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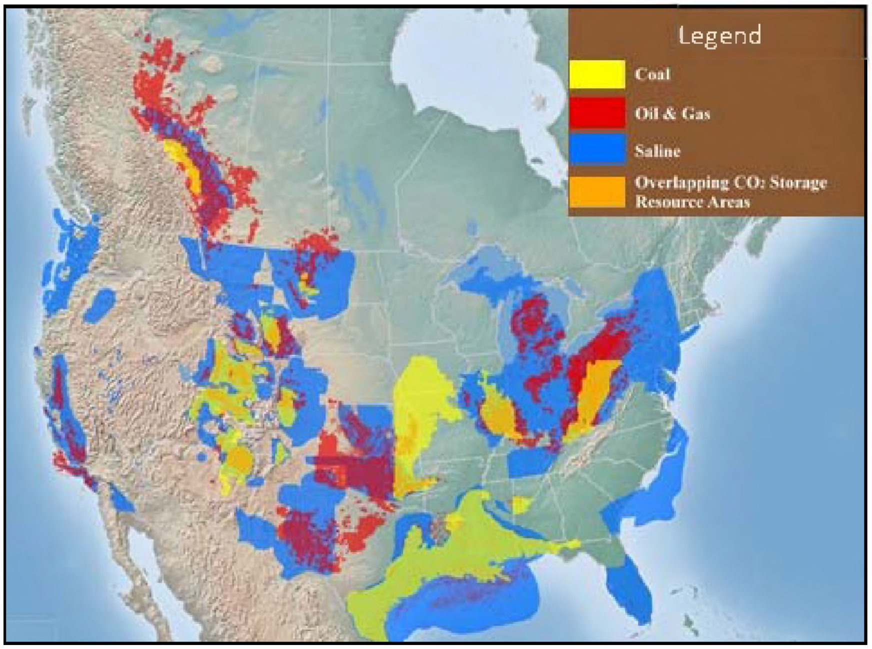

An Evaluation of Subsurface Microbial Activity Conditional to Subsurface Temperature, Porosity, and Permeability at North American Carbon Sequestration Sites

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NETL-TRS-8-2016

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Cover Illustration: The cover image depicts geological sites suitable for carbon sequestration in North America based on coal, oil and gas, saline formations, and CO_2 storage resource areas. Image created by NATCARB viewer (2015).

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An Evaluation of Subsurface Microbial Activity Conditional to Subsurface Temperature, Porosity, and Permeability at North American Carbon Sequestration Sites

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Acronyms, Abbreviations, and Symbols

Term	Description
CO_2	Carbon dioxide
IDW	Inverse distance weighting
Gt	Gigaton
H_2CO_3	Carbonic acid
mD	Millidarcy
NATCARB	National Carbon Sequestration Database
NETL	National Energy Technology Lab
NREL	National Renewable Energy Laboratory
ppmv	Parts per million by volume
$scCO_2$	Supercritical carbon dioxide
SECARB	Southeast Regional Carbon Sequestration Project

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EXECUTIVE SUMMARY

Several nations, including the United States, recognize global climate change as a force transforming the global ecosphere. Carbon dioxide (CO_2) is a greenhouse gas that contributes to the evolving climate. Reduction of atmospheric CO_2 levels is a goal for many nations and carbon sequestration which traps CO_2 in the Earth's subsurface is one method to reduce atmospheric CO_2 levels. Among the variables that must be considered in developing this technology to a national scale is microbial activity. Microbial activity or biomass can change rock permeability, alter artificial seals around boreholes, and play a key role in biogeochemistry and accordingly may determine how CO_2 is sequestered underground.

Certain physical parameters of a reservoir found in literature (e.g., temperature, porosity, and permeability) may indicate whether a reservoir can host microbial communities. In order to estimate which subsurface formations may host microbes, this report examines the subsurface temperature, porosity, and permeability of underground rock formations that have high potential to be targeted for CO_2 sequestration. Of the 268 North American wellbore locations from the National Carbon Sequestration Database (NATCARB; National Energy and Technology Laboratory, 2015) and 35 sites from Nelson and Kibler (2003), 96 sequestration sites contain temperature data. Of these 96 sites, 36 sites have temperatures that would be favorable for microbial survival, 48 sites have mixed conditions for supporting microbial populations, and 11 sites would appear to be unfavorable to support microbial populations. Future studies of microbe viability would benefit from a larger database with more formation parameters (e.g. mineralogy, structure, and groundwater chemistry), which would help to increase understanding of where CO_2 sequestration could be most efficiently implemented.

1. INTRODUCTION

Carbon dioxide (CO_2) is one of the largest contributing components of greenhouse gases. Reevaluation of pre-historic atmospheric CO_2 found pre-industrial CO_2 levels to be lower than previously understood (now 220 ppmv vs. previously thought 280 ppmv; Falkowski et al., 2000). The reevaluation infers that the industrial effects of atmospheric CO_2 levels are greater than previously calculated. Current atmospheric CO_2 (399 ppmv) represents an 81% increase rather than the previously cited 42.5% since the pre-industrial age (National Oceanic and Atmospheric Administration, 2014). The long residence time of atmospheric CO_2 (5–200 years; average of 31 years) further compounds the environmental complications associated with elevated CO_2 levels because atmospheric CO_2 concentrations would continue to increase for decades even if anthropogenic emissions of CO_2 ceased today (Pachauri and Reisinger, 2007).

