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IMPLICATIONS OF SURFACE SEEPAGE ON THE EFFECTIVENESS OF GEOLOGIC STORAGE OF CARBON DIOXIDE AS A CLIMATE CHANGE MITIGATION STRATEGY

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ABSTRACT

The probability that long-term geologic storage or sequestration of carbon dioxide (CO_2) will become an important climate change mitigation strategy will depend on a number of factors, namely (1) availability, capacity and location of suitable sites, (2) the cost of geologic storage compared to other climate change mitigation options, and (3) public acceptance. Whether or not a site is suitable will be determined by establishing that it can meet a set of performance requirements for safe and effective geologic storage (PRGS). To date, no such PRGS have been developed. Establishing effective PRGS must start with an evaluation of how much CO_2 might be stored and for how long the CO_2 must remain underground to meet goals for controlling atmospheric CO_2 concentrations. These requirements then provide a context for addressing the issue of what, if any, is an "acceptable surface seepage rate"? This paper provides a preliminary evaluation of CO_2 storage amounts, time-scales, and concordant performance requirements.

INTRODUCTION

To address the question, "How much CO_2 might be stored underground and for how long?" we developed estimates for the yearly amount of CO_2 that would need to be sequestered to meet atmospheric stabilization targets of 350, 450, 550, 650 and 750 parts per million by volume (ppmv). This was done by calculating the difference between the six IPCC SRES [1] marker emissions scenarios and the WRE [2] allowable emissions for a range of long-term atmospheric CO_2 stabilization targets. For each of these scenarios we assumed geologic sequestration would be used as a bridging technology, allowing for the gradual phase out of fossil fuels over a period of 300 years or less. Because the SRES emissions scenarios made projections of emissions over only the first 100 years, the 300-year emissions scenarios were created by extrapolating linearly from the year 2100 emissions to the steady-state emissions rates for stabilizing atmospheric CO_2 at target concentrations in the year 2300. The amount or increasing trend of emissions for all scenarios, except A1T and B1, made this extrapolation necessary.

To address a second important question, "What would be an acceptable surface seepage rate?" we first calculated the rate at which CO_2 might seep back to the surface, based on the simple conceptual model illustrated in Figure 1. We assumed that the amount of seepage would be proportional to the total amount of CO_2 stored underground at any given time. To determine what would be an acceptable seepage rate, we simply compared the calculated seepage to the allowable emissions for stabilization of atmospheric CO_2 at 350, 450, 550, 650 and 750 ppmv. When seepage was small compared to target allowable emissions, we concluded that geologic sequestration would be an effective means for mitigating net greenhouse gas emissions to the atmosphere. If seepage rates exceeded target allowable emissions, then sequestration options with lower seepage rates would be considered preferable.

Note that surface seepage is not necessarily equal to the rate at which CO_2 leaks from the primary storage reservoir, as the existence of stacked reservoirs [3,4] and natural seeps [5,6] demonstrates. Many subsurface processes such as solubility trapping, mineralization, diffusion, and residual gas trapping will attenuate the migration of CO_2 as it moves towards the land surface. Therefore, performance requirements for surface seepage rates should not be construed as performance requirements for leakage from the primary storage reservoir. Setting performance requirements for leakage from the primary storage reservoir is substantially more complex and requires more careful consideration of the physical and chemical processes that occur as CO_2 migrates through the subsurface, as well as of a number of legal and regulatory issues. In this study, we considered only a single criterion for assessing acceptable seepage rates – the effectiveness of geologic sequestration for mitigating greenhouse gas emissions. Use of additional criteria, based on risks to human health or the environment, may lower the acceptable seepage rates given below – e.g., to avoid hazardous accumulations from localized seepage in low-lying or confined spaces such as basements [7].

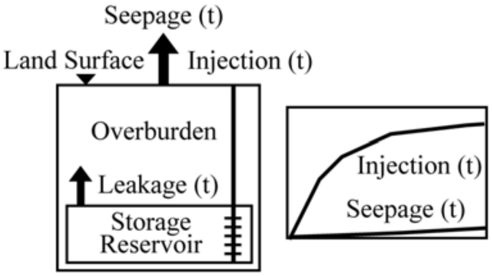

Figure 1: Conceptual model of seepage for evaluating effectiveness.

