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Public support for carbon dioxide removal strategies: the role of tampering with nature perceptions

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Abstract

Carbon dioxide removal (CDR) describes a suite of controversial approaches to mitigating climate change that involve removing existing carbon dioxide from the atmosphere. Through an online survey experiment with US adults ($N = 980$), we examine three factors that may shape public support for different types of CDR strategies: (1) perceptions that CDR tampers with nature, (2) individual-level variation in the degree to which people are uncomfortable with activities that tamper with nature, and (3) information about the risks and benefits associated with each CDR strategy. Using a moderated mediation analysis, we find that support for different CDR strategies is, in part, a function of how much each strategy is perceived to tamper with nature. Support for bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) was lower than support for afforestation and reforestation (AR), as BECCS and DAC were perceived to tamper with nature more. These effects were particularly strong among individuals generally opposed to the idea of humans interfering with natural processes. Moreover, we find evidence that describing the risks and benefits of each CDR strategy dampens support; for AR and BECCS, this effect was again mediated through perceptions of tampering, while for DAC, the effect of describing these tradeoffs appeared to operate independently of perceived tampering. We conclude that policymakers and science communicators need to be mindful of how CDR strategies are described to the public, as perceptions of tampering with nature may be an important driver of their acceptance.

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1 Introduction

Limiting climate change to 2 °C may be impossible without reducing the current concentration of greenhouse gases in the atmosphere (van Vuuren et al. 2013; IPCC 2014; Smith et al. 2016). Toward this end, researchers are exploring a number of strategies involving carbon dioxide removal (CDR). The goal of CDR—a form of geoengineering—is to create "negative emissions" by extracting existing carbon dioxide (CO_2) from the atmosphere and storing it in a manner that prevents it from re-entering the carbon cycle. The mechanisms for accomplishing this vary by CDR strategy and consequently entail different tradeoffs (Meadowcroft 2013; National Research Council 2015). Some strategies, for example, capture and store CO_2 in the biomass of trees or crops, thereby requiring massive land areas that may conflict with other land uses. Other strategies store CO_2 deep underground in geological formations, a process that has uncertain long-term consequences (National Research Council 2015). All CDR approaches have in common the human alteration or enhancement of some natural process—whether chemical or biological—to capture and store CO_2.

Despite the potential societal implications of CDR, only a small body of work has explored public perceptions of the risks and benefits of these technologies (Corner et al. 2013; Wright et al. 2014; Corner and Pidgeon 2015; Braun et al. 2017). Further, most social science research on geoengineering has disproportionately focused on perceptions of solar radiation management (for a review see Cummings et al. 2017), despite considerable uncertainty surrounding its efficacy. No study, to our knowledge, has compared support for the three CDR strategies most commonly discussed in climate mitigation scenarios: afforestation and reforestation (AR), bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC) (Clarke et al. 2014). Understanding which of these CDR strategies are seen as most acceptable to the public—and why—may provide valuable inputs for policy decisions and contribute to productive deliberative engagement around CDR deployment.

In this paper, we explore three factors that may shape public acceptance of AR, BECCS, and DAC: (1) perceptions that the CDR strategy tampers with nature, (2) individual-level variation in the degree to which people are generally uncomfortable with human activities that tamper with nature, and (3) information about the tradeoffs imposed by the CDR strategy. While several of these concepts have been examined in prior work, this paper presents one of the first efforts to experimentally compare support across multiple CDR strategies and to empirically test the nature of the psychological mechanisms that determine it.

1.1 Tampering with nature

Perceptions of risk are a key factor shaping public opinions of new technologies. Considerable research has demonstrated that technologies are perceived to be riskier—and therefore less acceptable—the more their consequences are "unknown" (because the effects are unobservable or delayed) and the more they provoke a sense of "dread" (because the negative consequences are potentially catastrophic and uncontrollable) (Slovic 1987, 2000; Bassarak et al. 2017). Other work suggests that "tampering with nature" may be another important category of perceived risk (Raimi et al. under review; Sjöberg 2000). That is, the more a technology is perceived to be unnatural or to alter natural processes in some way, the riskier it seems. Indeed, concerns about tampering with nature have been correlated with opposition to a variety of technologies including nanotechnology (Vandermoere et al. 2010), synthetic biology (Dragojlovic and Einsiedel 2013a, b), and genetically modified foods (Tenbült et al. 2005).

Whether something is perceived to tamper with nature is closely intertwined with how people conceptualize "nature" and society's relationship to it. The concept of nature is complex and dynamic, varying within and across cultures as well as over time (for an expansive discussion see Corner et al. 2013). In Western societies, nature has traditionally been viewed as an entity distinct from humans, to be manipulated and controlled for human benefit (Scott et al. 2018). Other representations characterize nature as fragile and "vulnerable" or portray it as a "powerful and vengeful" force (Hansen 2006, pp. 813–814). Hansen (2004, 2006) has argued that these discourses inform the meaning that people assign to human-nature interactions and evaluations of whether they are good or bad. Viewing nature as "good, pure, … and balanced," for example, suggests that nature is "best left to its own devices…[to] 'sort itself out'" (Hansen 2006, p. 813). This perspective complements research showing that people prefer "natural" over manmade products, environments, and outcomes (Rozin et al. 2004; Siegrist and Sütterlin 2014; Beute and de Kort 2018). Other representations of nature portray it as mysterious and powerful. Such depictions suggest that there is great folly in humans attempting to tamper, tinker, or interfere with how nature operates, as the consequences may be unpredictable and ruinous (Hansen 2006, p. 814). On the other hand, those endorsing power and dominion over nature may have a much more positive view of the technologies that enable such tampering (Dreezens et al. 2005).

