby carbon dioxide (CO_2) emissions are captured and injected underground into a geologic reservoir (storage reservoir) for permanent storage. The three-dimensional extent of injected CO_2 within a storage reservoir is referred to as the CO_2 plume. CCS policy frameworks in the United States and Canada require operators to demonstrate stabilization of the CO_2 plume (hereafter plume stabilization) prior to site closure. These policy frameworks do not imply that a CO_2 plume must cease movement entirely to be considered stable. Instead, plume stabilization means that the CO_2 plume 1) moves minimally and predictably in the storage reservoir such that it will not cross key project-defined boundaries (e.g., storage facility area) and 2) does not pose a threat to underground sources of drinking water (USDW), human health, or the environment. The operator must demonstrate this set of criteria is met during the postinjection phase of operations to demonstrate plume stabilization prior to site closure.

Plume stabilization can be demonstrated via multiple approaches, including risk assessment, numerical simulations, and monitoring data. CCS policy frameworks may require operators to apply all three approaches to demonstrate stabilization. A simulation-based approach for quantitatively demonstrating plume stabilization using a North Dakota case study is presented in this paper. The simulation-based approach identifies the point in time (t) when the CO_2 plume's rate of areal expansion (derivative of area with respect to time [dA/dt]) slows significantly in the postinjection period (primarily driven by pressure dissipation in the storage reservoir) and begins to approach a horizontal asymptote (referred to as $dA/dt_{critical}$). This point in time is referred to as $t_{critical}$ and is identified at the interpreted inflection point $dA/dt_{critical}$. The single metric used in this approach—dA/dt—was first tested by Harp and others (2019) who experimented with multiple metrics in various simulated geologic scenarios to illustrate plume stabilization.

The case study used in this paper is from the eastern Williston Basin in North Dakota. The CCS development scenario that was used assumes 20 years of CO_2 injection into the Broom Creek Formation, a deep saline aquifer, followed by 50 years of postinjection simulation. The metric dA/dt was selected for this case study because the storage complex (storage reservoir and associated confining units) is near horizontal (i.e., the Broom Creek Formation dips less than 1° over the simulated area) and the modeled storage reservoir properties (e.g., porosity and permeability) are relatively homogeneous. Five-year time steps were used to calculate dA/dt, and the CO_2 plume extent was defined as the area containing model grid cells with greater than 5% CO_2 saturation.

The grid cell size used was 1000 ft (305 m) in both the x and y directions (with local grid refinement of 200 ft [61 m] around the wellbores), and layer thicknesses were determined from analysis of the vertical variograms for each zone, which ranged between 5 and 7 ft (1.5 and 2 m, respectively).

In this case study, $dA/dt_{critical}$ was determined to be 0.1 mi^2/yr (0.26 km^2/yr), with $t_{critical}$ occurring at Year 10 of postinjection. An important assumption in the approach is that beyond $t_{critical}$ the plume can be considered to have ceased migration under the forces of pressure dissipation, capillary pressure, and CO_2 dissolution in brine, as any additional movement is anticipated to be insignificant relative to the CO_2 plume's areal extent at $t_{critical}$. This is an important assumption, as CCS policy frameworks may require the CO_2 plume to not cross key project-defined boundaries prior to site closure, such as a storage facility area (stabilized CO_2 plume plus a buffer area around the stabilized CO_2 plume extent) or leased pore space boundary.

In cases where the geology is relatively homogeneous and flat-lying, applying this simulation-based approach with dA/dt represents a relatively simple and straightforward solution for demonstrating plume stabilization that can be confirmed with monitoring data (e.g., time-lapse geophysical methods) prior to site closure.

Opportunities for future work related to plume stabilization were identified during the course of preparing this paper, such as 1) developing pressure dissipation and volumetric CO_2 plume metrics as alternatives to dA/dt and 2) adding case studies to confirm other storage complexes and whether or not differently modeled geologic scenarios would yield similar results.

References

Harp, D., Onishi, T., Chu, S., Chen, B., and Pawar, R., 2019, Development of quantitative metrics of plume migration at geologic CO_2 storage sites: Greenhouse Gas Science Technology, v. 9, p. 687–702. doi: 10.1002/ghg.

A QUANTITATIVE APPROACH FOR DEMONSTRATING PLUME STABILIZATION UNDER CCS POLICY FRAMEWORKS

1.0 INTRODUCTION

Carbon capture and storage (CCS) is a process that begins by capturing carbon dioxide (CO_2) from an emission source, such as a coal-fired power plant or ethanol production facility. The next step is to transport the CO_2 from the capture facility to the storage site via pipeline, and the final step is to inject the CO_2 into a permitted geologic reservoir (storage reservoir) for permanent storage. Operators implement CCS via geologic CO_2 storage projects to manage CO_2 emissions while still allowing the full range of economic and societal benefits derived from industry.

Within the United States and Canada, policy frameworks with authority to oversee geologic CO_2 storage operations include the U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) Class VI Program, states with Class VI primacy (i.e., North Dakota and Wyoming), EPA's Greenhouse Gas Reporting Program (GHGRP) Subpart RR; the California Air Resources Board (CARB) Low Carbon Fuel Standard (LCFS) Carbon Capture and Sequestration Protocol, and the Government of Alberta's CCS regulations. These policy frameworks require operators to provide assurance that CO_2 is safely and permanently stored, and a major component of that requirement is the demonstration of CO_2 plume stabilization (hereafter plume stabilization) in the postinjection phase.

The three-dimensional (3D) extent of injected CO_2 in the storage reservoir is referred to as the CO_2 plume. During injection operations, the CO_2 plume expands in the storage reservoir. Once injection ceases, the CO_2 plume eventually reaches a maximum spatial extent and stabilizes in the storage reservoir. CCS policy frameworks do not require the CO_2 plume to cease movement entirely to be considered stable. Instead, these frameworks specify that the CO_2 plume move minimally and behave predictably in the storage reservoir such that it will not cross key project-defined boundaries (e.g., storage facility area of leased pore space) and poses no threat to underground sources of drinking water (USDW), human health, or the environment.

Plume stabilization can be demonstrated via multiple approaches, including risk assessment, numerical simulations, and monitoring data. CCS policy frameworks may require operators apply all three approaches to demonstrate stabilization. A simulation-based approach adapted from Harp and others (2019) using a North Dakota case study is presented in this paper. This paper also includes a discussion of existing plume stabilization policy frameworks and comparison of their similarities and differences. This work was led by the Energy & Environmental Research Center (EERC) through the Plains CO_2 Reduction (PCOR) Partnership. The PCOR Partnership, funded by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL), the

North Dakota Industrial Commission's Oil and Gas Research Program and Lignite Research Program, along with more than 240 public and private partners, is accelerating the deployment of carbon capture, utilization, and storage (CCUS) technology. The PCOR Partnership is focused on a region comprising ten U.S. states and four Canadian provinces in the upper Great Plains and northwestern regions of North America (Figure 1-1). It is led by the University of North Dakota EERC, with support from the University of Wyoming and the University of Alaska Fairbanks.