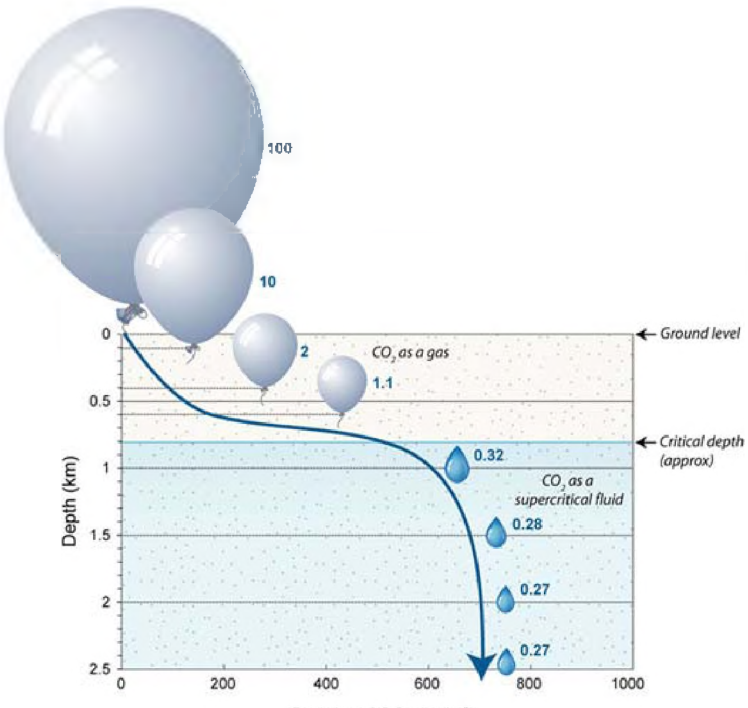

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Figure 1: CO_2 injected at depth. CO_2 injected below 0.8 km reaches a supercritical state. Supercritical fluids require less volume and diffuse through the pore space more efficiently than gas and traditional fluids. The numbers in this figure depict the volume of CO_2 at varying depths. (CO_2CRC, 2015).

Elevated atmospheric CO_2 levels underlie the importance of seeking mitigation strategies to offset atmospheric CO_2 emission. One of the most effective storage methods is subsurface carbon sequestration. CO_2 can be directly stored underground in the form of flue gas or transported offsite before being pumped into the subsurface. Supercritical CO_2 ($scCO_2$) is a phase at which CO_2 is reduced to 1/370th of its gaseous volume at surface pressure-temperature conditions (Figure 1). It is the preferred phase for injection during carbon sequestration (CO_2CRC, 2015). Carbon dioxide reaches a supercritical state where pressure exceeds 7.38 MPa (at depths deeper than 800 m) and where the temperature is greater than 31.1°C (Figure 2; Applied Separations, 2015). The majority of $scCO_2$ exists as a plume, dissolves into formation fluid, or reacts with the subsurface rock formations converting it into a semi-permanent mineral form as discussed below in the next section. However, varying lithologies result in variable geochemical reactions with $scCO_2$; therefore, underground reservoirs are monitored intensively to understand mineral reactions and to limit gas leakage.

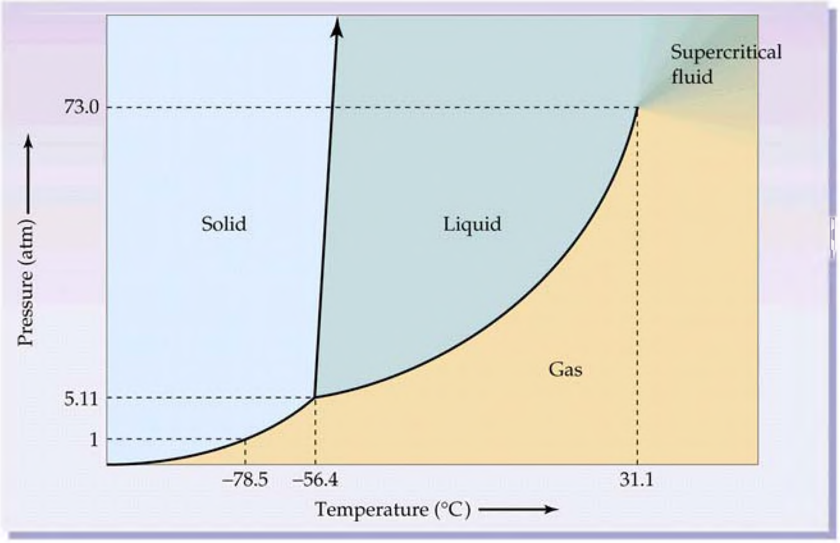

Figure 2: Pressure and temperature phase diagram for CO_2. This pressure-temperature phase diagram for CO_2 demonstrates the critical point (>7.38 MPa and > 31.1°C) at which CO_2 behaves as a supercritical fluid. (Socratic, 2015).