MODEL AND METHODS

Sequestration scenarios were generated from the SRES anthropogenic emissions scenarios shown in Figure 2A, which were extrapolated linearly from projected anthropogenic emissions levels in the year 2100 to the long-term, steady-state allowable emissions levels for a given target stabilization concentration in the year 2300: roughly 0.9 gigatonnes of carbon per year (GtC/yr) for 350 ppmv, 1.9 GtC/yr for 450 ppmv, 2.7 GtC/yr for 550 ppmv, 3.5 GtC/yr for 650 ppmv, and 4.3 GtC/yr for 750 ppmv [2]. (1 GtC = 3.667 $GtCO_2$). The WRE allowable emissions for a range of atmospheric CO_2 stabilization targets are shown in Figure 2B. The annual amount to sequester in a given year (*S*) was equal to annual anthropogenic emissions (*E*) for a given scenario, *i* (A1B, A1F1, A1T, A2, B1, or B2, according to [1]), minus allowable emissions, *T*, for a given stabilization target, *j* (350, 450, 550, 650, or 750 ppmv), according to Eqn. 1.

$$S(t)_{ij} = E(t)_i - T(t)_j \text{ ; if } E<T,\ S = 0 \qquad (1)$$

The model for seepage was in the form of Eqn. 2, where seepage in a given year, *L*(t), equaled a rate constant, *r*, times the cumulative amount of carbon remaining underground at the end of the previous year, *C*(t-1-z), raised to the power, *n*, plus a constant, *b*. The rate constant, *r*, was explored over three orders of magnitude and set to either 1% (10^{-2}), 0.1% (10^{-3}), 0.01% (10^{-4}), or 0.001% (10^{-5}) per year. The parameter, z, represented a lag time between injection and the inception of surface seepage. In this preliminary thought experiment, z = 0, *n* = 1, and *b* = 0.

$$L(t)_{ij} = r[C(t-1-z)_{ij}]^n + b \text{ ; if t<z, L = 0} \qquad (2)$$

The cumulative amount of carbon stored at the end of a given year was calculated using Eqn 3, where *I*(t) was the amount injected during the year in question.

$$C(t)_{ij} = C(t-1-z)_{ij} + I(t)_{ij} - L(t)_{ij} \tag{3}$$

To illustrate this methodology, we used SRES scenario A1B and a 550 ppmv target. The combination of scenario A1B with a 550 ppmv stabilization target was not chosen on the basis of probability or desirability and is not endorsed in any way. All scenarios were considered equally probable, and no determination of safe or reasonable stabilization targets has been made yet. Figure 2C-2F provides graphs for this scenario of the annual sequestration rate (S), the cumulative amount of carbon stored (C), the annual seepage (L) and the amount of carbon remaining underground over a 1000-year period. These show that the maximum annual sequestration rate would be about 10 GtC per year and that the cumulative amount of carbon stored would be about 1000 GtC. In addition, Figure 2E compares annual seepage to allowable emissions for the 550 ppmv target, which demonstrates that for seepage rates of 1% per year, seepage would be higher than the allowable emissions for the period from 2100 to 2280. Thus, in this scenario, geologic sequestration would not be effective. On the other hand, for all of the other seepage rates (0.1 to 0.001%/year), seepage would be well below the allowable emissions, indicating that sequestration could be effective. Figure 2F shows the amount of carbon remaining underground over a 1000-year period. For two of the cases (seepage rates of 0.01 and 0.001%), over 90% of the carbon would remain underground after 1000 years. For a seepage rate of 1% a year, most of the carbon would return to the atmosphere after 400 years, again demonstrating that geologic sequestration would not be effective if seepage rates were this high.

RESULTS

Calculations such as those illustrated in Figure 2 have been made for all permutations of the scenarios discussed above. The results are detailed in Table 1 and discussed below.