Figure 1-1. Geographic extent of the PCOR Partnership region comprising ten states (Alaska, Montana, Wyoming, North Dakota, South Dakota, Nebraska, Minnesota, Iowa, Missouri, and Wisconsin) and four Canadian provinces (British Columbia, Alberta, Saskatchewan, and Manitoba).

1.1 CCS Policy Frameworks in the United States and Canada

1.1.1 U.S. Environmental Protection Agency

In 2010, EPA established Class VI under the existing UIC Program as a new class of well designed exclusively to inject CO_2 for permanent storage. At the same time, EPA put forth a new set of rules and regulations under the UIC Program and GHGRP Subpart RR to govern Class VI well permitting and reporting, respectively. Under 40 Code of Federal Regulations (CFR) § 146.93(b) "Post-injection site care and site closure," the regulation states:

> "(b) The owner or operator shall monitor the site following the cessation of injection to show the position of the carbon dioxide plume and pressure front and demonstrate that [underground sources of drinking water] (USDWs) are not being endangered."

The operator of the geologic CO_2 storage project is required to do three things under 40 CFR § 146.93(b): 1) monitor the position of the CO_2 plume, 2) monitor the position of the pressure front, and 3) demonstrate that USDWs are not being endangered. Demonstrating plume stabilization is not a direct requirement under EPA Class VI regulations; however, the need to demonstrate plume stabilization is implied in the requirements for monitoring the plume and pressure front positions and, by extension, to provide assurance that USDWs are not endangered. This means operators must have a postinjection monitoring plan in place that includes modeling and simulation of the CO_2 plume and associated pressure front as well as methods for demonstrating containment of the CO_2 plume in the storage reservoir and nonendangerment of USDWs.

Under EPA's GHGRP Subpart RR regulations, which outline the monitoring, verification, and reporting plan requirements for Class VI injection operations, plume stabilization is also not explicitly defined. Plume stabilization is mentioned just once in the definition of the term maximum monitoring area (40 CFR § 98.449). In the definition, the phrase "until the plume has stabilized" appears. Clarification of what is meant by the phrase is provided in Section 5.1.1 of EPA's GHGRP technical support document (U.S. Environmental Protection Agency, 2010). A paragraph within Section 5.1.1 reads:

> "Plume stabilization is the basis of the free-phase plume boundary and depends on the rate of movement of the free-phase CO_2 and the moderation of pressures within the free-phase plume. The reporter should define what criteria will be used to determine when the free-phase plume is to be considered stable. For example, this could be stated in terms of when the rate of movement of free-phase CO_2 is less than a certain value (X foot per year), in any direction, greater than the natural (or not influenced by the site) hydrodynamic movement of the [injection zone], and the pressure change within the reservoir is less than a certain value (Y psi per year). The values of fluid movement and pressure would be generated from runs of the reservoir model. The values that define plume stability should be consistent with the proposed monitoring and modeling methods."

The free-phase plume boundary refers to the portion of CO_2 in the reservoir that is hydrodynamically trapped (sometimes referred to as structural or stratigraphic trapping) in the storage reservoir and which has not either dissolved or mineralized. EPA states that the stabilization of the free-phase CO_2 plume depends on the rate of movement of and the moderation of pressures within the free-phase CO_2 plume and suggests that operators develop a set of criteria appropriate for determining when the free-phase plume is stable. For geologic CO_2 storage projects operating under the regulatory authority of a state-administered Class VI program (e.g., North Dakota), EPA's GHGRP Subpart RR guidance places the responsibility of defining and demonstrating plume stabilization on the operator. In contrast, state-administered Class VI well programs may have more stringent or specific regulations regarding plume stabilization, which is important for the operator to consider.

1.1.2 North Dakota

In 2018, North Dakota obtained Class VI primary enforcement authority (primacy) from EPA. As part of the application for site closure and prior to obtaining a certificate of project completion from the State of North Dakota, an operator must demonstrate plume stabilization by complying with North Dakota Century Code (NDCC) Chapter 38-22-17(5)(d), which states:

> "(5) The certificate may only be issued if the storage operator: (d) Shows that the carbon dioxide in the storage reservoir has become stable. Stored carbon dioxide is stable if it is essentially stationary or, if it is migrating or may migrate, that any migration will be unlikely to cross the storage reservoir boundary."

In North Dakota, plume stabilization is explicitly defined in the regulations and is based on not crossing a key project-defined boundary (i.e., the storage reservoir boundary). In this context, storage reservoir boundary is used synonymously with storage facility boundary, which is defined through simulations of CO_2 injection volumes and storage potential based on regional or site characterization data that satisfy North Dakota's Class VI storage facility permit (SFP) application requirements. When the SFP boundary is defined, a buffer is established around the predicted (simulated) CO_2 plume boundary to ensure that the stabilized CO_2 plume will not cross the storage facility boundary.

Under the North Dakota Administrative Code (NDAC) Chapter 43-05-01-19(8), the operator must also do the following prior to site closure:

> "(8) Once it is demonstrated that underground sources of drinking water are no longer endangered, the final assessment under subsection 9 is complete, and upon full compliance with North Dakota Century Code section 38-22-17, the storage operator may apply to the commission for a certificate of project completion."

Similar to EPA's UIC Class VI regulations, North Dakota requires demonstration that USDWs are not endangered, although the demonstration is not directly linked to plume stabilization as implied under EPA regulation.

NDAC 43-05-01-19(9) lists additional requirements related to plume stabilization. For example, NDAC 43-05-01-19(9)(a)(2) requires operators to submit maps showing the distribution of elevated pressures in the storage reservoir for the CCS project, which is similar to EPA's UIC Class VI language regarding monitoring the pressure in the storage reservoir. NDAC Chapter 43-05-01-19(9)(a)(3) specifies that the predicted rate of CO_2 plume migration and the predicted time frame for the cessation of migration must also be measured. This requirement is reminiscent of EPA's UIC Class VI regulation for monitoring the CO_2 plume and suggests operators submit modeling and simulations data as well as monitoring data to confirm results and past predictions.

1.1.3 Wyoming

In 2020, Wyoming received Class VI primacy from EPA. Under Wyoming Administrative Code 20, Wyoming Code Rule (WCR) § 24-2(hh) defines plume stabilization:

> "The carbon dioxide that has been injected [into the] subsurface essentially no longer expands vertically or horizontally and poses no threat to USDWs, human health, safety, or the environment, as demonstrated by a minimum of three (3) consecutive years of monitoring data."