Several studies suggest that concerns about tampering with nature may be especially relevant to understanding public support for (or opposition to) CDR and geoengineering more generally. For example, in focus-group studies of geoengineering, concerns about manipulating nature and provoking unintended consequences are top-of-mind associations (Corner et al. 2013; Wibeck et al. 2015). Other studies reveal that perceiving a technology to tamper with nature is a strong—if not the strongest—negative predictor of acceptance for solar radiation management (Mercer et al. 2011; Visschers et al. 2017; Braun et al. 2017), carbon capture and storage sub-seabed, and afforestation (Braun et al. 2017).

Not all types of CDR are likely to provoke the same level of perceived tampering, however. People may be more amenable to CDR the more natural it seems. Afforestation and reforestation, in particular, seems to enjoy greater support than other climate change solutions (Braun et al. 2017)—perhaps because this strategy relies on biological processes already found in nature. In line with this notion, Corner and Pidgeon (2015) found that describing solar radiation management and direct air capture as analogous to natural processes (volcanic eruption and trees, respectively) led people to be more supportive of geoengineering as a response to climate change than when those analogies were not used.

Despite the prominence of tampering with nature concerns in studies of geoengineering techniques, no research to date has looked at the role of this variable in explaining how public support may differ across specific types of CDR. To bridge this gap in the literature, we conducted an online study to experimentally compare three types of CDR commonly discussed in climate mitigation scenarios: (1) afforestation and reforestation (AR), (2) bioenergy with carbon capture and storage (BECCS), and (3) direct air capture (DAC) (see Electronic Supplementary Material for more information about each). Given prior research on geoengineering strategies more broadly, we hypothesized the following:

H1a: Support for CDR will differ by CDR strategy.

H1b: The effect of reading about a specific CDR technique on support for that strategy will be mediated by perceptions that it tampers with nature. Specifically, the more a CDR technique is perceived to tamper with nature, the less we expect people to support it (Fig. 1a). Among the three CDR strategies studied, we expect support for AR to be the greatest as it will be perceived to tamper with nature the least.

While many studies point to the importance of "tampering with nature" as a factor in technology acceptance, it is unclear how much these effects are driven by individual differences. Prior research suggests that people vary in their comfort with human activities that interfere with nature (Raimi et al. under review; Corner et al. 2013). This may be especially true among people who see nature as sacred (Dragojlovic and Einsiedel 2013b), who object to

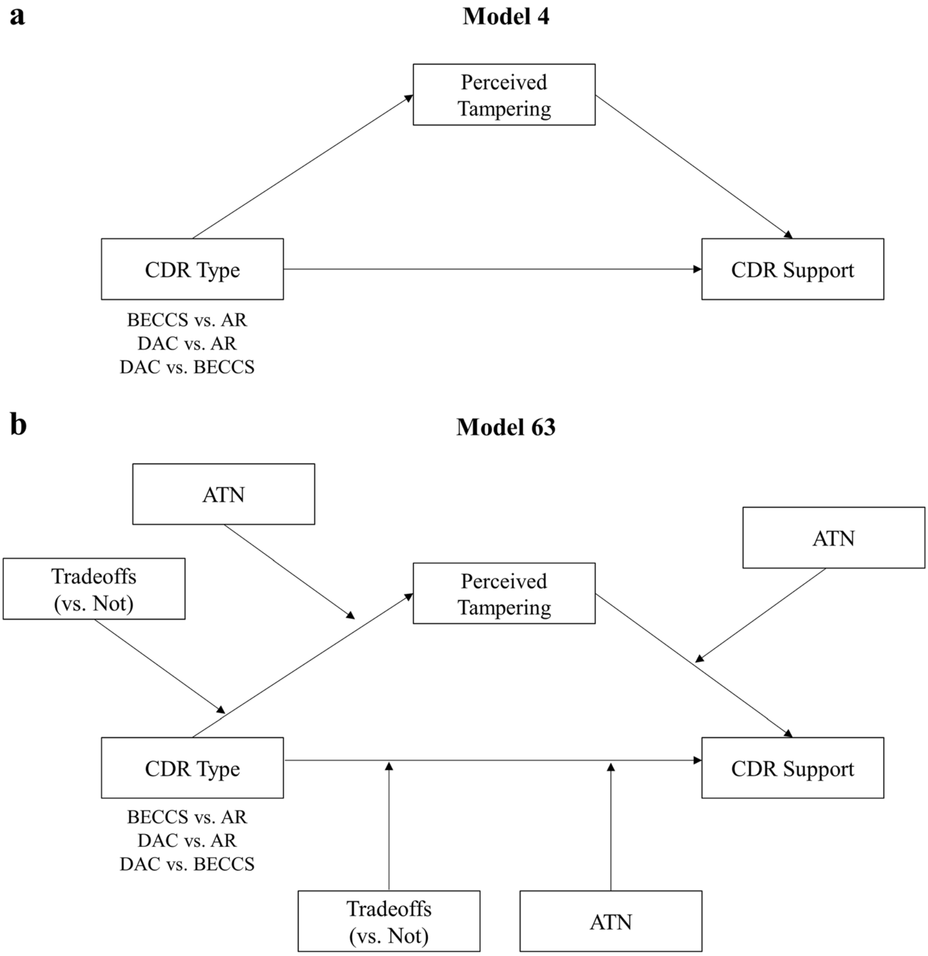

Fig. 1 Conceptual diagrams of mediation models. **a** Hayes Model 4: mediation of the effects of learning about different CDR strategies on CDR support through perceived tampering with nature. **b** Hayes Model 63: moderated mediation model to test whether the indirect effect of CDR type is conditional on aversion to tampering with nature (ATN) and on whether the tradeoffs associated with the CDR strategy are described