1.1 SEQUESTRATION IN GEOLOGIC FORMATIONS

The injectivity of CO_2 is highly dependent on the permeability of the geologic formation. Sedimentary reservoirs (i.e. clastic, carbonate, and shale) are ideal to host CO_2 as these reservoirs are connected through a network of pores, high porosity, and global distribution in comparison to other geologic formations (Metz, 2005; DOE, 2007; Ohtomo et al., 2013). These types of formations have the potential to store up to 2,000 Gt of CO_2 (Herzog, 2011). Depleted oil reservoirs, deep coal seams, and unconventional reservoirs also offer environments for CO_2 sequestration as demonstrated by several pilot injection sites (e.g. Bachu and Watson, 2009; Glossner, 2013). In addition, petroleum companies already employ several CO_2 injection techniques during enhanced oil recovery (Kharaka et al., 2009). The geophysical, geochemical, and ecological impacts of carbon storage are still unknown and are being studied. The potential for sequestered $scCO_2$ to migrate within subsurface formations is largely controlled by the porosity and permeability of the rock, the solubility of the CO_2 in the subsurface fluid, and the overlying impermeable caprock (e.g., shale) (Benson and Cole, 2008). The subsequent pathways of the CO_2 include:

- Hydrodynamic trapping under reservoir seals
- Residual trapping in reservoir rock pores
- Solution trapping as a dissolved species in formation waters (e.g. bicarbonate)

- Mineral trapping as a precipitate (e.g. calcite).

Carbonic acid (H_2CO_3) is a result of CO_2 dissolution in the formation fluids, the acid further dissociates into bicarbonate and carbonate ions. The H_2CO_3 and dissociated ions react with minerals in surrounding geologic formations and precipitates various metal carbonates. These carbonate species can lower formation porosity and permeability as pore spaces are filled. (e.g. Radha and Navrotsky, 2013; Verba et al., 2014). In addition to these natural reactions, biological processes may affect local geochemistry through nutrient cycling, metal deposition, and mineral dissolution and thus impact carbon storage or the wellbore (e.g. Mitchell et al., 2013).

1.2 ENVIRONMENTAL PARAMETERS OF SUBSURFACE LIFE THAT ARE RELEVANT TO CO_2 SEQUESTRATION

Geologic formation properties (e.g., temperature, acidity, porosity, permeability, depth) play an important role in carbon sequestration and microbial habitat. Temperature is a primary driver of microbial viability. Porosity and permeability of the geologic formation also influence microbial colonization through limitation of flow and nutrient availability.

Mesophilic microbes thrive in temperatures between 25–45°C, thermophilic microbes thrive in temperatures between 55–60°C, and hyperthermophilic microbes thrive at 90°C (Deming and Huston, 2000). Even more resilient hyperthermophilic microbes tolerate temperatures as high as 120–125°C. Kashefi and Lovley (2003) and Takai et al. (2008) discovered *Geogemma barossii* and *Methanopyrus kandleri* could live at 121°C in a hydrothermal vent in the Central Indian Ridge. Due to a temperature-depth gradient around 25°C/km (Nedreli, 2014), many potential sequestration sites are at an elevated temperature, suggesting that mesophilic, thermophilic, and hyperthermophilic organisms are likely to inhabit these wells. Subsurface paleo-temperatures that precluded microbial activity in the past may now cause subsurface formations to be devoid of a bacterial presence, despite being environmentally suitable for microbes. Colwell et al. (1997) analyzed core samples that exhibited no signs of life, despite current temperatures of 43–85°C; however, they noted that paleo-temperatures ranged between 120–145°C and concluded the high paleo-temperatures in the cored zone may have sterilized the system. Other formation conditions (e.g., porosity, permeability) may have inhibited microbial re-colonization once temperatures decreased sufficiently to permit life.

Pore-throat size controls the probability of microbial infiltration and successful colonization of microbes. One study indicated that pore-throat size must be twice the diameter of the prevalent bacteria for microbes to pass through a substrate (Updegraff, 1982). Once in place, microbes can often obtain the water and nutrients necessary for survival through fluid exchange when conditions are favorable for gravitational flow-through, even if pore-throat size decreases. The smallest known microbes are around 0.2 μm; therefore, pore-throat diameters greater than 0.4 μm may be necessary for bacterial passage. Furthermore, the transfer of genetic material from bacterial species, horizontal gene transfer, which is important for bacterial adaption in a carbon storage environment can be impacted by permeability (Massoudieh, et al., 2007).

Permeability varies with depth, and can range over five orders of magnitude within a foot. For example, in the Anschutz Ranch East Field in northeast Utah, the permeability changes from 664 mD to <0.01 mD between well depths of 3,677–3,678 m (Berndt, 1981). Permeability below 100 mD typically fails to allow bacterial penetration (Jenneman et al., 1985). However, Colwell et al. (1997) identified bacteria that reduce sulfate and iron (III) in a sedimentary formation in the

Wasatch Formation in western Colorado, where permeability ranged 0.001–1 mD. A deep site in Virginia was found to sustain thermophilic microbes with "very low permeability" (Boone et al., 1995). Fredrickson et al. (1997) suggested that some microbes may migrate to lower permeable rock from more permeable rock in search of organic compounds and electron donors; while they concluded that these microbes were able to survive with small pore-throat sizes in the sandstone, their existence in shales was undetectable and unlikely.