Total Amount of Carbon to Sequester

Target amounts of carbon to sequester varied from 0 to 4530 GtC, and averages for the five different stabilization targets ranged from 930 to 2490 GtC. Note that for all but a few scenarios, some amount of sequestration would be required. In particular, for stabilization at 350 and 450 ppmv, sequestration was required in all of the scenarios. For stabilization at 550 ppmv, sequestration was required in all but the B1 scenario. Even for stabilization at 650 and 750 ppmv, a significant amount of sequestration was necessary for the moderate to heavily fossil fuel intensive scenarios.

Surface Seepage of Sequestered CO_2

The amount of surface seepage of CO_2 depended on both the scenario selected as well as on the assumed seepage rate. In Table 1, annual seepage rates from scenarios that would exceed the stabilization target are highlighted in bold text. As shown, with few exceptions, seepage rates of 1%/year were unacceptably high. For stabilization at 350, 450 and 550 ppmv, seepage rates must be less than 0.01%/year to be acceptable for all of the scenarios. At 650 and 750 ppmv, seepage rates less than 0.1%/year would meet the criterion of acceptable seepage.

DISCUSSION AND CONCLUSIONS

The results presented here demonstrate that geologic sequestration can be an effective method to ease the transition away from a fossil-fuel based economy over the next several centuries, even if some small amounts of CO_2 seep from storage reservoirs back into the atmosphere. This conclusion is based on the following observations.

First, the quantities of CO_2 that must be sequestered (100's to 1000's of GtC) are in the range of the estimated global geological sequestration capacity [8,9,10]. Although well-characterized oil and gas reservoirs could accommodate much of emissions over the coming decades, sequestration requirements will eventually exceed the capacity of oil and gas reservoirs for most scenarios.