the idea of humans “playing God,” (Vandermoere et al. 2010; Hartman 2017), or who have a preference for what is perceived to be “natural” or pure (Rozin et al. 2004; Rudski et al. 2011; Li and Chapman 2012; Siegrist and Sütterlin 2014).

Based on these findings, we expect people to be less supportive of CDR the more they are generally averse to activities that tamper with nature. But, it is unclear how such aversion operates. Do people who are more averse to tampering with nature have a greater proclivity to see human activities as tampering? Or does their discomfort with tampering primarily lead them to be less supportive of activities that others also consider to tamper with nature? Could both mechanisms be at play? These questions informed the following hypotheses (Fig. 1b):

> H2: General aversion to tampering with nature (ATN) will moderate the relationship between CDR type and perceptions that each CDR strategy tampers with nature. Specifically, we expect the effect of learning about CDR on perceptions of tampering to be stronger among people who are more averse to human activities that tamper with nature.
> H3: ATN will moderate the relationship between perceived tampering and CDR support such that perceptions that CDR tampers with nature will have a stronger, negative effect on CDR support among individuals who are more averse to tampering.

1.2 Providing information about risks and benefits

Past research indicates that familiarity with CDR and other types of geoengineering strategies is generally low (Mercer et al. 2011; Corner et al. 2012; Scheer and Renn 2014; Pidgeon and Spence 2017; Cummings et al. 2017). This naturally raises the question: do perceptions of CDR change as more information is provided? Some research suggests that opinions will shift as people learn more about the risks and benefits. For example, Sütterlin and Siegrist (2017) found that individuals who learned about the uncertainties and risks associated with solar radiation management perceived the technology to have fewer benefits and greater risks as compared to individuals who only learned basic facts about the technology. Braun et al. (2017) similarly compared experimental conditions where participants read either a basic description of a climate change solution (solar radiation management, afforestation, or carbon capture and storage sub-seabed) or that basic description followed by a balanced discussion of the technology’s benefits and risks. In all cases, providing the additional information lowered public acceptance of the technology. Based on the above studies, we hypothesize the following:

> H4: Describing the tradeoffs associated with CDR technologies will decrease support for these strategies.

We further examine whether this hypothesized effect operates through changes in perceived tampering. As several CDR strategies have the potential to threaten existing land uses or ecosystems, providing information about these uncertainties may heighten perceptions that these technologies tamper with nature and thus lower support for them. However, not all tradeoffs associated with CDR involve altering nature, and the tradeoffs specific to each CDR strategy vary considerably. We therefore explore the following questions:

RQ1: Will learning about the pros and cons (i.e., tradeoffs) associated with CDR moderate how much CDR is perceived to tamper with nature and, subsequently, influence support for it?

RQ2: Are the effects of learning about tradeoffs on perceptions of tampering the same for all types of CDR?

2 Methods

2.1 Setting and participants

We tested our hypotheses and research questions using an online survey experiment fielded with US adults in July 2017. At the time of the study, CDR had received little attention in the US news. Most prior news coverage coincided with the release of scientific reports, including a National Academies of Sciences report on CDR in February 2015 and the "Summary for Policymakers" report released as part of the Intergovernmental Panel on Climate Change's (IPCC) fifth assessment report in 2013. Even then, most stories appeared as special features in select news outlets, not as headline news. As such, study participants were unlikely to have much familiarity with CDR or recent exposure to information about it (Feldpausch-Parker et al. 2015).

Survey respondents ($N = 1978$) were recruited by Survey Sampling International, with quotas used to approximate the age, gender, and education distributions found in the US Census. Originally, 1317 individuals were assigned to participate in the present experiment.[1] Those who dropped out of the survey ($n = 113$), failed both of the attention checks ($n = 95$), missed the reading comprehension question ($n = 99$), or indicated that we should not use their data ($n = 31$) were removed from the data set, leaving a final sample of 980. The sample was 48% female (52% male), with an average age of 45 ($SD = 15.33$) and a median education level of associates degree.

2.2 Procedure

Participants were randomly assigned to one of six experimental treatments according to a 3 (CDR type) × 2 (tradeoffs vs. no tradeoffs) factorial design. All participants were shown a mock Associated Press article that described the basic concept of carbon dioxide removal followed by a description of either AR, BECCS, or DAC and an illustration of the assigned CDR strategy. For half of participants, the article continued to a second page that described some of the key tradeoffs associated with that particular CDR strategy, including the cost per ton of stored CO_2, benefits beyond CO_2 capture, and potential concerns regarding either land use conflicts or the difficulty of deploying the technology at scale. This "tradeoffs" condition concluded with a graphic that highlighted four pros and four cons of the strategy (all articles are available in the Electronic Supplementary Material). Our objective was to present a balanced and neutral account of the main considerations for implementing each CDR strategy. Following exposure to the article, participants completed a reading comprehension check[2] and the measures described below.

