# Initial Public Perceptions of Deep Geological and Oceanic Disposal of Carbon Dioxide

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Two studies were conducted to gauge likely public perceptions of proposals to avoid releasing carbon dioxide from power plants to the atmosphere by injecting it into deep geological formations or the deep ocean. Following a modified version of the mental model interview method, Study 1 involved face-to-face interviews with 18 nontechnical respondents. Respondents shared their beliefs after receiving basic information about the technologies and again after getting specific details. Many interviewees wanted to frame the issue in the broader context of alternative strategies for carbon management, but public understanding of mitigation strategies is limited. The second study, administered to a sample of 126 individuals, involved a closed-form survey that measured the prevalence of general beliefs revealed in study 1 and also assessed the respondent's views of these technologies. Study results suggest that the public may develop misgivings about deep injection of carbon dioxide because it can be seen as temporizing and perhaps creating future problems. Ocean injection was seen as more problematic than geological injection. An approach to public communication and regulation that is open and respectful of public concerns is likely to be a prerequisite to the successful adoption of this technology.

## Introduction

Technologies that can capture $CO_2$ from fossil fuels, either before or after combustion, are being considered as a strategy to limit the rising atmospheric concentration (*1*−*3*). Rather than being released into the atmosphere, $CO_2$ could be injected into deep geological formations or dissolved in the deep ocean (*4*). While the elements of such a system exist on a commercial scale, research is in progress to refine the technology and reduce the cost. Several industrial-scale projects are also under way, with more planned. Substantial uncertainties remain regarding the assessment, management, and regulation of risks arising from $CO_2$ injection (*5*, *6*).

Several previous studies of public perceptions have found that a sizable minority of the U.S. public do not view the problem of climate change as real. Even among those who do view the problem as real, many do not express high levels of concern (*7*−*10*). Thus, the adoption of technologies to address the problem might be expected to meet with a mixed reaction. In a democracy, lack of public support can limit the implementation of even the most promising new technologies. Previous work in the U.K. has suggested that laypeople may have particular safety concerns about oceanic sequestration of carbon (*11*).

In this paper, we explore likely public perceptions in the United States of $CO_2$ disposal in deep rock formations and the ocean. We used a modified version of Carnegie Mellon's two-stage *mental model* method, which has been used to inform risk communications about such topics as radon in homes, climate change, and power frequency electric and magnetic fields (*12*). A strength of this procedure is that it is more likely than conventional survey methods to reveal decision-relevant beliefs (*12*, *13*). Here, we examine beliefs affecting the acceptance of technologies to capture and dispose of carbon dioxide. The first study involved semi-structured interviews that aimed to reveal people's relevant beliefs, also referred to as their mental model. Subsequently, closed-form surveys were administered to a larger sample to measure the prevalence of the beliefs uncovered in the interviews and to assess how they correspond to people's acceptance of carbon capture and storage. Results of both studies are reported below.

## Design of Study 1

The standard mental model interview typically begins with very general questions, followed by increasingly specific questions about issues raised by the interviewee, while maintaining an encouraging and nonjudgmental tone (*12*). Less than 5% of the public express any familiarity with carbon storage technologies (*14*), so it was necessary to modify the mental model methodology by presenting information during the interview. Consequently, we developed a three-tiered instrument that iteratively provided information and elicited beliefs (see Supporting Information). Care was taken to present information as objectively as possible. The resulting instrument bears some similarity to Kempton's semi-structured interviews (*9*), but in contrast, we gave respondents some information before asking any questions.

Part 1 of the interview provided basic background information. It explained that reducing the accumulation of $CO_2$ in the atmosphere so as to limit climate change is the motivation for the technology, briefly discussed pre- and post-combustion design options for carbon capture, and presented deep geological sites and the deep ocean as potential sites for sequestration. Part 2 addressed implementation issues, including the feasibility of the technology being developed, whether $CO_2$ would remain where it was stored, and the potential for the energy industry to adopt the technology. Part 3, the final section, presented five areas of potential concerns: $CO_2$ pipeline issues, slow leaks of $CO_2$ over a long time and fast "burps" of $CO_2$ in a short time from the sequestration sites, ocean ecology, and hydrogen safety.

The interviews with individuals took approximately 45 min each to complete. The interviews were audiotaped and

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transcribed. While conducting, transcribing, and coding mental model interviews is extremely time-consuming, repeated studies have found that after about 15–20 interviews, the rate of introduction of new concepts approaches an asymptote (*12*). So a relatively small sample is sufficient to identify generally held beliefs.

A convenience sample of individuals, without engineering or science degrees, was recruited from employees at Carnegie Mellon and a Parent-Teacher Organization at a Pittsburgh suburban parochial school. Eighteen adults participated in the individual interviews, with a mean age of 38 years and 83% having completed at least a Bachelor's degree. Ten (56%) were women. Interviewees were compensated with a $10 gift card for a local grocery store.

## Results from Study 1

After receiving the basic background information in part 1, 10 of our 18 respondents (56%) indicated that they were agreeable toward the general approach of carbon capture and sequestration (CCS). For example, a 63-year-old female remarked, "Well, it's the beginning, somebody has to start somewhere. And so this sounds like a good beginning". A 37-year-old female said, "I think it's a good idea because of the problems that we attribute to the $CO_2$, the global warming". Five interviewees (28%) judged the technology unfavorably. For example a 49-year-old female said "It makes me feel uncomfortable, the thought of putting the $CO_2$ either deep in the ground or deep in the ocean". Three (17%) interviewees were noncommittal. The same question was asked again after the presentation of implementation issues in part 2 and potential concerns, in part 3, at the end of the interview. Four respondents changed their assessments with the result that the final assessment was 9 (50%) favorable, 7 (39%) unfavorable, and 2 (11%) noncommittal.

As the interview proceeded through the three informational sections, respondents volunteered concepts that they found relevant for their assessment of the technology. Three (17%) voiced doubts about believing that global warming is a real problem. A 49-year-old male said, "I'm not convinced ... I don't know that there is a problem". However, two of those three noted that they would think favorably of the CCS technology if, in the words of a 53-year-old female, "This all boils down to how serious a problem is this ... if this is a definite serious problem, yes, fine".