Furthermore, microorganisms can affect storage environments in several mechanisms (e.g. biofilm formation, enhance mineralization through ureolysis). Biomineralization could be used to reduce leakage pathways at carbon injection sites (e.g. Cunningham et al., 2009; Mitchell et al., 2013). Biofilms, networks of extracellular polysaccharides and proteins that attach to microbes and solid surfaces, may alter the porosity and permeability of formations (Glossner, 2013). Biofilm formation may reduce permeability which could have a direct impact on a reservoir's pore volume and ultimately the amount of CO_2 that can be stored (Gulliver et al., 2014).

The role and the impact that microorganisms may play on rock properties in response to CO_2 injection at potential storage sites is limited in literature. This study maps the environmental conditions most suitable for microbial life (e.g., temperature, porosity, and permeability) in subsurface systems that are considered for carbon capture and/or sequestration. This work is part of a broader research effort investigating what types of microbes are most likely to grow in certain conditions, if the microbial activity will cause any additional risk of CO_2 leakage, or affect the volume of CO_2 that can injected and stored.

2. METHODS

This study reviewed data from subsurface systems describing environmental conditions that dictate survival of microbes (e.g. temperature, porosity, and permeability). A publically available repository of subsurface data is available through NATCARB (NETL, 2015), which is produced as part of the U.S. Department of Energy's (DOE) Fossil Energy Mission and the Regional Carbon Sequestration Partnerships. NATCARB contains 268 North American geological features (e.g., saline formations, oil reservoirs, coal deposits, basalt formations, and organic-rich shales) viable for CO_2 sequestration. These geological features are broken into three categories: 1) capture and storage sites; 2) capture sites; and 3) storage sites. Capture and storage sites capture and store CO_2 on location. Capture sites capture CO_2 on location and then transport the captured CO_2 for storage at another location. Strictly storage sites sequester CO_2 brought from other locations.

These locations were correlated with a geothermal heat flow map of the United States to examine the variety of temperature regimes at potential sequestration sites using ArcGIS 10.1 (Figure 3). From the heat flow map, this study then considered the likelihood that subsurface microbial life could survive in situ. In addition to temperature, the NATCARB database was cross-referenced with Nelson and Kibler (2003) to examine permeability and porosity.

Inverse distance weighting (IDW) was used to interpolate temperatures across the region representative of CO_2 injection depths. This method operates on the rationale that values will be more alike the closer they are to each other. In order to interpolate values, IDW uses surrounding observed values. The locations closest to the unmeasured site will have the most influence; as the distance from the observed value increases, that influence decreases. Porosity and permeability data was overlaid on the interpolated temperature surface (Figures 4 and 5). To more clearly display porosity and permeability data, the range of values were averaged for a formation on the given data and their value ranges were simplified into categories (Table 1):

Table 1: Categorization of porosity and permeability

Porosity (%)	< 1	1-10	10-20	> 20	
Permeability (mD)	< 0.1	0.1-1.0	1.0-10	10-100	> 100

This study then determined sites best suited as viable environments for microorganisms given the description of such environments in Parkes et al. (2000) and plotted their locations. Microorganism-suitable environments often ranked highest in both porosity and permeability. The likelihood of microbial life were categorized: favorable, mixed conditions, and unfavorable. Formations with high temperatures (>80°C), low average porosity and permeability were categorized as unfavorable to contain life. Formations with ideal temperature, permeability, and porosity were considered favorable. Formations with non-ideal conditions (e.g., favorable temperature, but low average permeability or porosity) were categorized as mixed conditions.

3. OBSERVATIONS

3.1 SUBSURFACE TEMPERATURE AT CARBON SEQUESTRATION SITES

Out of the total 268 data points from the NATCARB database only 96 sites had enough data to compare geothermal temperature to subsurface well temperature. The majority of the potential sequestration sites displayed well temperatures suitable for microbial survival, as shown in Figure 3. The geothermal heat flow map follows the trend to where life may be viable downhole with a few exceptions. The predominance of microbial-fostering temperatures underlines the importance microbial biogeochemical reactions could play in CO_2 sequestration. Only three sites—Jackson Dome in Mississippi, the Lawson Formation in Florida, and the Wilmington Graben offshore of Los Angeles, California—had temperatures too extreme to allow microbial life and are depicted in Figure 3 with red symbols.