[1] The other 661 participants recruited for the survey were assigned to an experimental condition that is irrelevant to the research questions in the present study.

[2] Participants were asked a multiple-choice question, "According to the article you just read, what is the goal of carbon dioxide removal?" Only those who correctly answered "To slow or reverse climate change" were included in the data set.

2.3 Measures

Support for carbon dioxide removal Participants indicated on 7-point semantic differential scales whether they thought "Using [the described CDR strategy] to combat climate change would be…" *A good idea/A bad idea* (reversed), *Impractical/Practical*, *A smart investment/A dumb investment* (reversed), *Foolish/Wise*, *and Acceptable/Unacceptable* (reversed). Items were averaged to form a scale of CDR support, with higher scores indicating greater support ($M = 5.06$, $SD = 1.43$, Cronbach's $\alpha = 0.95$).

Perceptions of tampering with nature Participants rated how much the CDR strategy they read about "is natural" (reversed), "tampers with nature," and "disturbs the natural order" from 1 = *Strongly disagree* to 7 = *Strongly agree*. We averaged these items to form a three-item scale ($M = 3.73$, $SD = 1.35$, $\alpha = 0.77$).

Aversion to tampering with nature Participants rated their agreement with 18 statements that reflected general discomfort with the idea of tampering with nature (from 1 = *Strongly disagree* to 7 = *Strongly agree*). Based on factor analysis and separate analyses reported elsewhere (Raimi et al. under review), we collapsed five of these items to form an Aversion to Tampering with Nature (ATN) scale: "People who push for technological fixes to environmental problems are underestimating the risks," "People who say we shouldn't tamper with nature are just being naïve" (reversed), "Human beings have no right to meddle with the natural environment," "I would prefer to live in a world where humans leave nature alone," and "Altering nature will be our downfall as a species," ($M = 4.48$, $SD = 1.05$, $\alpha = 0.78$).

Control variables In addition to age, gender, and education, we controlled for political ideology, which has been widely shown to strongly correlate with beliefs about climate change and support for proposed solutions (Feygina et al. 2010; McCright and Dunlap 2011; Campbell and Kay 2014; Kahan et al. 2015). Political ideology was measured from 1 = *Very liberal* to 7 = *Very conservative* ($M = 3.77$, $SD = 1.67$).

Familiarity with CDR At the end of the survey (after exposure to the mock news article), participants were asked, "Before taking this study, how familiar were you with carbon dioxide removal strategies?" from 1 = *Not at all (never heard of it before)* to 5 = *Very familiar* ($M = 1.83$, $SD = 0.98$). In line with our expectations, the vast majority of respondents were not familiar with CDR, with 47.6% of respondents saying they had never heard of it and 29.6% reporting being only "a little" familiar with it.

2.4 Analytic strategy

We used two-way analysis of covariance (ANCOVA) to examine support for CDR by CDR strategy (H1a) and tradeoffs condition (H4). All subsequent analyses were conducted using the PROCESS macro for SPSS (Hayes 2013), which uses a bootstrapping method to generate bias-corrected confidence intervals for the indirect effects. We constructed two models, beginning with a simple mediation analysis (PROCESS Model 4) to examine the relationship between learning about specific CDR strategies, perceptions that the strategies tamper with nature, and CDR support (H1b, RQ1; Fig. 1a). The second model (PROCESS Model 63) tested whether these indirect effects were conditional on aversion to tampering with nature (ATN) (H2 & H3; Fig. 1b), and whether the tradeoffs of the CDR strategy were described (RQ2: Fig. 1b). In order to compare each pair of CDR strategies, we ran each model twice using a different set of dummy variables. In the initial analysis, we compared BECCS and DAC to AR using indicator coding. In the second analysis, we treated BECCS as the reference category.

3 Results

3.1 H1a and H4: relative support for CDR strategies

We first examined whether support for CDR varied by strategy type, using two-way ANCOVA with CDR type (AR, BECCS, or DAC) and tradeoff condition (No, Yes) as predictors. Age, gender, education, political ideology, and ATN were included as covariates. Figure 2 summarizes the results. In line with H1a, there was a significant main effect for CDR type ($F(2, 969) = 64.66$, $p < 0.001$, $\omega^2 = 0.04$), with participants more supportive of AR than either BECCS or DAC (both ps < 0.001). No significant differences were found between BECCS and DAC ($p = 1.00$). We also observed a significant main effect for the tradeoffs condition ($F(1, 969) = 45.76$, $p < 0.001$, $\omega^2 = 0.11$), such that learning about the tradeoffs associated with CDR dampened support, as predicted by H4. We found no evidence of an interaction between CDR type and tradeoffs ($F(2, 969) = 0.64$, $p = 0.529$).