Several concerns were raised about the cost and efficacy of the technology. Fifteen (83%) voiced apprehension that, once implemented, CCS technology might yield unforeseen negative consequences. Nine (50%) mentioned the efficacy of the technology, expressing doubts as to whether CCS technology could actually yield reduced $CO_2$ emissions. Nine (50%) raised concerns about costs, often suggesting that these would be passed on to consumers. A 27-year-old male raised the possibility that CCS might just be a low cost fix, noting "I would be concerned ... that they're trying to save money by getting rid of it as cheaply as possible, as opposed to doing something that would be more environmentally safe".

One-third of the interviewees, while discussing sequestration, used terms such as "garbage" and "pollution" or compared $CO_2$ to some other type of waste. For example, a 25-year-old female said, "I don't think they know all the effects of where they could be putting the waste" while a 21-year-old male stated, "I think it is great that people are looking into other methods of disposing wastes [$CO_2$]". A 49-year-old male commented, "We're talking about putting something down in there. This almost sounds like nuclear waste". A 41-year-old male asked "Are you just dumping something ...". The many references to a "waste" paradigm suggest that people clearly recognized that the word sequestration was a synonym for disposal.

A number of interviewees expressed unease with a solution that relocates waste from one place to another. For example, a 25-year-old female said "It's just polluting it in a different place or putting it somewhere else." A 27-year-old male noted "... it's almost kind of like ... robbing Peter to pay Paul. You're doing one thing to improve something, but you're creating a problem elsewhere". And, a 44-year-old female said "... sometimes things are done to fix a problem and then you find out the fix was worse than the original thing ...".

Though the information provided did not indicate specific locations in which sequestration would be implemented, a "not in my backyard" (NIMBY) response was common. Thirteen (72%) mentioned concerns with siting at least once during the interview. Nine (50%) of these respondents broached comments about siting. However, the remaining four of these 13 (22%) did not express concerns until information was introduced in part 3 on possible leaks from pipelines and sequestration sites.

Without prompting from the interviewer, a number of interviewees suggested alternatives that might be used for carbon management. Six (33%) suggested that an effort should be made to expand the portfolio of energy production systems, with solar and wind energy production methods receiving the most interest. Ten (56%) suggested that we should identify a way to use $CO_2$ in a beneficial way or to explore other strategies to dispose of the $CO_2$. Suggestions included "send it out to space" or "changing it to dry ice".

The final segment (part 3) of the interview outlined potential concerns if carbon sequestration was implemented. Fifteen (83%) respondents expressed only minor concerns about the pipeline issues. Several noted that such pipelines were really not much different from natural gas pipelines. Eleven (61%) were in favor of pursuing the technology, even if slow leaks of $CO_2$ over a long time will potentially occur. For example, a 27-year-old male said of leaks "... if they weren't directly a threat to people or animals, so what? [The $CO_2$ was] ... going to go into the atmosphere anyway. So, monitor them and fix them when you find them, but it doesn't really seem like this would be much of an issue". Fast "burps" of $CO_2$ over a short time from the disposal locations were viewed as a moderate concern by 10 (56%) of the interviewees.

Potential effects of $CO_2$ on the ocean ecology evoked a strong response, with 15 (83%) expressing general concerns about adverse effects on aquatic life and 10 (56%) expressing concern about localized effects. A 21-year-old female said, "I know the ocean is very big and is very deep but I'm wondering what kind of effect it would have on our oceans". A 49-year-old female said "... if this extra $CO_2$ is absorbed into the ocean, would it disrupt whatever balance is in the ocean ... it might be harmful to things that live in the ocean". A 27-year-old male noted that "... I don't necessarily like the fact that it's being pumped down deep in the ocean, kind of like out of sight, out of mind". And a 44-year-old female said "... if we were to put it ... in the ocean, we could be messing with some form of life that's on the bottom. I don't think we have much knowledge of what's down there. Because we really can't explore that deep. So we'd be messing with something we have no knowledge of".

## Discussion of Study 1

Study 1 had several limitations. First, while half of the respondents in study 1 indicated that they viewed carbon capture and sequestration favorably, that judgment was made in a way that did not distinguish between geological and oceanic sequestration. Given the strong negative reactions elicited in respondents' discussions of oceanic disposal, clearly the two reservoirs should be considered separately when asking about overall public acceptance.

A second limitation of these results is that we were unable to determine the level of association between respondents' views of climate change and their evaluations of the technologies and other relevant beliefs, including those about climate change. Moreover, many respondents indicated a desire to consider carbon capture and sequestration in the context of a broader set of options for carbon management. Study 2 was designed to address these limitations, and to achieve greater statistical power through a closed-form survey of a larger sample.

## Design of Study 2

To examine the prevalence of, and relationships between, lay beliefs about carbon capture and sequestration, we used the results from study 1 to design a closed-form survey that could be administered to a larger number of respondents. Like the interview protocol, it provided information in as neutral a tone as possible about technologies for geological and oceanic disposal, interspersed with questions measuring beliefs (see Supporting Information). The structure of the survey and sequence of information presented and tasks is illustrated in Figure 1.

To assess beliefs accurately, survey questions should use wording that respondents and researchers interpret in the same way (*12*, *15*). Because interviewees in study 1 used various graphic alternatives to the word "sequestration", study 2 used "carbon capture and disposal (CCD)". We will discuss possible implications of this word choice in the conclusions.

As in the interviews, an introductory section (section 1) of the survey provided basic background information essential to motivate the need for managing $CO_2$ emissions. It briefly discussed the distribution of sources from which the world gets its energy, the associated emissions of $CO_2$, and increasing atmospheric concentrations.