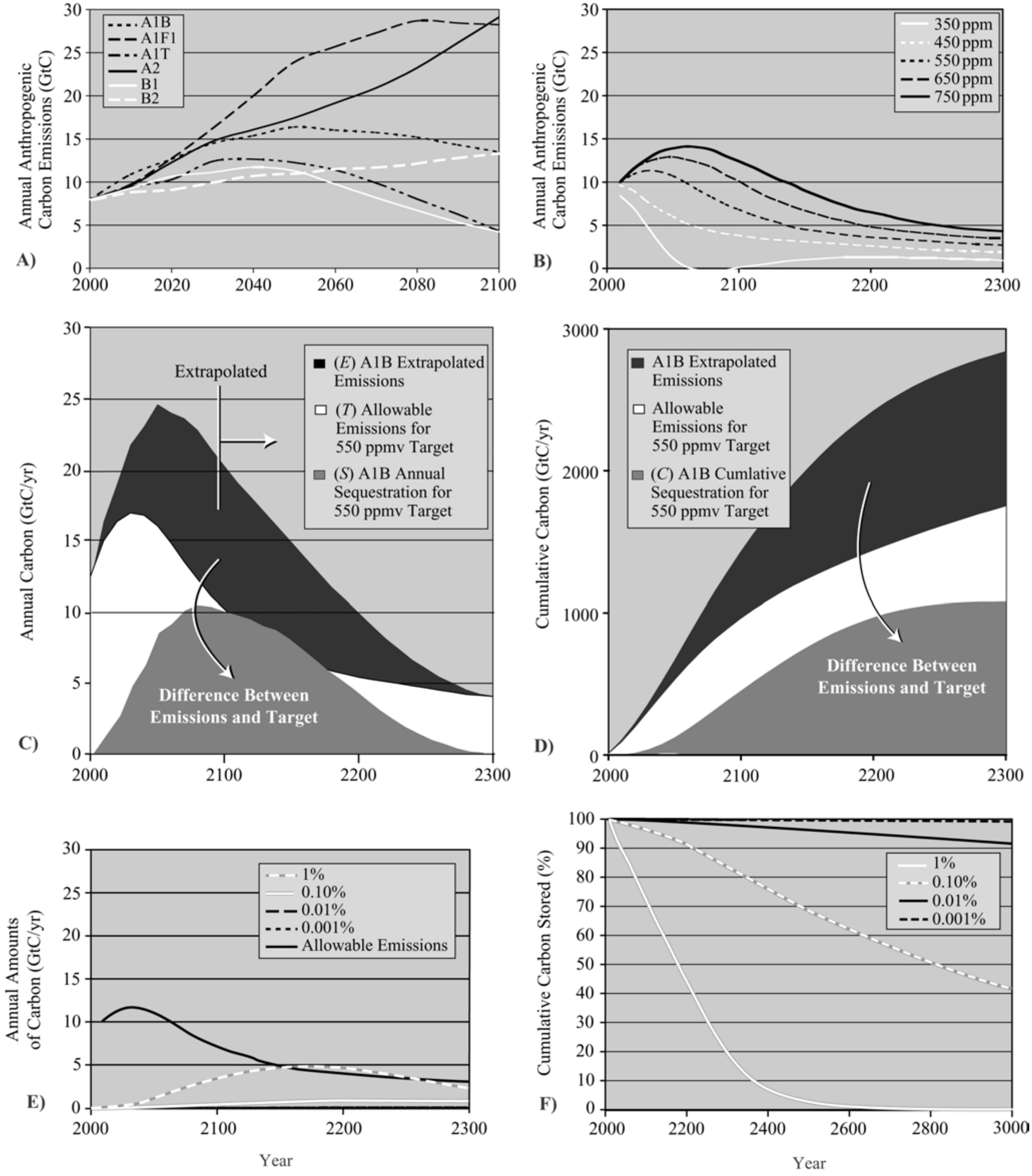

Figure 2: A) IPCC SRES illustrative and marker emissions scenarios; B) Allowable annual emissions for target concentrations of atmospheric CO_2; C) Annual sequestration for A1B/550 ppmv; D) Cumulative amount of carbon stored for A1B/550 ppmv; E) Annual seepage from stored carbon with a range of simple linear seepage rates compared to allowable emissions for A1B/550 ppmv; F) Percentage of cumulative carbon stored with simple linear seepage rates proportional to the amount of carbon stored for A1B/550 ppmv.

TABLE 1
SUMMARY DATA OF TARGET AMOUNTS TO SEQUESTER, MAXIMUM AMOUNTS SEQUESTERED, MAXIMUM ANNUAL SEEPAGE, AND PERCENTAGE OF CARBON REMAINING STORED AFTER 1000 YEARS