3.2 H1b & RQ1: perceptions of tampering with nature as a mediator

To test whether perceptions of tampering with nature explained observed differences in CDR support, we used PROCESS Model 4 (Fig. 1a) with 10,000 bootstrap iterations, controlling for age, gender, education, political ideology, and ATN. Table 1 summarizes the OLS regression results. Looking first at the direct effects of CDR type on perceptions that each strategy tampers with nature, we find that AR was perceived to tamper less than either BECCS or DAC, supporting H1b. No differences were found between DAC and BECCS ($b = -0.15$,

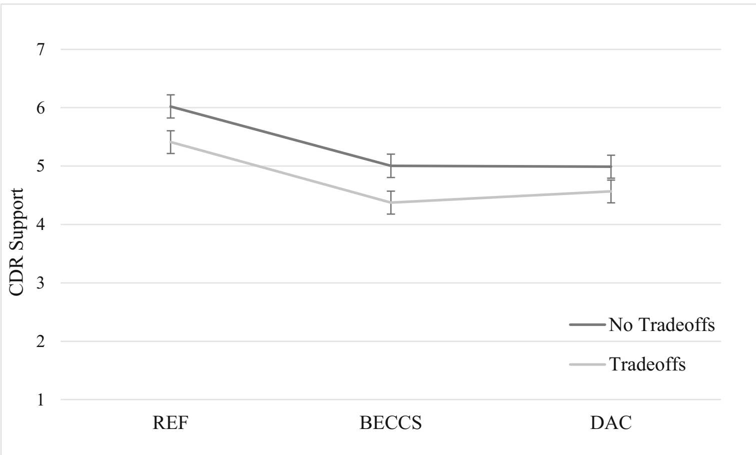

Fig. 2 Estimated marginal means for CDR support as a function of message condition. Error bars represent 95% confidence intervals

SE = 0.10, *p* = 0.108, 95% CI [− 0.34, 0.03]). We additionally observed a significant positive effect for the tradeoffs condition, suggesting that on average, learning about the tradeoffs associated with CDR increases perceptions of tampering with nature (RQ1).

In line with H1b, reading about BECCS and DAC had significant, negative indirect effects on support for CDR through tampering with nature, relative to learning about AR (Table 1). That is, support for BECCS and DAC was lower than support for AR, because BECCS and DAC were perceived to tamper with nature more. Even when controlling for this mediation, however, learning about BECCS and DAC significantly and negatively predicted CDR support, suggesting that factors other than perceptions of tampering reduce support for these strategies as compared to AR. When comparing DAC to BECCS, the indirect effect was not significant.

3.3 Moderated mediation model

The simple mediation analysis provided evidence that BECCS and DAC were perceived to tamper more with nature than AR, which in turn led to lower levels of support for BECCS and

Table 1 Mediation analysis (Hayes Model 4) to test whether perceptions of tampering with nature mediate the effect of learning about different types of CDR on CDR support

	Direct effects on perceived tampering with nature						
	b	*SE*	*t*	*p*	95% CI		R^2
					Lower	Upper	
BECCS condition	0.93	0.10	9.67	< .001	0.74	1.12	0.19
DAC condition	0.77	0.10	8.09	< .001	0.59	0.96	
Tradeoffs condition	0.48	0.08	6.16	< .001	0.33	0.64	
ATN	0.21	0.04	5.62	< .001	0.14	0.29	
Control variables							
Age	− 0.01	0.00	− 2.96	.003	− 0.01	0.00	
Gender (female)	0.12	0.08	1.48	.138	− 0.04	0.28	
Education	0.04	0.03	1.34	.179	− 0.02	0.09	
Political ideology	0.12	0.02	4.78	< .001	0.07	0.16	
Intercept	1.69	0.26	6.46	< .001	1.17	2.20	
	Direct effects on CDR support						
	b	*SE*	*t*	*p*	95% CI		R^2
					Lower	Upper	
BECCS condition	− 0.49	0.09	− 5.62	<.001	− 0.66	− 0.32	0.45
DAC condition	− 0.49	0.09	− 5.71	<.001	− 0.66	− 0.32	
Tradeoffs condition	− 0.28	0.07	− 3.96	<.001	− 0.41	− 0.14	
ATN	− 0.07	0.03	− 2.21	.028	− 0.14	− 0.01	
Perceived tampering with nature	− 0.58	0.03	− 20.56	<.001	− 0.63	− 0.52	
Control variables							
Age	0.00	0.00	− 1.68	.093	− 0.01	0.00	
Gender	− 0.05	0.07	− 0.68	.496	− 0.19	0.09	
Education	− 0.02	0.02	− 0.99	.321	− 0.07	0.02	
Political ideology	− 0.08	0.02	− 3.94	<.001	− 0.13	− 0.04	
Intercept	8.62	0.23	36.98	<.001	8.16	9.08	
	Indirect effects through perceived tampering						
	Coeff.	boot *SE*			Boot 95% CI		
					Lower	Upper	
BECCS vs. AR	− 0.53*	0.06			− 0.66	− 0.41	
DAC vs. AR	− 0.45*	0.06			− 0.57	− 0.33	
DAC vs. BECCS	0.09	0.05			− 0.02	0.20	

*$p < 0.05$

DAC. We hypothesized that these indirect effects may depend on individual differences in discomfort with human activities that tamper with nature. Specifically, we expected individuals who are more averse to tampering with nature to be more inclined to see BECCS and DAC as tampering relative to AR (H2) and thus to be less supportive of them (H3). Additionally, we expected that the effect of learning about CDR might depend on the specific tradeoffs described (RQ2). Our previous analyses, which accounted for the main (or average) effect of the tradeoffs condition, found that reading about tradeoffs increased perceptions of tampering and decreased support for CDR (RQ1). But, as our mock newspaper articles illustrate, the specific tradeoffs associated with each type of CDR vary considerably in terms of costs, land-use conflicts, and feasibility. To simultaneously test whether these differences might lead to different perceptions of tampering and, thus, support for CDR (RQ2) as well as the potential moderating role of ATN, we used PROCESS Model 63 (Fig. 1b). This model looks for interactions between CDR type and tradeoffs on perceived tampering and support, while allowing each link in the mediation model to be moderated by ATN.[3,4] We describe the results for each moderator below; the full regression results and conditional indirect effects are reported in the Electronic Supplementary Material.