While most Americans (85 ± 3% in 2002) report that they have heard of global warming (*16*), levels of concern have remained modest ("worry a great deal" 26 ± 3% in 2004 after a brief high of 40 ± 3% in 2000) (*17*, *18*). Study 1 and previous studies (*7*−*10*) have found a sizable minority of respondents who expressed doubts that global warming is a real or a serious problem. Because such beliefs can confound interpretation of judgments about mitigation technologies, we asked respondents in section 2a whether they believe: (a) that continuous release of $CO_2$ will result in climate change; (b) that the government *should* limit emissions; and (c) that the government *will* limit $CO_2$ emissions. Each was followed by a seven-point scale ranging from completely disagree to completely agree. These questions were followed by section 2b, which presented a list of 15 social and economic issues (education, crime, health care, climate change, etc.), included to measure the relative importance of climate change. Respondents were asked how important each was on a seven-point scale ranging from not important to extremely important.

Next, in section 3, respondents were asked to set aside their personal beliefs about climate change and suppose that the government had mandated a 50% reduction in $CO_2$ emissions. They were asked to rank their willingness-to-pay for "different methods of meeting the goal to reduce $CO_2$ emissions by 50%", hypothetically offered by their electricity supplier. Framing the options in terms of a 50% reduction enabled us to include efficiency and coal-to-natural-gas fuel switching. Some of the reduction methods were described as using "a mixture of generation systems that produce little or no $CO_2$, combined with regular coal-burning power plants". Biomass, hydroelectric, nuclear, solar, and wind power and oceanic and geological CCD options were treated in this way. Energy efficiency was described as reducing the amount of energy used by 50% through using more efficient appliances, with the power being generated completely from

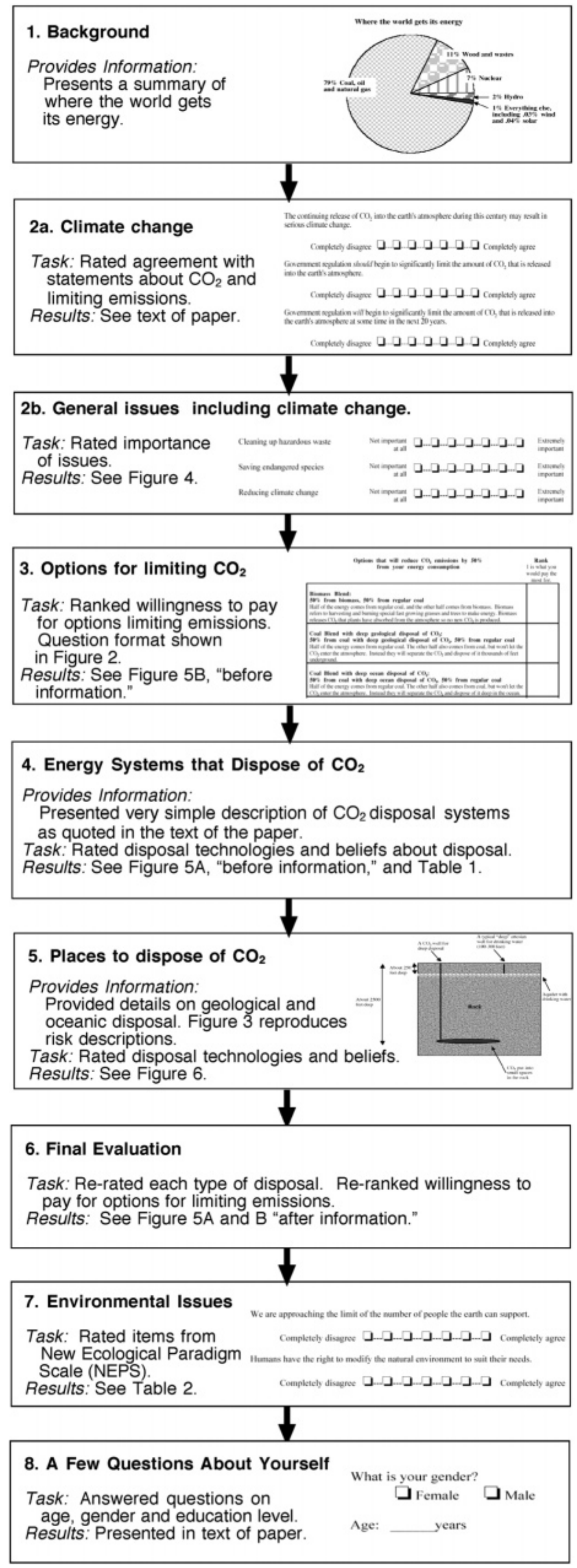


**FIGURE 1. Summary of the structure of the survey instrument used in study 2.**

regular coal. The natural gas option was described as involving power generated solely from natural gas, thus being the only option that did not involve burning at least some coal. All options were assumed to have the same effects on reducing $CO_2$ emissions. The exact language and response format of the survey are reproduced in Figure 2.

Please write a "1" in the box next to the option you would pay the most for, a "2" in the box next to the option you'd pay the next most for, and so on for all 9 of the options.

| **Options that will reduce $CO_2$ emissions by 50% from your energy consumption** | **Rank** 1 is what you would pay the most for. |
|---|---|
| **Biomass Blend:**<br>**50% from biomass, 50% from regular coal**<br>Half of the energy comes from regular coal, and the other half comes from biomass. Biomass refers to harvesting and burning special fast growing grasses and trees to make energy. Biomass releases $CO_2$ that plants have absorbed from the atmosphere so no new $CO_2$ is produced. | |
| **Coal Blend with deep geological disposal of $CO_2$:**<br>**50% from coal with deep geological disposal of $CO_2$, 50% from regular coal**<br>Half of the energy comes from regular coal. The other half also comes from coal, but won't let the $CO_2$ enter the atmosphere. Instead they will separate the $CO_2$ and dispose of it thousands of feet underground. | |
| **Coal Blend with deep ocean disposal of $CO_2$:**<br>**50% from coal with deep ocean disposal of $CO_2$, 50% from regular coal**<br>Half of the energy comes from regular coal. The other half also comes from coal, but won't let the $CO_2$ enter the atmosphere. Instead they will separate the $CO_2$ and dispose of it deep in the ocean. | |
| **Energy Efficiency:**<br>**100% regular coal**<br>All of the energy comes from regular coal. This option will replace appliances and lights in your house with much more efficient ones so that you use half as much electricity while enjoying using your lights and appliances just as much as you do now. Using less electricity will result in less $CO_2$ being produced. | |
| **Hydro-electric Blend:**<br>**50% from hydro-electric, 50% from regular coal**<br>Half of the energy comes from regular coal, and the other half comes from hydro-electric. Hydro-electric refers to making electricity with water power from dams. Hydro-electric produces no $CO_2$. | |
| **Natural gas Blend:**<br>**100% from natural gas**<br>The energy comes from burning natural gas in highly efficient plants. Burning natural gas efficiently produces about half as much $CO_2$ as burning coal. | |
| **Nuclear power Blend:**<br>**50% from nuclear power, 50% from regular coal**<br>Half of the energy comes from regular coal, and the other half comes from nuclear power.<br>Nuclear power produces no $CO_2$. | |
| **Solar power Blend:**<br>**50% from solar power, 50% from regular coal**<br>Half of the energy comes from regular coal, and the other half comes from solar. Solar power refers to making electricity with energy from the sun. Solar power produces no $CO_2$. | |
| **Wind power Blend:**<br>**50% from wind power, 50% from regular coal**<br>Half of the energy comes from regular coal, and the other half comes from wind. Wind power refers to making electricity with energy from the wind. Wind power produces no $CO_2$. | |