Under Wyoming's Class VI UIC Program, operators must demonstrate to the regulator that the CO_2 plume essentially no longer expands and poses no threat to USDWs, human health, or the environment with at least three consecutive years of monitoring data. These requirements are similar to those presented under North Dakota's regulations; however, North Dakota does not require three consecutive years of postinjection monitoring data but does require that the CO_2 plume not expand past a key project-defined boundary.

Wyoming's legislature passed State Senate Bill SF0047, which requires a minimum 20-year period before a certificate of project completion will be issued to the operator, regardless of the outcome of the plume stabilization demonstration. This means that operators of geologic CO_2 storage projects in Wyoming will be subject to a minimum 20-year period of postinjection site care management, regardless of whether plume stabilization is demonstrated before 20 years. In contrast, North Dakota regulations have no minimum number of years during postinjection site care monitoring to demonstrate plume stabilization. EPA recommends at least 50 years of postinjection monitoring as a minimum period prior to site closure (40 CFR § 146.93[b][1]), although under 40 CFR § 146.93(b)(2), operators can apply for site closure as soon as the monitoring data demonstrate satisfactorily to the regulator that plume stabilization has occurred.

1.1.4 Government of Alberta

The Government of Alberta established the first Canadian CCS regulatory framework under the CCS Statutes Amendment Act (SAA) in 2010 and with the Carbon Sequestration Tenure (CST) Regulation in 2011. Plume stabilization is not explicitly mentioned in the CST. In Chapter 14-9.120(3)(f) of the CCS SAA regarding site closure, the rule stipulates:

> "(3) The Minister may issue a closure certificate to a lessee in respect of the lessee's wells and facilities within the location of the agreement if the Minister is satisfied that

> (f) the captured carbon dioxide is behaving in a stable and predictable manner, with no significant risk of future leakage."

Alberta conducted a regulatory framework assessment (RFA) in 2012 with a panel of subject matter experts who suggested several changes to the regulations to clarify certain points, including plume stabilization. The RFA Panel published a list of 71 recommendations summarizing their findings. Recommendation 63 from the RFA relates to plume stabilization and clarifies what is meant under Chapter 14-9.120(3)(f) of the CCS SAA, which reads:

> "The regulator and the project operator should agree on how the project will demonstrate that CO_2 behavior is predictable and trending towards stability for the site and how the evidence being collected supports these criteria.
>
> "The Government of Alberta should require the following performance criteria for closure of a project:
>
> a. Sequestered CO_2 and affected fluids are conforming to the objectives and regulatory requirements as described in the project application and approvals.
>
> b. There is no significant adverse effect of sequestered CO_2 or affected fluids to health, the environment and other resources (including but not limited to hydrocarbons, non-saline groundwater and pore space outside the operator's sequestration lease).
>
> c. Sequestered CO_2 and affected fluids are contained in the sequestration complex.
>
> d. Sequestered CO_2 is behaving in a predictable manner.
>
> e. Sequestered CO_2 is expected to continue to behave in a predictable manner and is trending towards stability.
>
> f. The project-specific risk profile is decreasing and the risk of future leakage or adverse effects on health, the environment or other resources is acceptable.
>
> g. Decommissioning and abandonment is complete as required by the regulator.
>
> h. Surface reclamation is complete to the extent agreed upon with the regulator for the post-closure period."

The CCS SAA regulation required operators to demonstrate there is no significant risk of leakage of CO_2 outside the storage reservoir and the plume's behavior is stable and predictable. Recommendation 63 emphasizes the working relationship between operator and regulator and suggests that the operator ensure the project-specific risk profile is decreasing and that any risks to human health and the environment are acceptable. Like North Dakota, Recommendation 63 stipulates that the CO_2 plume must not migrate past a specified boundary. The recommendation further specifies that nonsaline groundwater (i.e., USDWs) must be protected and that affected fluids are fully contained in the storage (sequestration) complex, which is the same across all frameworks reviewed in this paper. Recommendation 63 from the RFA does not clarify what is meant by a CO_2 plume "trending towards stability" but recommends that operators consider a risk assessment as part of the approach to demonstrate plume stabilization. Performing a risk assessment for a site closure application is also recommended in North Dakota under NDAC Chapter 43-05-01-19(9)(a)(12).

1.1.5 California Air and Resources Board

In 2019, CARB finalized a Carbon Capture and Sequestration Protocol permanence certification application within its LCFS incentive program. Under CCS Protocol Chapter A Section (2)(a)(85), plume stabilization means:

> "CO_2 plume migration and pressure changes are small and predictable, such that the measured rate of plume migration has a high certainty of no CO_2 leakage over a 100-year period."

In Chapter C Section 5.2(3)(C), the rule states:

> "(3) Post-injection site care and monitoring requirements are as follows: (C) No sooner than 15-years post injection completion, the CCS project operator may submit evidence to CARB that plume stabilization has occurred. Such evidence must include modeling pursuant to subsection C.2.4.4, updated using operational and post-injection monitoring measurements. The evidence must also include measured plume migration rates. In order for CARB to determine that plume stabilization has occurred, the evidence must show that plume migration over a 100-year period would not result in CO_2 leakage, that the modeling shows good conformance with measurements, and that overall CO_2 leakage risk is reduced. Following verification, CARB will use the submitted evidence to determine whether plume stabilization has occurred."

To demonstrate plume stabilization to CARB, operators must monitor the site in the postinjection period for a minimum of 15 years. This is different from Wyoming's 2022 legislation SF0047, which requires operators to wait 20 years before applying for site closure (and presumably maintaining a postinjection monitoring plan). It is also different in that CARB directly ties the 15-year minimum to plume stabilization demonstration, while in Wyoming plume stabilization can be demonstrated as soon as three consecutive years of monitoring data strongly support the demonstration. CARB is also unique in that operators must provide assurance there is high certainty of no CO_2 leakage over a 100-year period, which implies risk assessment should play a key role in demonstrating plume stabilization, similar to EPA and North Dakota requirements. CARB also requires modeling and simulation results to be compared with monitoring data to show conformance, and operators must show that the risk for CO_2 leakage is reduced, which also implies the use of some sort of risk assessment.

1.1.6 Summary

Common elements found throughout the policy frameworks for demonstrating plume stabilization include:

- Tracking the movement of the CO_2 plume over time to ensure the CO_2 does not cross a key project boundary and that the CO_2 plume behavior in the storage reservoir is migrating minimally and predictably based on criteria or thresholds established by the operator.