3.3.1 H2 and H3: the moderating role of aversion to tampering with nature

Our results provide evidence that ATN influences (1) the extent to which CDR technologies are perceived to tamper with nature (H2) and (2) the strength of the relationship between perceived tampering and CDR support (H3). In support of H2, the effects of learning about BECCS and DAC (compared to AR) on the perception that these technologies tamper with nature were significantly moderated by ATN (BECCS, $b = 0.33$, $SE = 0.09$, $p < .001$; DAC, $b = 0.19$, $SE = 0.09$, $p = 0.030$). Figure 3a probes these interactions, controlling for tradeoff condition. For BECCS and DAC, perceived tampering increases with ATN ($b_{\mathrm{BECCS}} = 0.37$, $SE = 0.07$, $p < 0.001$; $b_{\mathrm{DAC}} = 0.29$, $SE = 0.06$, $p < .001$), whereas for AR, perceptions of tampering remain consistent at different levels of ATN ($b_{\mathrm{REF}} = 0.04$, $SE = 0.06$, $p = 0.568$). The interaction between DAC (vs. BECCS) and ATN on perceived tampering was not significant ($b = -0.14$, $SE = 0.09$, $p = 0.128$). In support of H3, we also observed a small interaction between ATN and perceived tampering on CDR support ($b = -0.07$, $SE = 0.02$, $p = < 0.001$; Fig. 3b). Simple slope analysis indicated that as ATN increases, the negative effect of perceived tampering on support becomes stronger ($b_{\mathrm{lowATN}} = -0.49$, $SE = 0.04$, $p < 0.001$; $b_{\mathrm{modATN}} = -0.57$, $SE = 0.03$, $p < 0.001$; $b_{\mathrm{highATN}} = -0.64$, $SE = 0.03$, $p < 0.001$). Finally, we found no evidence that ATN moderates the direct link between BECCS and CDR support ($b = 0.12$, $SE = 0.08$, $p = 0.141$) or that of DAC and CDR support ($b = 0.06$, $SE = 0.08$, $p = 0.427$), as compared to AR.

3.3.2 RQ2: the moderating role of learning about CDR tradeoffs

We next examined whether the effect of learning about CDR tradeoffs on perceived tampering differs by CDR strategy (RQ2). Looking at the link between CDR and perceived tampering, the

[3] We did not anticipate an interaction with ATN on the direct link between CDR type and support, as that would suggest that people averse to tampering with nature react differently to CDR even after controlling for the indirect effect through perceived tampering. We controlled for this interaction since it is part of the regression model for the mediator.

[4] Before running Model 63, we ran Model 69 to check for three-way interactions between CDR Type, Tradeoffs condition, and ATN on Perceived tampering and on CDR Support, respectively. None were significant.