**FIGURE 2. Format and exact language used in the ranking task in part 3 of study 2.**

In section 4 of the survey, energy systems which dispose of $CO_2$ were presented. The concept of CCD was explained, with the following brief introduction of the oceanic and geological disposal:

"Systems are being developed that separate $CO_2$ from fossil fuel and dispose of it. Such systems would allow the world to continue to use coal and other fossil fuels while drastically reducing the amount of $CO_2$ that is released into the atmosphere. Large systems like this have already been built. Engineers believe that with further refinement such systems could allow us to continue to use coal to make electricity without releasing $CO_2$ into the atmosphere. The cost of the electricity from such a system might be about 50% higher.

One question is where should the $CO_2$ be put after it has been separated? Engineers are working to develop two possibilities of where they will pump it under very high pressure:

- Several thousand feet down into deep rock formations
- Into the deep ocean where it will dissolve in the water"

Respondents were then asked to separately rate the two disposal options on a seven-point scale with end points completely oppose and completely favor. This was followed by a list of reasons for opposing and favoring CCD, as raised by interviewees in study 1. The left column in Table 1 reproduces the precise wording of the questions. As before, respondents indicated their agreement with each reason on a seven-point scale.

Section 5 of the survey provided detailed, but separate, information about each potential disposal type, geological and oceanic, through a semi-technical discussion with diagrams (see Supporting Information). Figure 3 reproduces the descriptions of the risks that were provided for geological and oceanic disposal. Respondents were randomly assigned to one of two survey versions, counterbalancing the order in which they received this specific information about each CCD option.

Immediately following the description of each disposal type, respondents were again asked to indicate how much

**TABLE 1. Beliefs about General $CO_2$ Disposal, Sorted by Mean**

| survey text | mean[a] ($\sigma$) | corr coeff[b] ocean final | corr coeff[b] rock final |
|---|---|---|---|
| Before we start using $CO_2$ disposal, we need to know how well it will do what they say it will do. | 6.1 (1.4) | −0.35*** | −0.18* |
| Instead of $CO_2$ disposal, we should find ways to use the $CO_2$. | 5.7 (1.3) | −0.10 | −0.06 |
| One reason that $CO_2$ disposal is bad is that it may cause additional problems that we can't foresee at this time. | 5.6 (1.5) | −0.30*** | −0.26** |
| Instead of $CO_2$ disposal, we should develop other methods of reducing the $CO_2$ level in the atmosphere (such as getting energy from the sun and the wind). | 5.6 (1.6) | −0.15 | −0.13 |
| One reason that $CO_2$ disposal is bad is that it just puts the pollution somewhere else rather than solve the problem. | 5.4 (1.7) | −0.36*** | −0.44*** |
| Instead of $CO_2$ disposal, we should develop ways to reduce our use of energy. | 5.3 (1.8) | −0.21* | −0.25** |
| One reason that $CO_2$ disposal is bad is that it is tampering with nature. | 4.8 (1.9) | −0.42*** | −0.43*** |
| Protecting the environment should require sacrifice and changes in our life style, and $CO_2$ disposal does not do that. | 4.7 (1.9) | −0.30*** | −0.29*** |
| One reason that $CO_2$ disposal is good is that it should allow us to keep using the resources we are using now, while reducing the $CO_2$ level in the atmosphere. | 4.6 (1.6) | 0.16 | 0.24** |
| $CO_2$ disposal just sounds like a way for the coal and oil industries to resist change to using other methods of energy (such as from the sun and wind) and will help them to make more money. | 4.6 (1.9) | −0.28** | −0.31*** |
| One reason that $CO_2$ disposal is good is that it will give the world time to find better low costs ways to produce energy without adding $CO_2$ to the atmosphere. | 4.5 (1.7) | 0.08 | 0.31*** |
| One reason that $CO_2$ disposal is good is that it is going to make a better way of living for future generations. | 4.5 (1.6) | 0.20* | 0.25** |
| One reason that $CO_2$ disposal is good is that it will allow Third World countries to use coal for their industrial revolution the way we did. | 3.6 (1.8) | 0.03 | 0.02 |

[a] Scale from 1 = completely disagree to 7 = completely agree. [b] (*) $p < 0.05$; (**) $p < 0.01$; (***) $p < 0.001$.

**Partial text from *5.1 Deep rock formations*:**

The first set of risks involves the possibility that some of the $CO_2$ may leak out. If the leaks are very slow then the primary impacts will be:

- Damage to the roots of plants and to surface vegetation
- Release of at least some $CO_2$ back into the atmosphere

If leaks developed, it would probably be possible to move at least some of the $CO_2$ to another more secure location (in much the way that we remove natural gas and pipe it around).

Letting a little bit of $CO_2$ leak into the atmosphere would not be a serious problem, but if a lot of it were to leak out that would defeat the purpose of the system. In the worst possible situation, we could put a large quantity down in the ground and then later have a large amount leak back out.