- Maintaining a postinjection monitoring plan at least until plume stabilization is demonstrated.

- Showing conformance of models and numerical simulation results with monitoring data and risk assessment.

- Indicating nonendangerment to USDWs, human health, or the environment.

One key difference between the policy frameworks is the minimum number of years required for postinjection monitoring and site closure approval. CARB requires 15 years of postinjection monitoring while Wyoming DEQ requires three consecutive years to demonstrate plume stabilization (and 20 years minimum before the site can be closed). In contrast, EPA and the North Dakota Industrial Commission (NDIC) establish no minimum requirements for the duration of postinjection site care and site closure.

1.2 Plume Stabilization Studies

Early studies on plume stabilization focused on characterizing key physical or chemical trapping mechanisms, which include structure and stratigraphy (hydrodynamic), dissolution (solubility), and mineralization (e.g., Nelson and others, 2005; Doughty, 2010; Zeidouni and others, 2016). Hydrodynamic trapping refers to a porous rock layer (the storage reservoir) capped by an essentially impermeable rock layer (the sealing formation or cap rock) that prevents upward migration of CO_2. In solubility trapping, CO_2 dissolves in the formation water or reacts with the water to form carbonic acid and other aqueous carbonate species. In mineralization trapping, CO_2 undergoes chemical reactions with silicate minerals rich in Ca, Mg, and Fe, resulting in the formation of solid carbonate rock. These trapping mechanisms work together to inhibit CO_2 plume expansion after cessation of CO_2 injection and collectively contribute to plume stabilization. The rates of these trapping mechanisms vary depending on the site-specific geologic conditions and CO_2 injection schedule of the geologic CO_2 storage project.

Since few commercial-scale geologic CO_2 storage projects have operated for long enough to observe CO_2 plume extents throughout operational and postinjection phases, studies rely on geologic modeling and numerical reservoir simulation to evaluate plume stabilization. For example, Harp and others (2019) developed three plume migration metrics based on spatial moment analysis: 1) change in area (A) of the CO_2 plume with time (t) (dA/dt) – defined as the rate of change in circumferential area of the CO_2 plume, 2) the mobility of the CO_2 plume – defined as the effective centroid velocity in the x- and y-directions of the CO_2 plume, and 3) the spreading of the CO_2 plume – defined as the effective longitudinal dispersion coefficient along the primary and secondary axes of the CO_2 plume. Harp and others (2019) showed that these metrics were effective on simulated CO_2 plumes in both flat and tilted storage reservoirs and for homogeneous and heterogeneous permeability fields.

The National Risk Assessment Partnership (NRAP) developed the open-source integrated assessment model (NRAP-Open-IAM) as a platform solution to "help address questions about a potential CCS site's ability to contain injected CO_2 and protect groundwater" (Vasylkivska and others, 2021). The tool features built-in workflows and outputs metrics for quantifying plume migration and leakage risks; the tool is capable of quantitatively assessing plume stabilization based on work presented in Harp and others (2019). Pawar and others (2021) used the NRAP-Open-IAM to determine whether plume stabilization guarantees nonendangerment of groundwater from data based on the Rock Springs Uplift in southwestern Wyoming, USA. The authors concluded that a "risk assessment coupled with numerical predictions" should be sufficient for demonstrating nonendangerment of groundwater in conditions where the plume's mobility is nonzero, as movement of the CO_2 plume itself does not directly imply endangerment to groundwater (Pawar and others, 2021). The basic argument is that it is more important to show the CO_2 plume poses no threat to the environment over proving the plume itself experiences zero movement.

2.0 RECOMMENDED TECHNICAL APPROACH

Commonalities between the policy frameworks reviewed in this paper lay the groundwork for recommending an approach to help demonstrate plume stabilization. Because monitoring data are required for any geologic CO_2 storage project and key differences exist between policy frameworks, the technical approach described in this section and the sections that follow would have to be supplemented with monitoring data and at an appropriate frequency and duration for the specific storge project.

Time-lapse 3D seismic is a primary monitoring technique for tracking the evolution of CO_2 plumes in geologic CO_2 storage projects. The process requires a baseline (preinjection) 3D seismic survey followed by subsequent repeat surveys during the operational and postinjection phases. When the seismic data sets are compared with one another, changes in the seismic response due to changes in CO_2 saturation in the storage reservoir are used to infer the extents of the CO_2 plume (White and others, 2014).

Interpretation of time-lapse 3D seismic data (seismic inversion and differencing between baseline and subsequent surveys) has been documented to be sensitive to the presence of CO_2 at concentrations exceeding 5% (Roach and others, 2014). However, CO_2 concentration differences imaged with time-lapse seismic may not be able to detect concentration gradients within the plume, making it potentially impractical to use the plume centroid approach to quantify the mobility/stability as defined by Harp and others (2019). For example, regions of the CO_2 plume with 10%–20% CO_2 saturation may be indistinguishable from regions of the CO_2 plume with 20%–40% CO_2 saturation. Thus effectively calculating a plume centroid may be beyond the technological limitations of current time-lapse 3D seismic analysis, depending on the site-specific conditions of the CCS project. With this possible limitation in mind, the recommended technical approach discussed in this paper focuses on CO_2 plume areal extent, which is measurable using time-lapse 3D seismic.

The recommended technical approach presented herein uses the derivative of area (dA/dt) metric presented in Harp and others (2019), since all policy frameworks require operators to track the CO_2 plume over time as part of demonstrating plume stabilization. The simulation-based approach identifies the point in time (t) when the CO_2 plume's rate of areal expansion (derivative of area with respect to time [dA/dt]) slows significantly in the postinjection period (primarily driven by pressure dissipation in the storage reservoir) and begins to approach a horizontal asymptote (referred to as $dA/dt_{critical}$). This point in time is referred to as $t_{critical}$ and is identified at the interpreted inflection point $dA/dt_{critical}$.

The derivative of area is calculated using CO_2 plume predictions generated from reservoir simulations for the operational and postinjection phase of a project. Area calculations are performed using a binary indication of the CO_2 plume boundary (i.e., individual grid cells in the model are either inside or outside of the CO_2 plume). In this paper, the CO_2 plume extent is defined as ≥5% CO_2 saturation, after the findings of Whittaker and others (2004), White and others (2014), and Roach and others (2014, 2017). The CO_2 plume boundary is defined as the region where the pore space in the storage reservoir transitions to formation water with no measurable CO_2 present. Therefore, the CO_2 plume inside the boundary contains 5% or more CO_2 saturation.