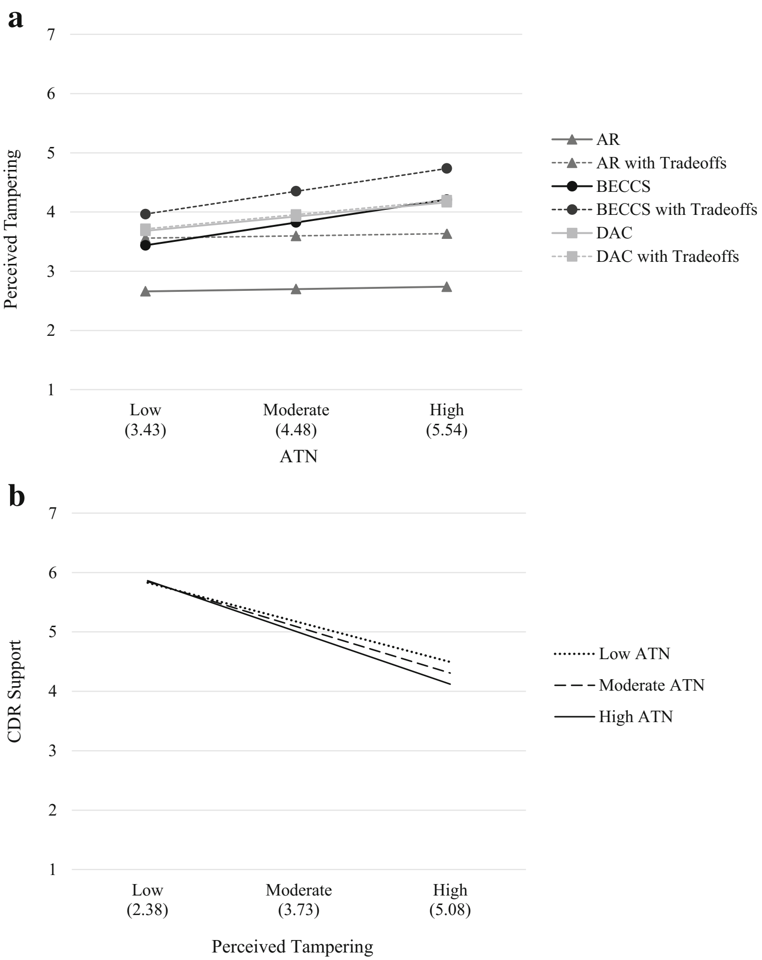

Fig. 3 Moderating effects of ATN and tradeoffs (Model 63). Panel **a** shows the effect of CDR type on perceived tampering with nature at different levels of ATN (mean and mean ± 1 *SD*), with tradeoffs described (dashed lines) and without (solid line). Panel **b** depicts the effect of perceived tampering with nature on CDR support at three levels of ATN (mean and mean ± 1 *SD*)

model revealed a significant interaction between DAC and tradeoffs when compared to either AR ($b = -0.86$, $SE = 0.18$, $p < 0.001$) or BECCS ($b = -0.49$, $SE = 0.19$, $p = 0.010$). As shown in Fig. 3a, when tradeoff information is provided, perceptions of tampering increase for both AR and BECCS but not DAC. These effects are consistent across different levels of ATN. There was also a significant interaction between BECCS (vs. AR) and tradeoffs ($b = -0.37$, $SE = 0.19$, $p = 0.050$), indicating that the effect of learning about tradeoffs was stronger for AR than it was for BECCS. Table 2 summarizes the conditional effects of each treatment on perceptions of tampering at different levels of ATN, with and without tradeoffs. These conditional effects can be interpreted as the distances between the points plotted in Fig. 3a.

Table 2 Conditional effects of CDR type on perceptions of tampering with nature

			Conditional effects on perceived tampering		
ATN	Tradeoffs	CDR comparison	Coefficient	Boot *SE*	Boot 95% CI
Low	No	BECCS vs. AR	0.78*	0.16	0.46, 1.09
		DAC vs. AR	1.02*	0.16	0.71, 1.33
		DAC vs. BECCS	0.24	0.16	− 0.08, 0.57
	Yes	BECCS vs. AR	0.41*	0.17	0.08, 0.73
		DAC vs. AR	0.16	0.16	− 0.16, 0.48
		DAC vs. BECCS	− 0.25	0.17	− 0.58, 0.08
Moderate	No	BECCS vs. AR	1.12*	0.13	0.86, 1.39
		DAC vs. AR	1.22*	0.13	0.96, 1.49
		DAC vs. BECCS	0.10	0.13	− 0.16, 0.36
	Yes	BECCS vs. AR	0.75*	0.13	0.49, 1.01
		DAC vs. AR	0.36*	0.13	0.10, 0.62
		DAC vs. BECCS	− 0.39*	0.13	− 0.66, − 0.13
High	No	BECCS vs. AR	1.47*	0.17	1.14, 1.81
		DAC vs. AR	1.43*	0.17	1.10, 1.75
		DAC vs. BECCS	− 0.05	0.16	− 0.37, 0.28
	Yes	BECCS vs. AR	1.10*	0.16	0.78, 1.42
		DAC vs. AR	0.56*	0.16	0.25, 0.88
		DAC vs. BECCS	− 0.54*	0.16	− 0.85, − 0.23

*$p < 0.05$

4 Discussion

4.1 Overview of key findings

The purpose of this experiment was to examine whether perceptions of tampering with nature explain differences in support for three forms of carbon dioxide removal (CDR) commonly discussed in climate modeling scenarios: afforestation and reforestation (AR), bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC). Furthermore, we explored whether the effects of learning about these strategies were moderated by whether the tradeoffs associated with each CDR strategy were described as well as by characteristics of the audience, specifically, their aversion to human activities that tamper with nature. As expected, each of these factors—perceptions that CDR tampers with nature, general aversion to tampering with nature, and providing information about tradeoffs—significantly impacted support for CDR.

In line with H1b, participants were more supportive of AR as a strategy to address climate change because it was perceived to tamper less with nature than either BECCS or DAC. This effect was more pronounced among individuals more averse to human activities that tamper with nature. Specifically, individuals with higher levels of aversion to tampering with nature were more likely to see BECCS and DAC as tampering with nature, but not AR (H2). Moreover, ATN enhanced the negative effect of perceived tampering, further reducing support for CDR (H3). These results complement—and help explain—recent research showing that people are more supportive of afforestation and reforestation than other forms of geoengineering (Braun et al. 2017). These findings also seem to confirm a conjecture brought up by recent work on the moral hazard effects of CDR, suggesting that reforestation may not provoke moral hazard effects as much as DAC or BECCS due the perceived naturalness of this technique (Campbell-Arvai et al. 2017).