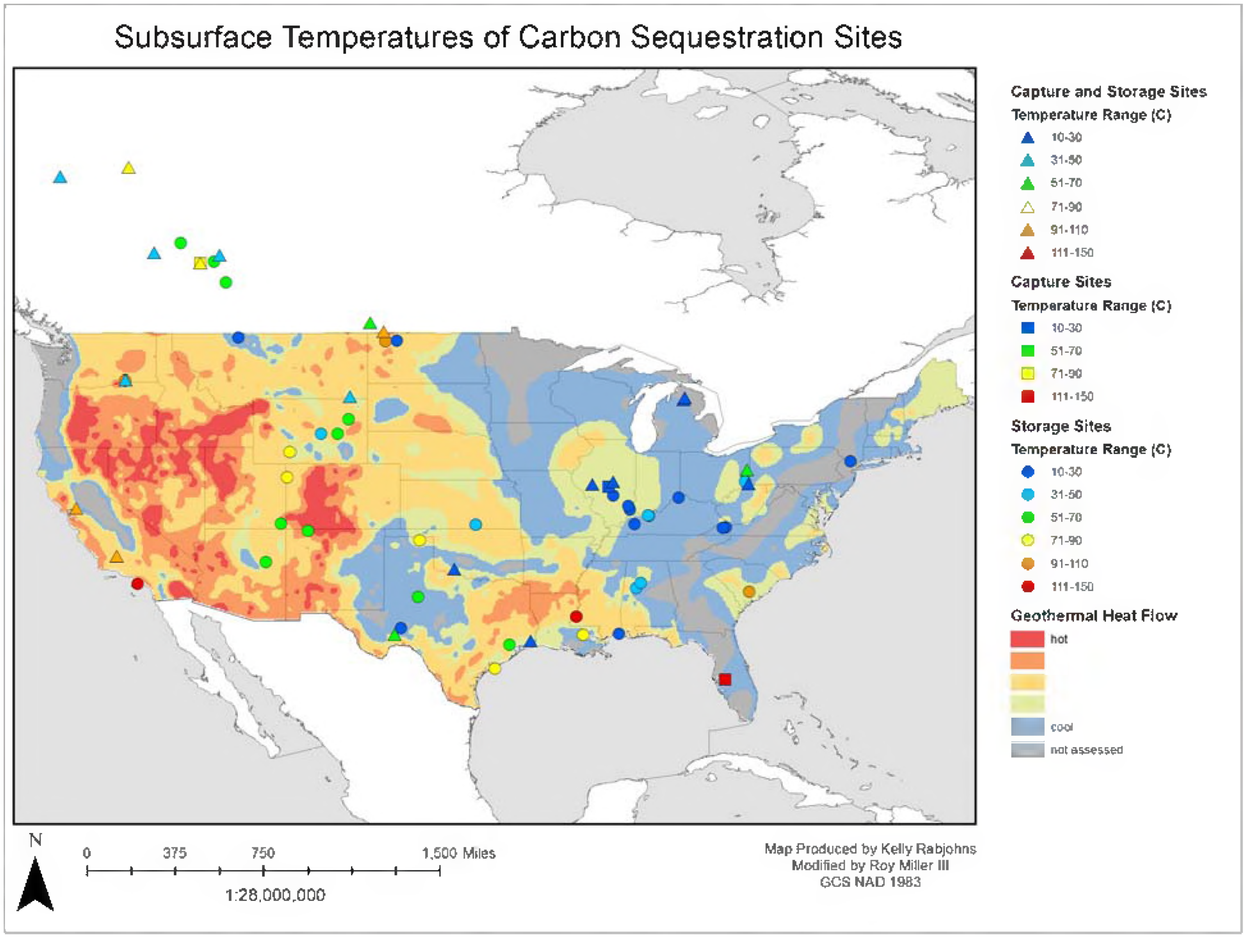

Figure 3: Subsurface temperatures of the current carbon sequestration sites overlaying a geothermal heat flow map of the United States. This GIS data was developed by the National Renewable Energy Laboratory (NREL), which is operated by the Alliance for Sustainable Energy, LLC for the U.S. Department of Energy.

3.2 PERMEABILITY, POROSITY, AND LIKELIHOOD OF LIFE

Of the 96 potential sites that would be suitable for microbes based on the geothermal data, 48 sites had well temperature data, 45 sites had porosity data, 42 sites had permeability data, and 14 sites had temperature, permeability, and porosity data. All available averaged porosity and permeability data was plotted over the interpolated subsurface temperature to identify regions conducive to microbial organisms. Figure 4 depicts the average porosity and temperature of carbon storage sites. Figure 5 depicts the average permeability and temperature of carbon storage sites. There is no correlation between temperature to permeability or porosity. All of the temperature, porosity, and permeability data was compiled to then qualitatively determine the likelihood for microbial life at carbon storage sites (Figure 6). The likelihood of life-favorable, mixed conditions, and uninhabitable or unfavorable conditions is discussed in the next section.