For each time step in the simulation output, the CO_2 plume area, change in CO_2 plume area, and the derivative of area with time were calculated from the model grid cells. The 3D storage reservoir contains multiple geologic model layers. For calculating the CO_2 plume area, the storage reservoir layers were projected onto a 2D plane to express the CO_2 plume extent in map view. Any x-y map view grid cell which included a single cell thickness of ≥5% CO_2 saturation (anywhere in the z-domain) was included within the plume boundary. Because seismic may only detect saturated areas of greater than 20 ft (6 m) in thickness, this approach represents a conservative view (overestimate) of the measurable size of the CO_2 plume.

Using the derivative of area metric, this paper defines plume stabilization for the particular case study presented in Section 3 as a 5-year delta <0.5 mi^2 (~0.1 mi^2/yr), or <2% of plume area. The use of the 5-year time duration is based on regulatory guidance, which requires a CO_2 plume reevaluation at 5-year increments (NDAC Chapter 43-05-01-05.1.1[b][1] and WCR § 24-14[b][xii]).

3.0 NORTH DAKOTA CASE STUDY

3.1 Geologic Model

The case study used in this paper is from the eastern Williston Basin in North Dakota. The geologic model represents a storage complex, comprising the Amsden Formation as the lower confining zone (dolostone); the Broom Creek Formation as the storage reservoir (aeolian sandstone and dolostones); and the Opeche Formation, Minnekahta, Spearfish, and Piper Formations as the upper confining zone (siltstones) (Figure 3-1). The geologic model did not include the overburden strata above the Piper Formation, which provide the physical scale (estimated at thousands of feet) between the storage complex, the USDWs (Fox Hills and Hell Creek Formations), and the ground surface.

The model was generated in Schlumberger's Petrel software using inputs from core measurements, well logs, and 3D seismic data obtained from the PCOR Partnership region. The grid cell size used was 1000 ft (305 m) in both the x and y directions (with local grid refinement of 200 ft [61 m] around the wellbores), and layer thicknesses were determined from analysis of the vertical variograms for each zone, which ranged between 5 and 7 ft (1.5 to 2 m). Geologic properties (e.g., interpreted lithofacies, porosity, and permeability) were distributed in the model based on horizontal variograms constrained by 3D seismic data and used as inputs for the numerical simulation of CO_2 injection (Figure 3-2). The geologic model extent was approximately 23 by 23 mi (37 by 37 km), which provided sufficient areal extent to capture the CO_2 plume throughout the operational and postinjection phases and to eliminate potential pressure effects near the lateral boundaries of the model. Boundary conditions along the north and eastern extents of the geologic model were defined as partially closed, because of anticipation of the storage reservoir approaching zero thickness tens to hundreds of miles beyond the modeled area. The western and southern boundaries were defined as open because the formation is expected to remain continuous in those directions. Vertically, the upper and bottom boundaries of the model are defined as closed to represent the relatively low porosity, low permeability lithofacies of the upper and lower confining zones.

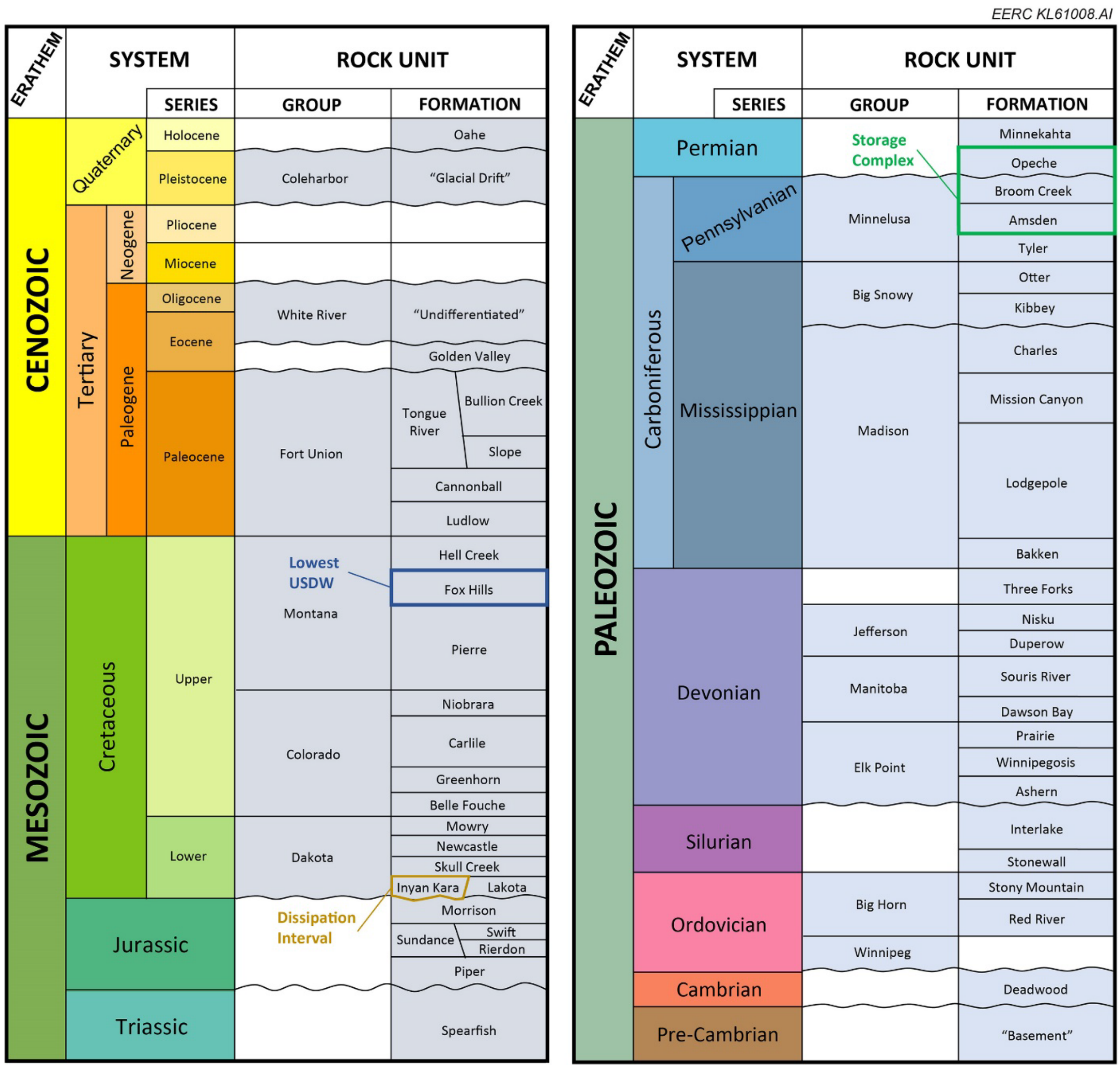

Figure 3-1. Stratigraphic column identifying the storage complex (green polygon) consisting of Broom Creek Formation reservoir and confining zones (Opeche and Amsden) and lowest USDW (Fox Hills Formation, blue polygon) for the case study used for the geologic model and simulations in this paper. Figure was modified from Bluemle and others (1981) and Murphy and others (2009).