Target	**350 ppmv**				**450 ppmv**				**550 ppmv**				**650 ppmv**				**750 ppmv**			
Lkg Rate	***1%***	***0.10%***	***0.01%***	***0.001%***	***1%***	***0.10%***	***0.01%***	***0.001%***	***1%***	***0.10%***	***0.01%***	***0.001%***	***1%***	***0.10%***	***0.01%***	***0.001%***	***1%***	***0.10%***	***0.01%***	***0.001%***
Scenario	**Target Total Sequestration (GtC)**																			
B1	925	925	925	925	275	275	275	275	9	9	9	9	0	0	0	0	0	0	0	0
A1T	808	808	808	808	356	356	356	356	60	60	60	60	0	0	0	0	0	0	0	0
B2	2020	2020	2020	2020	1450	1450	1450	1450	983	983	983	983	626	626	626	626	0	0	0	0
A1B	2360	2360	2360	2360	1790	1790	1790	1790	1080	1080	1080	1080	860	860	860	860	498	498	498	498
A2	4290	4290	4290	4290	3720	3720	3720	3720	3210	3210	3210	3210	2790	2790	2790	2790	2430	2430	2430	2430
A1F1	4530	4530	4530	4530	3960	3960	3960	3960	3450	3450	3450	3450	3030	3030	3030	3030	2670	2670	2670	2670
Average	2490	2490	2490	2490	1920	1920	1920	1920	1470	1470	1470	1470	1220	1220	1220	1220	930	930	930	930
	Maximum Amount Sequestered (GtC)																			
B1	413	778	906	923	182	258	273	275	8	9	9	9	--	--	--	--	--	--	--	--
A1T	473	737	799	807	242	339	354	355	47	59	60	60	--	--	--	--	--	--	--	--
B2	800	1720	1980	2010	569	1250	1430	1450	415	860	969	982	276	556	618	625	--	--	--	--
A1B	918	2000	2320	2360	670	1520	1760	1790	447	930	1060	1080	326	743	847	858	186	432	490	497
A2	1700	3680	4220	4280	1480	3200	3660	3710	1310	2780	3160	3210	1140	2430	2750	2790	989	2110	2390	2420
A1F1	1770	3870	4450	4520	1540	3390	3890	3950	1360	2970	3400	3450	1190	2610	2980	3030	1030	2300	2630	2660
Average	1010	2130	2450	2480	781	1660	1890	1920	597	1270	1440	1460	488	1060	1200	1220	368	808	918	931
Percent	40.7	85.7	98.3	99.8	40.6	86.3	98.4	99.8	40.8	86.6	98.5	99.9	40.1	86.7	98.5	99.8	39.5	86.7	98.5	99.8
	Maximum Annual Seepage (GtC/yr)																			
B1	**4.5**	0.8	0.09	0.009	**2.0**	0.3	0.03	0.003	0.1	0.0	0.00	0.000	--	--	--	--	--	--	--	--
A1T	**5.1**	0.7	0.08	0.008	**2.6**	0.3	0.04	0.004	0.5	0.1	0.01	0.001	--	--	--	--	--	--	--	--
B2	**8.7**	**1.7**	0.20	0.020	**6.2**	1.3	0.04	0.004	**4.5**	0.9	0.10	0.010	3.0	0.9	0.10	0.010	--	--	--	--
A1B	**10.0**	**2.0**	0.23	0.024	**7.3**	1.5	0.08	0.008	**4.9**	0.9	0.11	0.011	**3.5**	0.7	0.08	0.009	2.0	0.4	0.05	0.049
A2	**18.5**	**3.7**	0.42	0.043	**16.0**	**3.2**	0.11	0.011	**14.2**	**2.8**	0.32	0.032	**12.4**	2.4	0.27	0.028	**10.7**	2.1	0.24	0.239
A1F1	**19.3**	**3.9**	0.45	0.045	**16.8**	**3.4**	0.39	0.040	**14.8**	**3.0**	0.34	0.034	**12.9**	2.6	0.30	0.030	**11.2**	2.3	0.26	0.263

	Percentage Remaining Stored after 1000 years			
Lkg Rate	*1%*	*0.10%*	*0.01%*	*0.001%*
Percent	0.0	41.0	91.5	99.1

(Maximum Annual Seepage numbers in bold exceed the long-term, steady-state emissions level for the chosen stabilization target. See Model and Methods section for steady-state values. Seepage is unlikely to be allowed to be 100% of anthropogenic emissions even in a non-carbon energy world, but it is a logical preliminary cut-off point.)

Therefore, large amounts of CO_2 will need to be sequestered in deep brine-filled geologic formations, which are poorly characterized compared to oil and gas reservoirs. Consequently, as very large quantities of CO_2 are sequestered underground, the probability of selecting less favorable sites with higher seepage rates will increase.

Second, this analysis has shown that for seepage rates of less than 0.01% per year, geologic sequestration would be effective for mitigating the buildup of atmospheric CO_2 for all of the scenarios evaluated. At seepage rates of 0.01% and below, the maximum annual seepage never exceeds 0.5 GtC/yr. For comparison, the total estimated worldwide volcanic and magmatic degassing is estimated to be 0.07 to 0.13 GtC/yr [7], and the estimated long-term, steady-state level for stabilization at 350 ppmv is 0.9 GtC/yr. In addition, a 0.01% seepage rate would ensure that at least 90% remained effectively sequestered after 1000 years. Because seepage rates less than 0.01%/year meet several criteria for all scenarios, this may be a reasonable performance requirement for surface seepage.

Finally, by comparison to natural hydrocarbon seepage rates from oil and gas fields, rates of 0.01%/year (10^{-4}/year) or less from CO_2 storage reservoirs appear to be achievable. For example, worldwide oil seepage is estimated to be 0.2 Million tonnes/year out of a total reservoir of 10^7 Mt (assuming 50 Myr residence time), or on the order of 10^{-8}/year [5]. Although less is known about the ability of brine formations to retain buoyant gases, detailed site-specific studies and careful site selection can be used to identify sites with seepage rates that meet the performance requirements identified above.

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