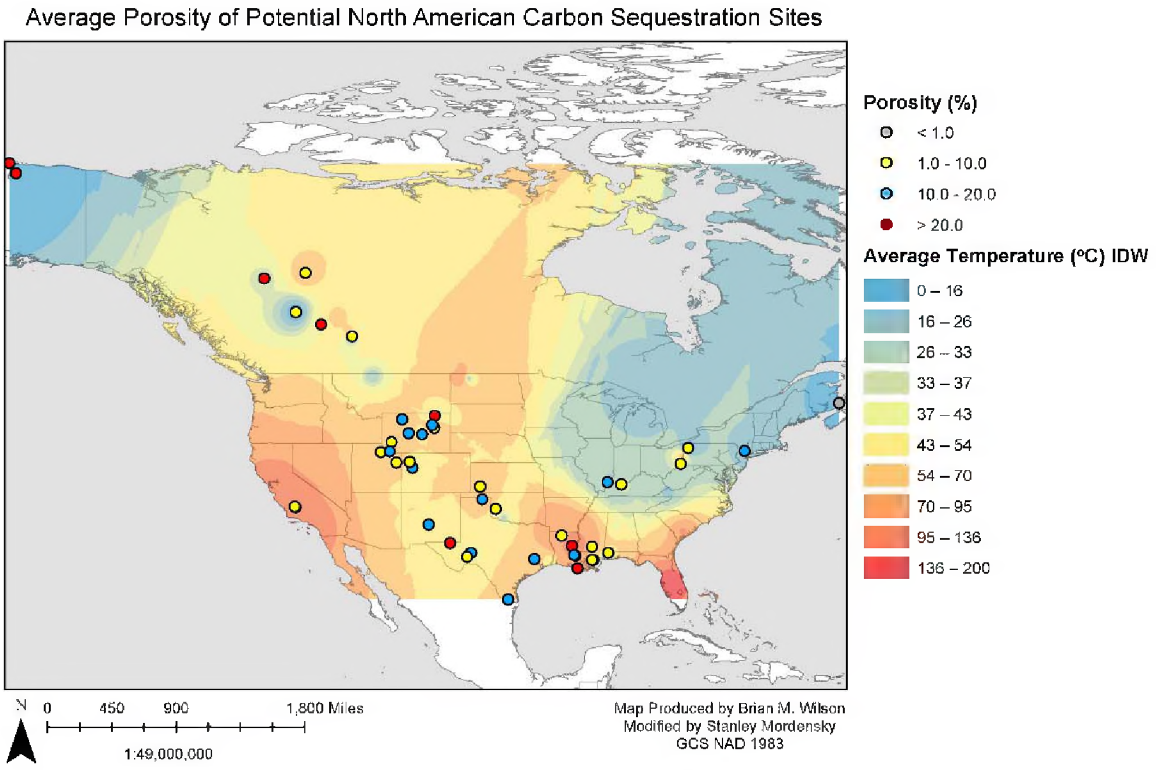

Figure 4: Average porosity of 45 carbon storage sites across North America over interpolated wellbore temperatures.

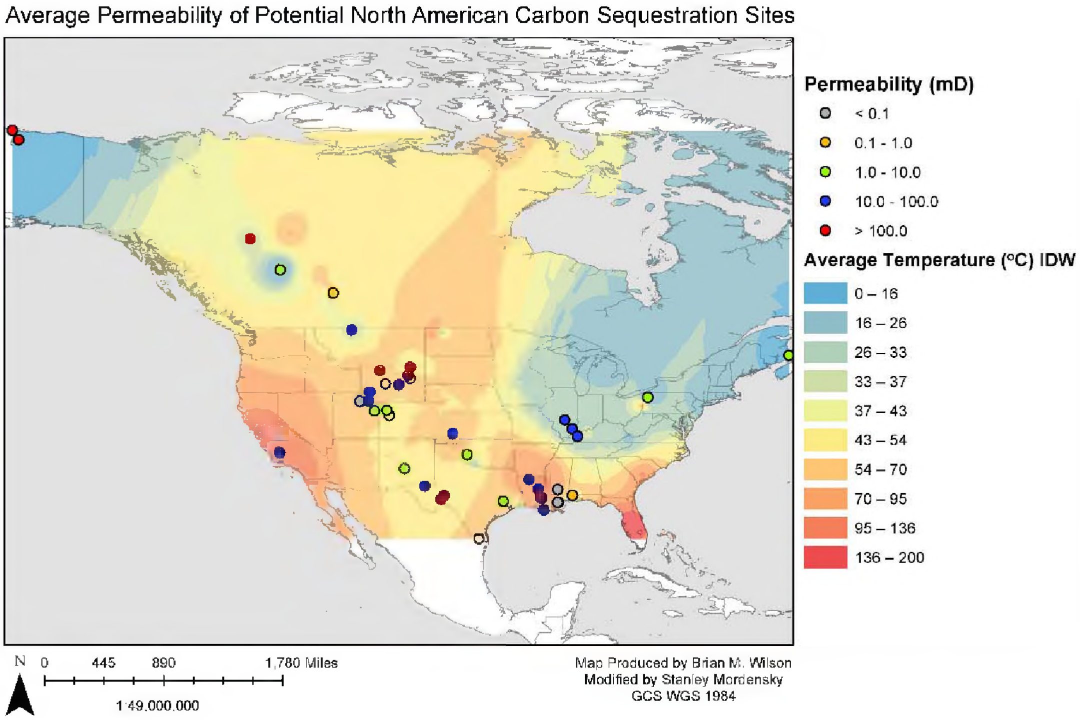

Figure 5: Average permeability of 42 carbon storage sites across North America over interpolated wellbore temperature.