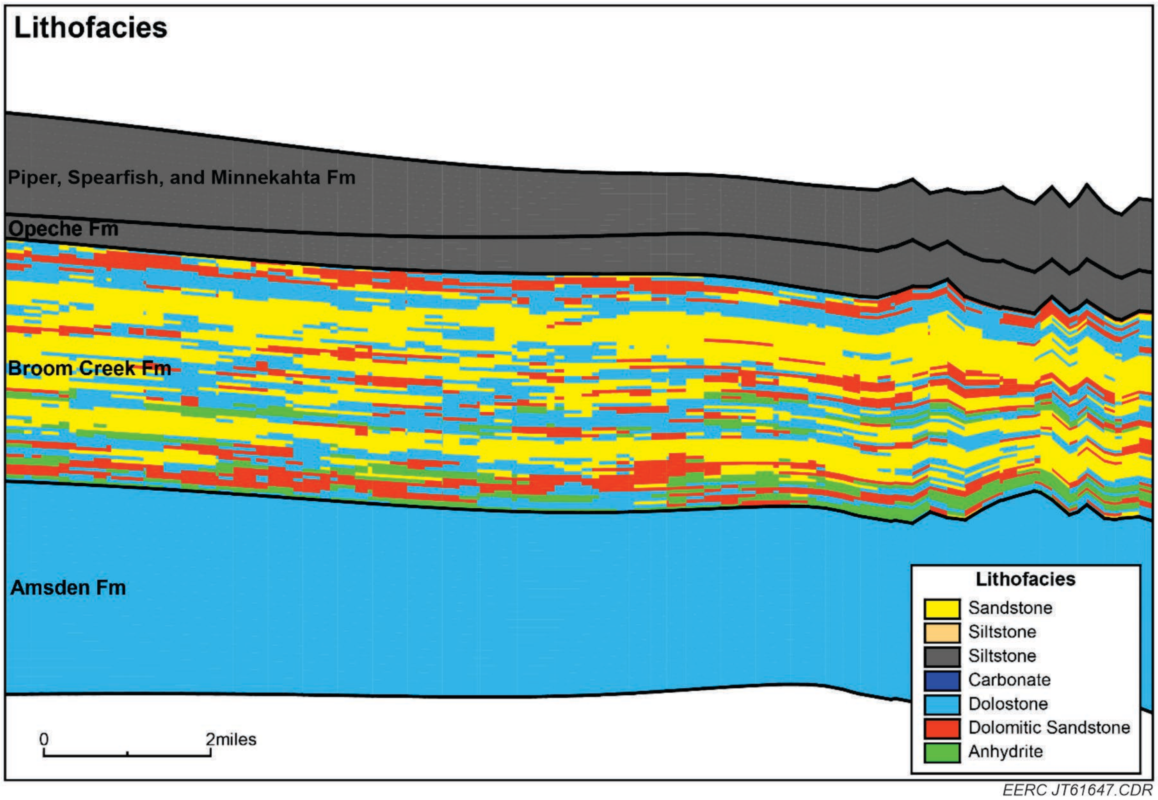

Figure 3-2. Cross-sectional view of the geologic model used for this case study, illustrating the distributed lithofacies property.

3.2 Numerical Reservoir Simulations

The geologic model provided the basis for multiphase fluid flow simulations in Computer Modelling Group's (CMG's) GEM software (Computer Modelling Group, 2019). Fluid flow properties were determined from core measurements and scaled to the model based on average porosity values for each lithofacies and permeability measured during brine injectivity tests.

Injection of CO_2 was simulated with two wells positioned in the center of the model. A total of 77 million metric tons (tonnes) were injected over 20 years (Years 1–20), and an additional 50 years of postinjection were simulated (Years 21–70). The distribution of gas (CO_2) saturation within the model domain at each simulated time step was used to define the CO_2 plume extent within the storage reservoir. The 3D model outputs include CO_2 saturation values for each grid cell, ranging between 0% (no CO_2) and 100% minus the irreducible water saturation. However, these numerical solutions imply a degree of precision that is not observable in the deep subsurface, as regions of storage reservoir with very small percentages of CO_2 saturation are below the detection thresholds for time-lapse 3D seismic; therefore, a 5% CO_2 saturation cutoff was applied.

3.3 Plume Metrics

Table 3-1 summarizes model time steps from Year 1 through Year 70, the CO_2 plume area in square miles, the "delta" or difference in CO_2 plume area (dA) between subsequent time steps, and the growth rate per year (derivative of area with respect to time, dA/dt). For example, in Year 1, the CO_2 plume area was 1.5 mi^2 (3.9 km^2); therefore, dA/dt between Year 1 and Year 0 (prior to CO_2 injection) was 1.5 mi^2. Similarly, in Year 2, the CO_2 plume area was 3.3 mi^2 (9.8 km^2); therefore, the change in area (dA) between Year 2 and Year 1 was (3.3 – 1.5 mi^2) = 1.8 mi^2 (4.7 km^2). The derivative of area with respect to time in Year 2 was the change in area (dA = 1.8 mi^2) divided by the difference in time (dt) (1 year). Please note, two different time steps from the simulation results are included in this example: Years 1–5 increment by 1 year and Years 6–70 increment in 5-year time steps.

The CO_2 plume metric dA/dt, along with variables A (area) and change in A (or "delta"), are plotted in Figure 3-3 using the data presented in Table 3-1 to illustrate the evolution of the CO_2 plume graphically. As shown in Figure 3-3, the CO_2 plume area expands rapidly during the operational phase (Years 1–20) from zero to approximately 26.8 mi^2. The rate of expansion of the CO_2 plume area then begins to slow and approach a horizontal asymptote ($dA/dt_{critical}$) after Year 20. The growth rate per year (derivative of area with respect to time, dA/dt) provides the best metric for establishing plume stabilization. For example, at Year 30, or 10 years into the postinjection phase, $dA/dt_{critical}$ is approximately 0.1 mi^2/yr and remains nearly constant for the remaining life of the simulation. In this simulation case, at Year 30, the 5-year delta has stabilized at roughly 2% of the CO_2 plume area ([0.6 mi^2/29.5 mi^2]*100% = 2%), and after Year 30, the CO_2 plume delta is always less than 2%. Therefore, the stabilized plume boundary was chosen at Year 30 based on this inflection point, ($t_{critical}$). The absolute value of delta may be expected to vary between injection projects of different sizes, as would the percentage of delta with respect to the total plume area. However, the asymptotic character of plotting dA/dt is expected to persist once the plume stabilizes.