We breathe small amounts of $CO_2$ all the time. However, in high concentrations $CO_2$ can kill you. Thus in the unlikely event that a fast leak were to develop, there would be a risk of death if the leak was not detected and if people and animals did not evacuate the area near the leak.

In addition to risks from leaks, there are some other kinds of risks. If we pump a lot of $CO_2$ into the ground it will increase the pressure underground. This may create a modest risk of small earthquakes, and could cause gentle ground motion that might damage buildings.

Finally, $CO_2$ can act as a solvent or weak acid. As a result, it may free up some contaminants that are bound to the rocks, such as heavy metals. In most cases they would remain thousands of feet below the surface, but there is a small chance they could move upward.

**Partial text from *5.2 Disposal of $CO_2$ in the deep ocean*:**

Putting $CO_2$ into the ocean will increase the $CO_2$ concentrations, first locally, then over the whole of the deep ocean. The water becomes more acidic with the increased $CO_2$ concentration. This would likely cause harm to microscopic animals, plants and fish near the point where the $CO_2$ comes out of the pipeline into the ocean. Once the $CO_2$ is well mixed into the water, the increase in acidity is less.

**FIGURE 3. Text used in part 5 of the survey instrument used in study 2 to describe the potential risks of deep geological disposal and deep oceanic disposal.**

they opposed or favored it, and how much they disagreed or agreed with a list of issues raised by study 1 participants, which may have affected their decision. Except for a question about geological storage causing seismic activity, the questions were analogous for the two types of storage.

Section 6 presented a final evaluation for the two types of disposal. Respondents were asked, for the third time, to rate how much they opposed or favored oceanic and geological disposal. A second ranking of their willingness-to-pay was also elicited for the nine methods of reducing $CO_2$ emissions by 50%.

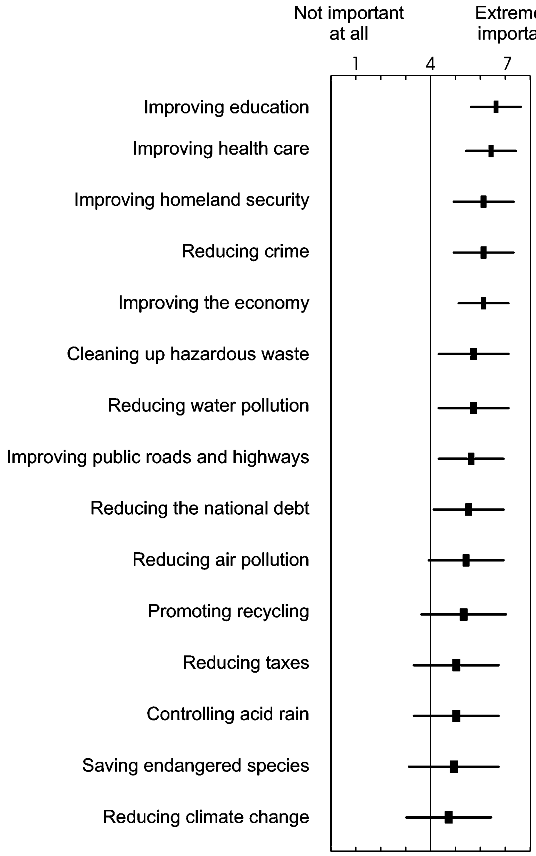


**FIGURE 4. Evaluation by respondents in study 2 of the importance of 15 social and economic issues on a seven-point scale which ran from 1 = not important at all to 7 = extremely important. Short heavy bars in the center report standard errors of the mean. Long thin bars report standard deviation. Issue descriptions exactly reproduce the language from part 2b of the survey instrument.**

Section 7 of the survey addressed general environmental issues, using Dunlap et al.'s 15-item New Ecological Paradigm Scale (NEPS) (*19*). Section 8 asked for demographic information such as age, gender, and education level.

The judgment and decision-making literature tends to use convenience samples (*20*), because it is assumed, and typically found, that the cognitive processing of information is relatively stable across different populations. We followed this convention. A convenience sample for this study was recruited through community organizations in the greater Pittsburgh, PA, area, such as church-based social groups and parents of children on athletic teams. A total of 126 people, with an average age of 52, completed the survey, 64% of who were women, and 55% of who had completed at least a Bachelor's degree. Completion of the survey took about 40 min, and the organizations were compensated $15 for each participant.

## Results from Study 2

Respondents showed relative agreement with the idea that carbon release leads to climate change ($4.6 \pm 0.16$) and that the government should ($4.7 \pm 0.17$) and will ($4.0 \pm 0.16$) take action, on a seven-point scale, where 1 is completely disagree and 7 is completely agree. The numbers inside the parentheses are the means and standard errors of the mean.

Relative to other current social and economic issues, respondents reported greater concern about issues related to people than the environment, with climate change having their least concern, as displayed in Figure 4. This is consistent with previous findings among U.S. respondents (*7*−*9*). Respondents who rated climate change as more important reported higher agreement with believing increasingly higher levels of $CO_2$ resulting in climate change ($r = 0.376$, $p = 0.000$), suggesting relatively consistent beliefs across measures in this study.

**Acceptability of Carbon Disposal.** Respondents' judgments of the acceptability of oceanic and geological $CO_2$ disposal were measured by using both rating scales and rankings of willingness-to-pay for different energy options. Within-subject *t*-tests revealed no significant difference between ratings of oceanic ($3.4 \pm 0.17$) and geological disposal ($3.8 \pm 0.17$) before receiving more specific information about each, with $t(125) = 1.5$, $p = 0.13$. However, after respondents received information, their ratings revealed more opposition to oceanic disposal ($2.5 \pm 0.15$) relative to geological disposal ($3.3 \pm 0.17$), with $t(122) = 4.3$, $p = 0.000$. The results are illustrated graphically in Figure 5A.

Figure 5B reports mean ranks of respondents' willingness-to-pay for the range of alternative carbon management strategies provided before (left) and after (right) they received information about carbon disposal technology. Even before information, mean ranks for both CCD options were systematically the lowest of all mitigation options presented (Figure 5B). As with the ratings, initial rankings of oceanic and geological disposal were not significantly different (Wilcoxon's paired rank $z = -0.91$, $p = 0.37$), but final rankings showed significantly less acceptance of oceanic than of geological disposal (Wilcoxon's paired rank $z = 2.27$, $p = 0.023$).