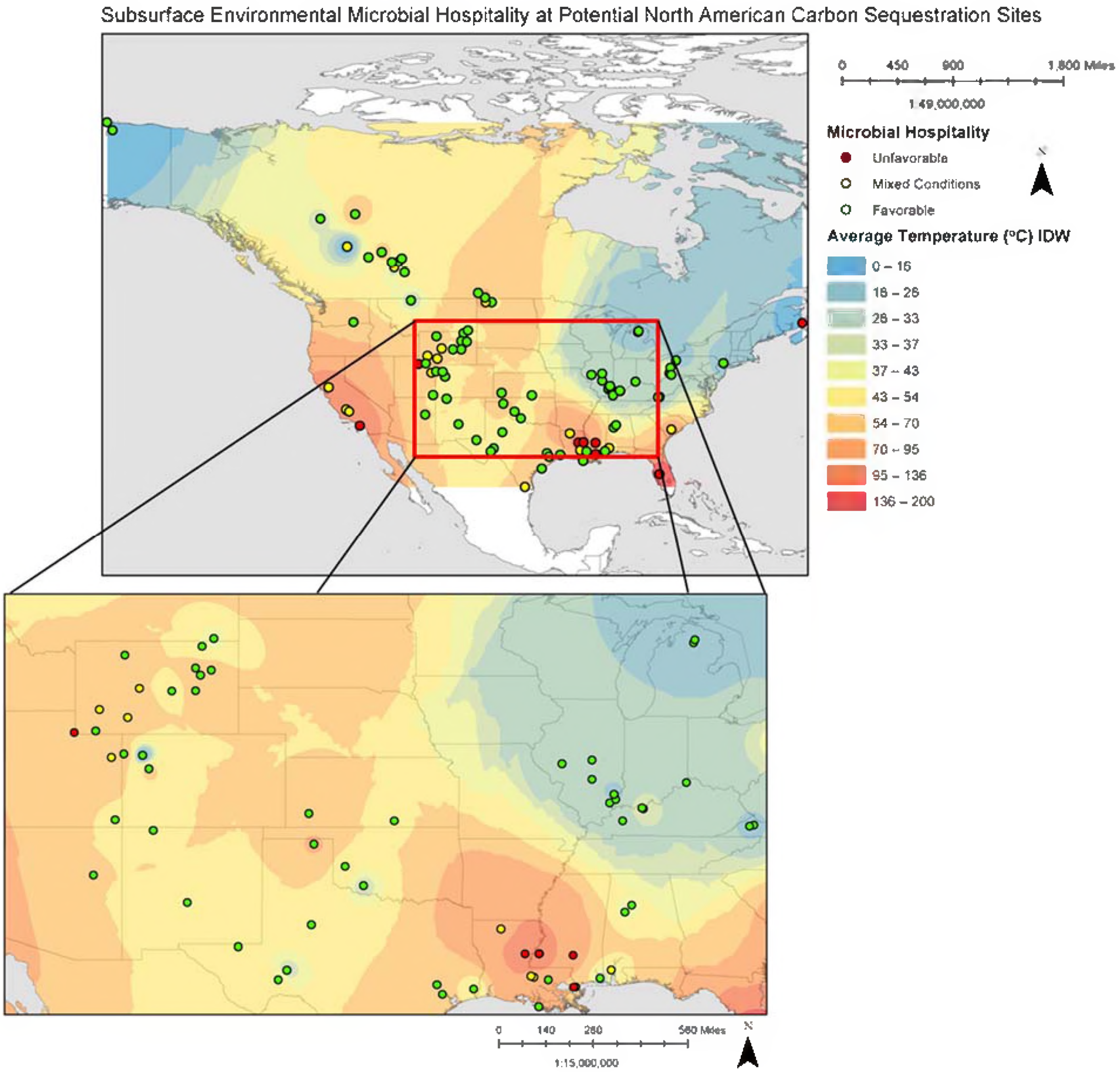

Figure 6: Microbial likelihood at 96 carbon storage sites across North America by interpolated averaged porosity, permeability, and temperature.

3.3 SEQUESTRATION SITES WITH CONDITIONS FAVORABLE FOR MICROBIAL COMMUNITIES

Based on permeability, porosity, and temperature data, 35 sites are favorable for fostering microbial life. Figure 6 depicts that most of the favorable zones correlate strongly with regions of moderate subsurface temperatures. A subset of six carbon storage locations in this study most favorable to contain microbial life are described in Table 2. This is based on the assumption that ideal conditions of <50°C and >100 mD.