Table 3-1. Summary of the CO_2 Plume Simulations for Years 1 Through 70

Simulation Year	Years since Injection	CO_2 Plume Area, A (mi^2)	Delta, dA, (mi^2)	dA/dt (mi^2/yr or mi^2/5 years)
2023	1	1.5	1.5	1.5
2024	2	3.3	1.8	1.8
2025	3	4.8	1.5	1.5
2026	4	6.2	1.4	1.4
2027	5	7.4	1.3	1.3
2032	10	14.2	6.7	1.3
2037	15	20.5	6.3	1.3
2042	20	26.8	6.3	1.3
2047	25	28.9	2.1	0.4
2052	30	29.5	0.6	0.1
2057	35	29.8	0.3	0.1
2062	40	30.2	0.3	0.1
2067	45	30.5	0.4	0.1
2072	50	30.7	0.2	0.0
2077	55	31.0	0.3	0.1
2082	60	31.2	0.3	0.1
2087	65	31.6	0.3	0.1
2092	70	32.0	0.4	0.1

An important observation is that following the 5-year time step from Year 30–35, subtle changes occur along the CO_2 plume boundary throughout the life of the simulation (Figure 3-4). These changes indicate that CO_2 takes a long time (hundreds of years) to completely dissolve in the formation fluid or mineralize in the reservoir and cease movement entirely. However, an important assumption in the approach is that beyond $t_{critical}$ the plume can be considered to have ceased migration under the forces of pressure dissipation, capillary pressure, and CO_2 dissolution in brine, as any additional movement is anticipated to be insignificant relative to the CO_2 plume's areal extent at $t_{critical}$. Within the plume, the pressure and CO_2 saturation gradients are also changing as the reservoir slowly equilibrates postinjection, and these internal dynamics were discussed by Harp and others (2019), who developed metrics for calculating the mobility of the plume centroid and defining plume mobility. The challenge with these additional metrics is that dynamics of internal concentration gradients within the plume body are difficult, if not impossible, to measure quantitatively and, therefore, may not be verifiable via current monitoring technologies.

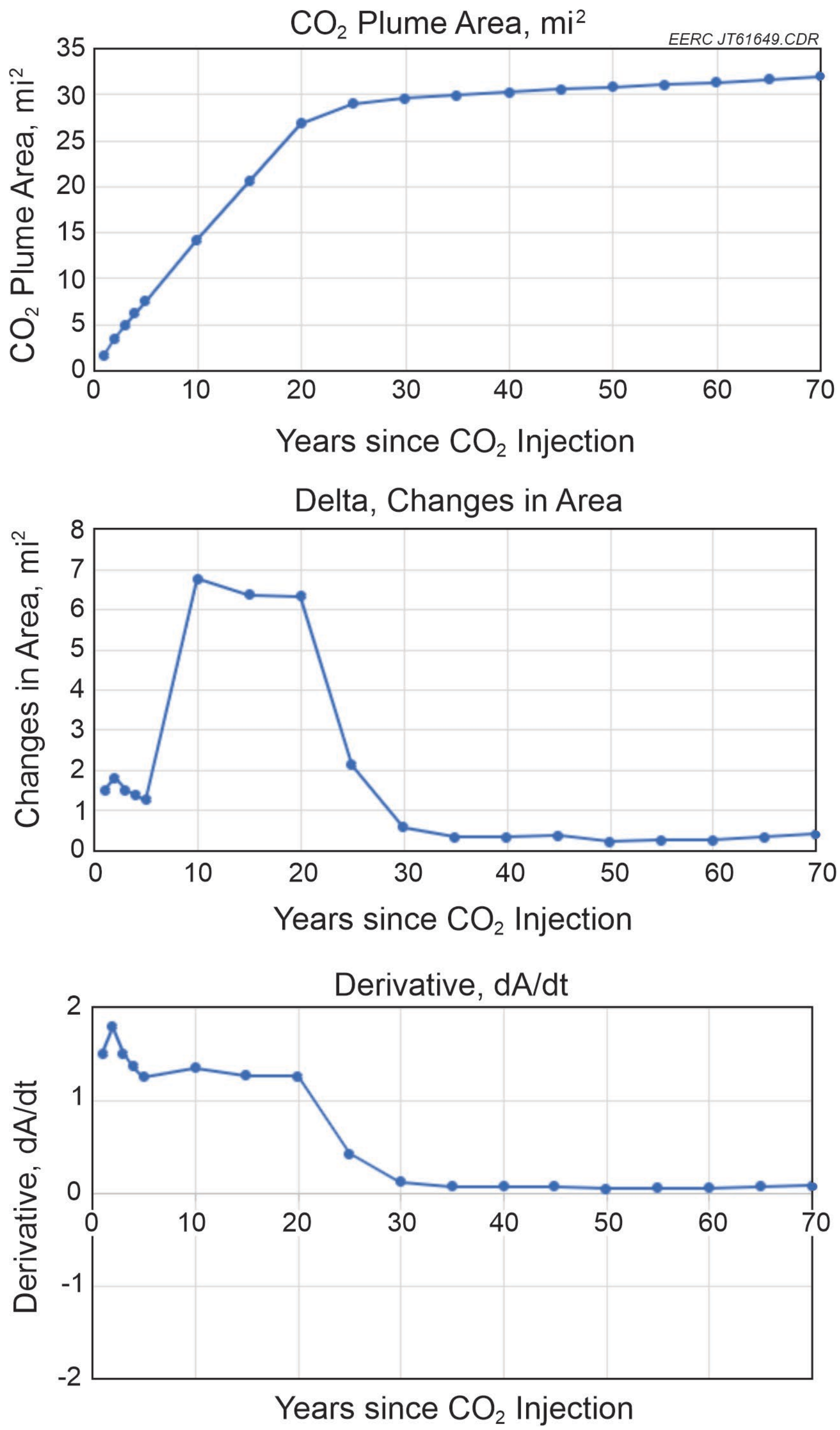

Figure 3-3. Time-series plots showing the simulated CO_2 plume area (A, top), change in area (delta, middle), and derivative of area with respect to time (dA/dt, bottom). Injection begins at Year 0 and ends at Year 20. In this case, $dA/dt_{critical}$ is approximately 0.1 mi^2/yr, and $t_{critical}$ is interpreted at 30 years (Year 10 postinjection). Note that if time steps were calculated annually, then there is a possibility that $dA/dt_{critical}$ and $t_{critical}$ may occur between Year 25 and Year 30.