Consistent with prior research (Braun et al. 2017; Sütterlin and Siegrist 2017), we also found that describing the risks and benefits of CDR strategies decreased support for each strategy (H4). The underlying mechanism for this effect, however, appears to vary by CDR type (RQ1, RQ2). For AR and BECCS, describing the tradeoffs decreased support by heightening perceptions that these forms of CDR tamper with nature. For DAC, describing the tradeoffs had no effect on perceived tampering, yet support still declined relative to the no-tradeoffs condition. One explanation for these results concerns the pros and cons highlighted in each article. Whereas the tradeoffs articles for AR and BECCS mentioned that local ecosystems and biodiversity could be threatened, the article for DAC merely noted that land would be needed to supply wind or solar energy for DAC operations. In addition, greater uncertainty was attached to the feasibility of deploying DAC at scale. Thus, support for DAC may have declined as participants questioned the reliability of this unproven technology, the feasibility of implementing it, or the costs involved. Additional research is needed to examine whether the observed results hold if the tradeoffs of DAC are framed with greater emphasis on land use and ecological impacts.

4.2 Policy implications

Our results have several practical implications for climate policy. In particular, our findings suggest there is a significant mismatch between which CDR strategies the public finds acceptable and what science suggests is prudent and viable. Among the three CDR strategies examined, support was greatest for AR, regardless of whether the tradeoffs were described. But as Braun et al. (2017) note, this strategy is one of the least effective geoengineering strategies for addressing climate change. AR is estimated to reduce annual global carbon dioxide emissions by approximately 15%, while DAC and BECCS have the potential to abate 30–50%, respectively (Lenton 2010; Meadowcroft 2013; National Research Council 2015; Smith et al. 2016). Moreover, of the three CDR strategies examined, BECCS is considered to be most ready for large-scale deployment (Sanchez et al. 2015). Yet, participants perceived BECCS to tamper the most with nature when details were provided about its risks and benefits. These negative perceptions may add to the challenge of siting and expanding BECCS facilities (Buck 2016; Fridahl and Lehtveer 2018) and point to the need for governments and BECCS proponents to address these concerns before relying on this form of CDR to mitigate climate change. Further, as our research suggests that there is a low level of knowledge about CDR technologies among the public, meaningful public engagement and dialogue on this topic is of vital importance (Ballantyne 2016).

4.3 Theoretical contributions

This research also makes several theoretical contributions to the fields of risk analysis and science communication. First, whereas other studies have looked at tampering with nature as a predictor of support for individual geoengineering strategies (using a separate regression model for each technology) (Visschers et al. 2017; Braun et al. 2017), this is the first study to show—through a comparative mediation analysis—that differences in perceived tampering between various types of CDR translate to differences in support. This provides useful information for policymakers and scientists about which specific types of CDR might be most to amenable to the public and why. This insight is important, as decision-makers will have to consider not just whether to implement CDR at all, but also which form a CDR intervention should take.

A second contribution concerns the role of aversion to tampering with nature. Looking at past research, “tampering with nature” is an ambiguous concept that captures both attitudes toward a target technology as well as trait-level differences in worldviews. Our results suggest that it is important to measure both qualities separately. In this study, individual differences in tampering with nature aversion and perceptions about the extent to which each CDR technology tampers with nature affected support for these technologies both independently and jointly. Thus, focusing on only one aspect of tampering with nature misses important nuances that may explain support for (or opposition to) emergent technologies. Our moderated mediation model also provides insights as to how aversion to tampering with nature operates: individuals more averse to activities that tamper with nature are more likely to see activities as tampering; at the same time, ATN strengthens the negative effect of perceived tampering on support. More research is needed to understand how prevalent this aversion is in the population and what attributes of a technology provoke this reaction.

4.4 Limitations and future research

Some of the limitations of our study point to directions for future research. As our mock newspaper articles described multiple facets of each CDR strategy, it is unclear exactly which pieces of information triggered perceptions of tampering with nature or, likewise, what types of tradeoffs were seen as problematic. Further studies may benefit by teasing apart these effects to understand how people weigh the multiple risks and benefits associated with carbon dioxide removal technologies. We also note that participants in our study only learned about one type of CDR. Without a point of comparison, they may not have known how to evaluate details concerning, e.g., costs per ton of CO_2 sequestered or the potential percentage of global greenhouse gas emissions that could be abated. Perceptions of tampering with nature and, consequently, support for using CDR may change when people are asked to consider the tradeoffs of several CDR strategies simultaneously. Future within-subjects research is needed to explore these questions. We also note that our study did not consider heterogeneity within the sample beyond basic socio-demographic questions. It is possible that the effects of perceived tampering and ATN vary with other characteristics of the audience such as religious beliefs, environmental concern, or how respondents view humankind’s relationship to nature. For example, some individuals may not perceive CDR as tampering with nature if they view human activity as part of the natural order. Thus, readers should be careful to interpret our findings as average effects; the extent to which AR, BECCS, and DAC are perceived to tamper with nature may be much smaller for some (who do not believe tampering is possible) and much greater for others (who see nature as distinct from humans). The interactions we found between CDR type and ATN further illustrate this point. Finally, as our study employed an online survey experiment, additional research is needed to determine whether the results replicate in more realistic settings, where people may be more or less likely to pay close attention to the information presented depending on their stake in the issue.

4.5 Conclusion

In sum, the results of this experiment shed light on the factors that influence public opinion of CDR strategies at a relatively early stage in their development, when the public is largely unfamiliar with them. Notably, our findings provide strong evidence that people are sensitive to what information is provided about CDR, particularly details about how a technique uses or affects nature as well as information about potential long-term uncertainties. The more a CDR strategy is perceived to tamper with nature the less likely the public is to support it. As a result, the way CDR strategies are initially framed by policymakers or the mass media may have substantial consequences for their future acceptance and deployment.

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