**Implementation of $CO_2$ Disposal.** Respondents' mean agreement with interviewees' statements about the general concept of $CO_2$ disposal are reported in Table 1. As in the study 1 interviews, respondents wanted the efficacy of disposal to be better demonstrated before it is adopted. They seemed uncomfortable with a process that treats $CO_2$ as waste and concerned that unintended consequences may develop in the future. They did not view the fact that CCD would allow extensive use of coal in the developing world to be a compelling argument in its favor. Almost all of these statements were sensibly correlated with respondents' final ratings of both CCD options, suggesting the robustness of study 1 results.

Figure 6 shows the results for belief statements that were presented with analogous wording for the geological and oceanic CCD options. With the exception of respondents' views about government research investments, all respondents' belief statements were sensibly correlated with their final assessments of oceanic and geological disposal (not shown). The absolute value of these correlation coefficients ranged from 0.41 to 0.60 for the correlations between statements about geological disposal to its final rating and from 0.37 to 0.65 for the oceanic comparisons, with all having $p = 0.000$.

The means of analogous statements revealed consistently more favorable beliefs about geological disposal than about oceanic disposal, with most showing significant paired *t*-test results. For example, respondents believed that oceanic disposal would be more likely to affect animals after it mixes in the ocean than geological disposal would affect animals if the $CO_2$ leaked to the surface ($t(124) = 3.79$, $p = 0.000$). Furthermore, respondents believed that oceanic disposal would be more likely to have serious unintended consequences in the long run ($t(124) = 3.45$, $p = 0.001$) and have negative impacts on animals living deep under the surface ($t(124) = 7.94$, $p = 0.000$). Moreover, the ocean was seen as a less appropriate place to put waste of any kind ($t(124) = 5.41$, $p = 0.000$). Respondents also believed that oceanic disposal could not be made as safe as most other technologies ($t(122) = 3.30$, $p = 0.001$).

**Attitudes about Humans and Nature.** Internal consistency of the 15 items of the NEPS (presented in Table 2) was

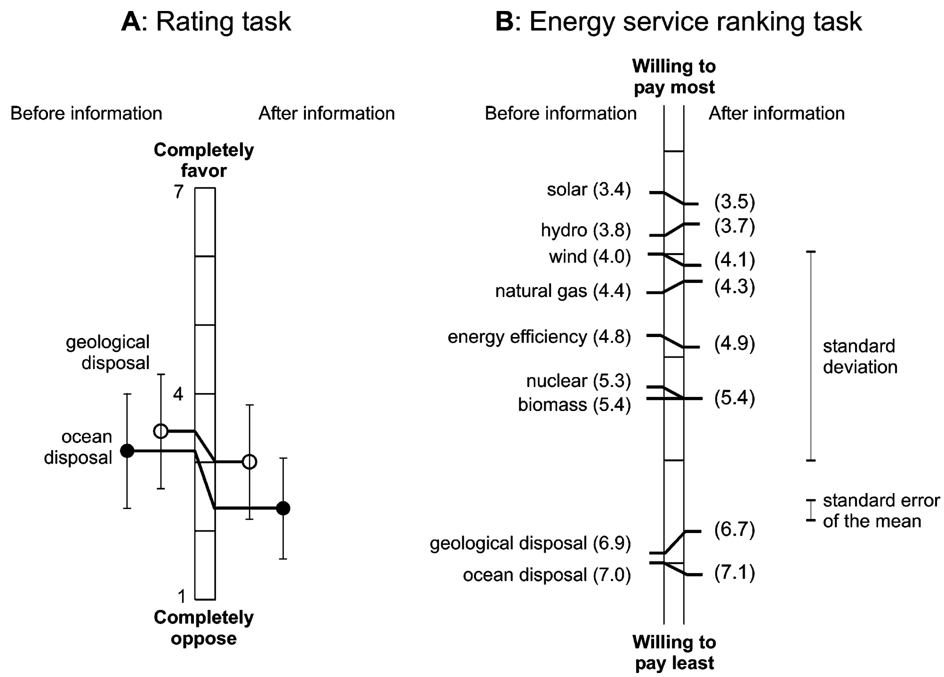


**FIGURE 5. (A) Mean ratings of geological disposal (open circles) and ocean disposal (solid circles) before (left) and after (right) receiving information about the technologies for the respondents of study 2. Circles are mean rating scores and are approximately the size of the standard error of the mean. Bars are standard deviations. (B) Mean ranks, in terms of willingness-to-pay, of nine options by which respondents' electricity supplier might achieve a 50% reduction in $CO_2$ emissions. The left column shows the ranking before information, and the right shows rankings after information. Ranks for all of the nondisposal options are significantly different from the ranks of the disposal options. Ranks for the two disposal options are not significantly different from each other before respondents received information but become significantly different after receiving information.**

**TABLE 2. Responses to the NEPS (New Ecological Paradigm Scale) Sorted by Mean**

| statement | code[a] | mean[b] | s |
|---|---|---|---|
| Despite our special abilities, humans are still subject to the laws of nature. | + | 6.1 | 1.2 |
| The earth has plenty of natural resources if we can just learn how to develop them. | − | 5.4 | 1.6 |
| When humans interfere with nature it often produces disastrous consequences. | + | 5.2 | 1.8 |
| Balance of nature is very delicate and easily upset. | + | 5.1 | 1.7 |
| Plants and animals have as much right as humans to exist. | + | 5.0 | 2.0 |
| Humans are severely abusing the environment. | + | 4.9 | 2.0 |
| If things continue on their present course, we will soon experience a major ecological catastrophe. | + | 4.4 | 1.9 |
| The earth is like a spaceship with very limited room and resources. | + | 4.3 | 2.0 |
| Human ingenuity will ensure that we do NOT make the earth unlivable. | − | 4.0 | 2.0 |
| We are approaching the limit of the number of people the earth can support. | + | 3.8 | 2.1 |
| The so-called "ecological crisis" facing humankind has been greatly exaggerated. | − | 3.8 | 2.0 |
| Humans were meant to rule over the rest of nature. | − | 3.8 | 2.1 |
| Humans will eventually learn enough about how nature works to be able to control it. | − | 3.6 | 1.9 |
| Humans have the right to modify the natural environment to suit their needs. | − | 3.5 | 1.9 |
| The balance of nature is strong enough to cope with the impacts of modern industrial nations | − | 3.2 | 1.8 |