Table 2: Most favorable CO_2 sequestration sites to foster microbial life based on temperature, porosity, and permeability data

Site Name	Location	Temp. (°C)	Average Porosity (%)	Average Permeability (mD)
Collums Field	NE Wyoming	40	31.5	897
Oregon Basin Field	NW Wyoming	46	13.3	124
Upper Aux Vases Storms Consolidated Field	Illinois	30	18	116
Yates Oil Field	Central Texas	28	17	175
Fort Nelson	British Columbia	33	24	900
Sharon Ridge	SW Texas	52	10	150

3.4 MIXED CONDITION SEQUESTRATION SITES

Forty-eight of the 96 fields could potentially contain microbes, but high temperatures (60–109°C), or low permeability or porosity downgrade the likelihood that life exists to mixed conditions. Six of these sites have ideal microbial temperatures (<50°C), but may have questionable porosity or permeability that may not support life as shown in Table 3. As discussed previously, there are microbes that can survive in low permeability or porosity formations (e.g. Watsatch Formation; Colwell et al., 1997). Therefore, the sites with lower permeability should not be ruled out entirely as they might still host microbes. For example, the Storms Consolidated Field in Illinois has ideal temperature, porosity and permeability exists in the upper strata; the permeability in the lower Aux Vases reservoir decreases to 40mD. In addition, there are seven sites that had temperatures 50–60°C with microbially conducive porosity and permeability as detailed in Table 3 that could support thermophilic microbes. The other 33 sites have temperatures that thermophiles (60–70°C) and 2 well sites hyperthermophiles (80–105°C) and mixed permeability or porosity could exist. For sites >80°C the probability of life is limited and still relies on other characteristics of the formation (i.e. pH of fluid and nutrient sources).

Table 3: CO_2 sequestration sites favorable to support life with notable limitations

Site Name	Location	Limiting Factor
Lincoln Roads Field	SW Wyoming	1.44% Porosity
Hatters Pond Field	SW Alabama	0.54 mD Permeability
Natural Buttes Field	NE Utah	1.08% Porosity
Elmworth Field	West Alberta	1.25 mD Permeability
Shadyside Field	Central Ohio	6% Porosity
Elk City Fields	Central Oklahoma	2.14 mD Permeability / 7.09% Porosity

Table 4: Sequestration sites with subsurface temperatures 50–60°C

Site Name	Location	Temperature (°C)
Frio Brine Pilot Field	SE Texas	56
Scurry Area Canyon Reef Operators Field	NW Texas	55
San Juan Basin Field	NW New Mexico	52
Two Elk Site Field	NE Wyoming	59
Fenn Big Valley Project	SE Alberta	55
Aneth Oil Field	SE Utah	52
West Coast Regional Carbon Sequestration Partnership Arizona Utilities	NE Arizona	54

3.5 SEQUESTRATION SITES WITH CONDITIONS UNFAVORABLE FOR MICROBIAL COMMUNITIES

Eleven of the 96 sites should be considered uninhabitable to microbial survival because the temperature is in excess of 122°C, the porosity is less than 0.5%, or the permeability is under 0.5 mD as shown in Table 5. A total of four sites are unlikely to contain microbial organisms due to high temperature even for extreme thermophiles to thrive. The other 7 sites have permeability or porosity that are so low that microbial survival would be limited. These 11 sites may be ideal if storage of supercritical CO_2 involves avoiding conditions favorable to microbial survival; however, any future mitigation methods involving microbes at these sites would also be unlikely.

Table 5: Sites with temperatures, permeability, and porosity that make microbial life uninhabitable or unfavorable

Site Name	Location	Temp. (°C)	Porosity (%)	Permeability (mD)
Wildsville Field	SE Louisiana	135	21.7	38.2
Wilmington Graben Field	SW California	140	N/A	N/A
SECARB Validation Phase II Test Site/Phase III Pilot Site	SW Mississippi	124	N/A	N/A
Polk Station	West Florida	200	N/A	N/A
Fort Pike	South Louisiana	61	9	0.076
Stoney Creek Field	NE New Brunswick	38	0.108	7.56
Anshutz Ranch East Field	NE Utah	61	7.66	0.1
Bassfield Field	South Mississippi	79	4.83	0.013
McAllen Ranch Field	South Texas	61	13.3	0.5
Crystal Field	South Alberta	61	8.46	0.477
Riverton Dome Field	Central Wyoming	53	13.43	0.43

4. CONCLUSIONS

This report provides a framework to understand ideal subsurface conditions for microbial growth and activity in CO_2 capture, utilization, and storage sites. After considering the effects of temperature, porosity, and permeability, the likelihood for microbial life in CO_2 storage locations in North America were categorized. Of the 268 sites from the NATCARB database and the 35 sites from Nelson and Kibler (2003), a total of 36 sites were found favorable to microbial survival, 48 sites with mixed conditions for supporting microbial survival, and 11 sites either uninhabitable or unfavorable for microbial survival. A total of 6 sites contained ideal porosity, permeability, and temperature characteristics in which microbial life would survive and possibly thrive. A more extensive collection of subsurface wellbore characteristics would lend credence to this study. Lack of access to published reports proved to be the primary obstacle to obtaining data required for a more complete analysis. Of the 303 total potential carbon capture and/or carbon storage sites, 207 sites had no associated permeability and/or porosity data to correlate. Porosity and permeability could not be interpolated based on depth as these geological factors are too spatially and vertically variable. Furthermore, although the data was collected, this study could not draw conclusions regarding pH of the formation fluid, pressure, and salinity due to the lack of publically available data that may contribute to microbial presence and survival in potential carbon storage sites. This demonstrates the need for future datasets to reduce uncertainty and develop significant spatial results.

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