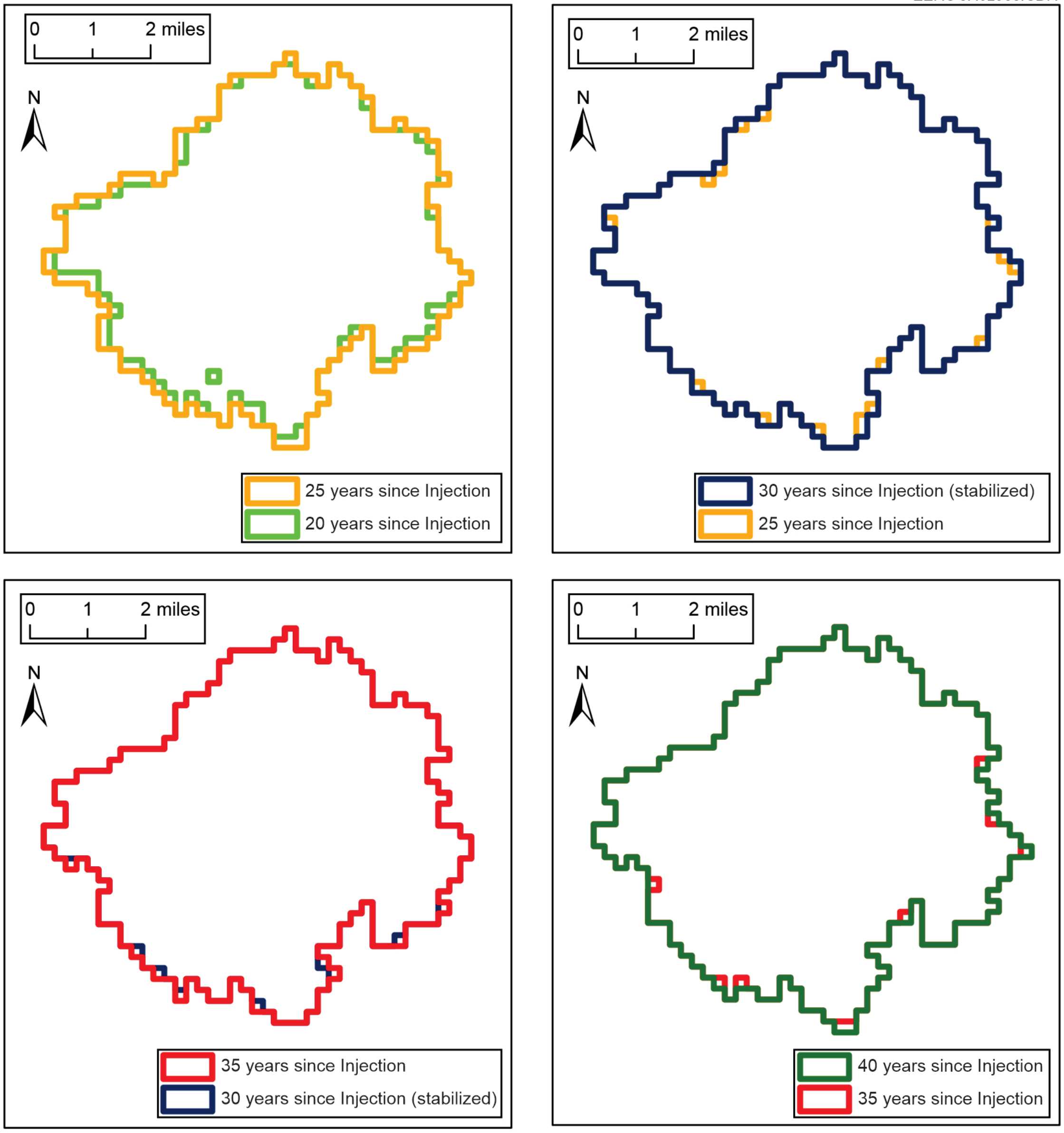

Figure 3-4. Map view of CO_2 areal changes over time. Top left: 20 and 25 years since injection boundaries (green and orange, respectively). Top right: 25 and 30 years since injection boundaries (orange and blue, respectively); stabilized plume boundary at Year 30. Bottom left: 30 and 35 years since injection boundaries (blue and red, respectively). Bottom right: 35 and 40 years since injection boundaries (red and green, respectively). Areal calculations of these boundaries can be seen in Table 3-1.

4.0 CONCLUSIONS

CCS rules and regulations from existing policy frameworks related to CO_2 plume stabilization were reviewed and placed into a list of common themes and key differences. The exercise highlighted the operators' responsibilities for demonstrating plume stabilization in partial fulfillment of postinjection monitoring and site closure requirements. The exercise also supported the argument presented in Pawar and others (2021) that it is more important to show the CO_2 plume poses no threat to the environment beyond the storage reservoir than proving the plume itself experiences zero movement. A single key metric, dA/dt, was applied from Harp and others (2019) as a quantitative approach to establish plume stabilization and used numerical simulation and modeling results of a representative storage reservoir complex in North Dakota as a case study. The metric dA/dt was chosen because of rules and regulations that call out the need to measure the change in area of the plume and plume extents over time. As dA/dt approached $dA/dt_{critical}$, the CO_2 plume's growth was both minimal and predictable, assuming a ~5% CO_2 saturation detection limit in the storage reservoir. Based on prior studies, monitoring plume evolution with time-lapse seismic should allow operators to acquire data necessary to show conformance with modeling and numerical simulation efforts and demonstrate plume stabilization within a postinjection period that is dependent on site-specific factors.

5.0 FUTURE WORK

Opportunities for future work were identified during the process of writing this paper. The first is to develop a separate volume-based approach using a thickness cutoff (in addition to percent saturation cutoff). The approach would test an alternate parameter for quantifying the CO_2-saturated pore space throughout the 3D model extent as a way to measure plume stabilization. Pairing these results with monitoring data (e.g., time-lapse seismic surveys or monitoring wells) would help reduce uncertainty in the use of modeling outputs to quantitatively describe plume stabilization. These data will become available as geologic CO_2 storage projects progress to the injection and monitoring phases.

A second opportunity for future work is to compare model and simulation results with multiple case studies to represent a wider variety of subsurface conditions (e.g., fluvial reservoir with strong lateral heterogeneity). Because each CCS site has unique subsurface conditions, applying a single metric to demonstrate plume stabilization may not be appropriate until it is shown to produce a consistent result under a variety of real or simulated circumstances. Running simulations under a wide set of geologic conditions would also help shed light on the theoretical minimum number of years required to carry out postinjection monitoring activities before a CO_2 plume could be shown to be stable and if there is a chance plume stabilization could be demonstrated prior to the time frames stated in the CCS policy frameworks reviewed in this paper.

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