[a] Agreement with the eight "+" items and disagreement with the seven "−" items indicate pro-NEP responses. $N = 120$. [b] Scale from 1 = completely disagree to 7 = completely agree.

evaluated via principal components analysis and Cronbach's α reliability. The unrotated factor analysis shows that a dominant construct (eigenvector of responses) explains 32% of the variance, compared to only 11% from the second factor, and a pattern of eigenvalues of 4.8, 1.7, 1.6, and 1.0. From the reliability analysis, the corrected item-total correlations range from a low of 0.30 to a high of 0.67, with a Cronbach's α of 0.84, and deleting any of the 15 items lowers the value of α. These internal consistency results are similar to those of Dunlap et al. (*19*). To form a single NEPS measure, the mean score across these 15 items for each respondent was calculated such that higher values indicate a more pro-

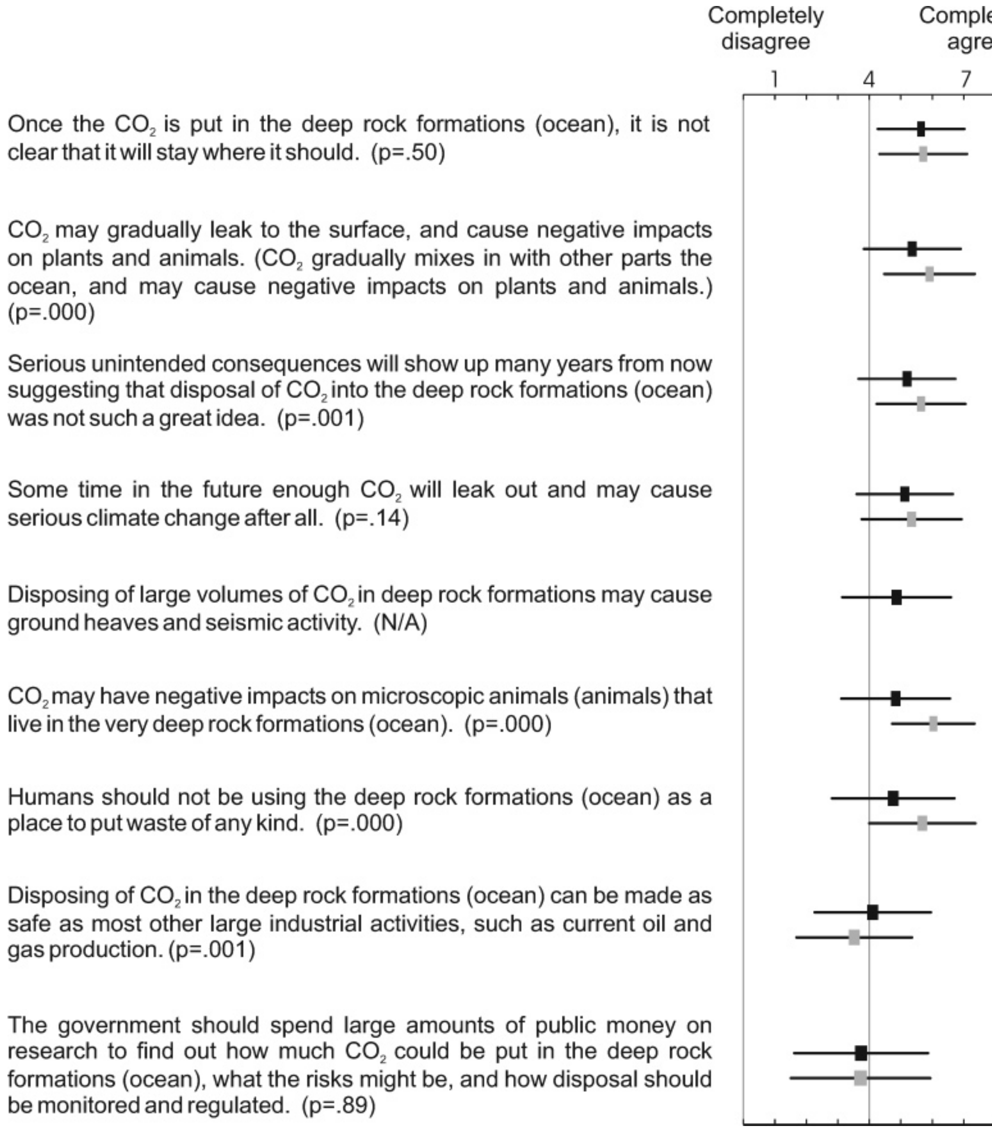


**FIGURE 6. Summary of responses in study 2 to a series of questions which asked respondents to make judgments about carbon disposal on a seven-point scale that ran from 1 = completely disagree to 7 = completely agree. Dark upper bars are for geological disposal; lighter lower bars are for ocean disposal. Short heavy bars in the center report standard errors of the mean. Longer bars report standard deviation. The question about ground heave and seismic activity was only asked for the case of geological disposal. Descriptions exactly reproduce the language from part 5 of the survey instrument.**

environmental view. The resulting mean score across respondents was 4.50, with a standard error of the mean of 0.09. The NEPS measure was significantly correlated with the final ratings of oceanic ($r = -0.399$, $p = 0.000$) and geological disposal ($r = -0.262$, $p = 0.003$), suggesting that more pro-environmental respondents gave lower ratings to the disposal options.

## Discussion

To date, the U.S. public is largely unaware of technologies for carbon capture and disposal. In a recent web-based survey, Curry and Herzog (*14*) found that only about 2.5% of their U.S. respondents had previously heard of carbon sequestration in the past year, and about 4% had heard of carbon capture and storage in the past year (1200 paid responses obtained out of 1700 surveyed). In a sample of 112 Dutch lay respondents, Huijts (*21*) found that 85% of her respondents reported little or no prior knowledge of carbon capture and disposal, although only 5% reported they had never heard of the topic. Gough et al. (*11*) report that none of the 19 respondents in two focus groups conducted in the U.K. had previously heard of the technology (group 1 consisted of 10 postgraduate students with a scientific background; group 2 consisted of nine members of the general public who were friends of the facilitator).

Thus, the first challenge in studying likely public perception is that respondents must be informed about the technology before they can answer questions. While we and others have tried to provide a balanced briefing, it is important to remember that future public reactions will result from a very different learning process, spread out over a much longer period of time, and probably dominated by messages from advocates and opponents. Thus, the public's decision context will be rather different from the ones we have created in our studies.

Because mental model interviews impose relatively little framing on an issue, allowing respondents to express views in their own framing, Study 1 allowed us to identify two issues that might not have been apparent if we had started immediately with a closed-from survey of our own design.

First, as noted previously, interviewees exhibited a strong desire to frame decisions about whether to engage in carbon capture and disposal in the broader context of a consideration of alternative strategies for carbon management. Attitudes toward carbon capture and disposal will no doubt evolve in parallel with a growing understanding of those alternatives, in much the same way that they have already evolved within portions of the environmental NGO community (*22*−*24*). At the moment, however, the U.S. public appears to be poorly informed about the relative cost and feasibility of alternatives such as wind, solar, and nuclear. Moreover, their initial dislike for oceanic carbon sequestration relative to other carbon management options seems to increase with more detailed information. Note that providing additional information about an unfamiliar technology does not always lead to a decrease in ratings of acceptability. For example, Maharik found more positive attitudes toward using nuclear energy sources in space after presenting additional information (*25*).

While we made special efforts to present neutral information, media attention about CCD may be less balanced, emphasizing extreme views and the sensational such as the disasters at Lakes Nyos and Monoun in Cameroon (*26*). Second, there appears to be general unease with a strategy that reminds many of what Tarr (*27*) has termed "the search for the ultimate sink", the oft-repeated story that first we put it here but it caused problems, so then we put it there where it also caused problems, and so on. Whether this reaction is technically legitimate is an open question that cannot be resolved without further research and field experience. However, it does appear to be a framing that will color the perceptions of many members of the public and which opponents of the technology will likely be able to use to significant effect.

Our results suggest that deep geological disposal may receive more public support than deep oceanic disposal. This result emerged strongly in the comments of respondents in study 1 and is reinforced in the systematic differences observed in the specific evaluative questions in study 2. It is still apparent, though more muted, in the ranking of alternative management technologies.

In study 2, respondents who were more pro-environmental (as indicated by their NEPS scores) were less approving of either type of carbon disposal. Our sample was older and better educated than the U.S. population, with a median age of 48 versus 35 for the United States (*28*), and the proportion of those with a B.S. was 55% versus 24% (over 25) in the U.S. population (*29*). Because education is positively and age negatively related to NEPS scores (*18*), we cannot draw definite conclusions about how the general public will rate carbon disposal technologies. Yet, study 2 suggests that, as they receive more information, their *relative* preference may be for geological disposal over oceanic disposal.

These results for the acceptability of geological disposal are 15−20% lower than those obtained by Huijts (*21*) in her sample of 112 Dutch lay respondents. For example, recalculating mean responses to Huijts' five-point scale to a seven-point scale, the Dutch respondents' mean rating of "the suitability of [deep geological] carbon dioxide storage as a solution to [the] climate problem" was 4.3, with the "benefits for society" of this technology rated as 4.6. These results are probably not surprising given the much higher level of concern about global warming in Dutch society.

From their much smaller focus group studies in the U.K., Gough et al. (*11*) conclude that "in principle, carbon capture and storage may be seen as an acceptable approach as a bridging policy while other options are developed". They also indicate that geological disposal was seen as more acceptable than oceanic disposal.

On the basis of these earlier studies, one might have anticipated that carbon separation with geological sequestration will be acceptable to the U.S. public. But the results displayed in Figure 5B, in which even nuclear power ranks as a more preferred option, should be enough to give one pause, and at a minimum, suggest that the way in which the public becomes informed about this technology, the way the technology itself performs, and the way in which the public debate gets framed could dramatically shape future public perceptions.

In response to presentations of our work at professional meetings, some proponents of the technology have argued that the apparently weak support for the technology reflected in the results reported in Figure 5B arises from the fact that we chose to use the word "disposal" rather than "sequestration" or "storage" in study 2. Given a careful reading of the transcripts in study 1, we doubt this is the case. While framing effects can be important, we believe that respondents understood very clearly what was entailed, with many talking in terms of "dumping" and "waste" even when the concept was introduced to them using the more benign sounding "sequestration". Giving it different names, such as "sequestration" or "storage" or even "carbon dumping" as Greenpeace has sometimes described it, will probably have little impact on perceptions in the long run as people come to understand what the technology entails. However, hope for simple linguistic fixes springs eternal within the community of technology proponents, so we can expect ongoing study and debate on this issue.

To prevent dramatic climate change, it will likely be necessary to reduce $CO_2$ emissions by more than a factor of 2 below business-as-usual over the next 50 years. It seems likely that $CO_2$ capture and storage technologies can significantly reduce the cost of achieving this objective, so there may be a strong motivation for employing these technologies. The results of this study suggest that, at best, the public is likely to view this technology with mixed feelings. High levels of public acceptance will almost certainly require: broader public understanding of the need to limit carbon dioxide emissions and of the costs and risks of alternative options for carbon management; a much stronger scientific understanding and a larger empirical base for claims about the likely efficacy and safety of disposal; and an approach to public communication, regulation, monitoring, and emergency response that is open and respectful of public concerns. An open and inclusive approach does not guarantee success. However, an arrogant approach such as the one adopted in the past by the industries responsible for nuclear power and genetically modified crops could create a level of public distrust that makes the widespread implementation of carbon sequestration in the United States difficult, if not impossible.

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## Supporting Information Available

The survey and the interview. This material is available free of charge via the Internet at http://pubs.acs.org.

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