Perceptions of naturalness predict US public support for Soil Carbon Storage as a climate solution

Shannan K. Sweet[1,2] · Jonathon P. Schuldt[1] · Johannes Lehmann[2,3] · Deborah A. Bossio[4] · Dominic Woolf[2]

Abstract

Soil Carbon Storage has emerged as a feasible strategy for removing carbon dioxide from the atmosphere, raising important questions regarding whether the general public supports the strategy as a means to address climate change. We analyzed data from a national probability survey of 1222 US adults who reported believing in climate change at least "somewhat" to estimate public support for Soil Carbon Storage and how it compares to other leading Carbon Dioxide Removal (CDR) strategies. Overall, a majority of the sample expressed support for Soil Carbon Storage—regardless of whether the strategy involved the use of biochar (a form of charcoal made from organic matter) or not (55% and 62%, respectively)—placing Soil Carbon Storage ahead of Bioenergy plus Carbon Capture and Storage (32%) and Direct Air Capture (25%), and behind only Afforestation and Reforestation (73%), in terms of public support. In addition, perceiving Soil Carbon Storage as "natural" strongly predicted individual-level support, a pattern that held for every CDR strategy featured on the survey. Results demonstrate broad US public support for Soil Carbon Storage as a climate change mitigation strategy at a time when scientists and policymakers are actively considering the political, not just technical, feasibility of different climate solutions.

✉ Jonathon P. Schuldt
   jps56@cornell.edu

1   Department of Communication, Cornell University, Ithaca, NY 14853, USA

2   Soil and Crop Science, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853, USA

3   Department of Global Development, Cornell University, Ithaca, NY 14853, USA

4   The Nature Conservancy, Arlington, VA, USA

1 Introduction

1.1 Carbon Dioxide Removal (CDR) strategies

According to the Intergovernmental Panel on Climate Change (IPCC 2018), anthropogenic climate change—due largely to carbon dioxide emissions (Cox et al. 2000; Solomon et al. 2009)—increased the global average temperature to 1 °C above pre-industrial levels in 2017. However, the same IPCC report concluded that maintaining a global temperature increase of less than 1.5 °C would substantially reduce risks to ecosystems and humans relative to 2 °C of warming (IPCC 2018). There is a growing consensus that meeting this target will be difficult to achieve via reductions in greenhouse gas emissions alone. In addition to reducing emissions, strategies that create "negative emissions" scenarios—for example, Carbon Dioxide Removal (CDR) strategies—will likely also be needed (Van Vuuren et al. 2018). CDR strategies remove carbon dioxide from the atmosphere using chemical and/or biological solutions to capture and store carbon dioxide (Corner and Pidgeon 2014; Field and Mach 2017; Lawrence et al. 2018; Rogelj et al. 2018, Smith et al. 2016).

As several CDR strategies have emerged in recent years, scholars have recognized that gaining policy traction in this area will require not only demonstrating the scientific feasibility of these techniques (Caldeira et al. 2013; Fuss et al. 2018) but also understanding public opinion on the issue, including the psychological factors that predict support for different strategies (Campbell and Kay 2014; Minx et al. 2018; Shrum et al. 2020). This may be particularly important in the USA, where the issue of climate change and proposed policy solutions have been politically polarized for decades (Dunlap et al. 2016; McCright and Dunlap 2011). Although recent public opinion data reveal that a majority of the US public is concerned about climate change and its implications for society (Borick and Rabe 2012; Brulle et al. 2012; Leiserowitz et al. 2019; Schuldt et al. 2020; Van Boven and Sherman 2018), there is limited consensus on which strategies should be used to address the issue (Corner et al. 2013; Faran and Olsson 2018; Kahan et al. 2015; Preston 2013). This is partly because public opinion is often shaped by subjective risk perceptions, whether it regards a global pandemic (Dryhurst et al. 2020; Walter et al. 2012; van der Weerd et al. 2011) or new technological breakthroughs (Bassarak et al. 2017; Sjöberg 2000; Slovic 2000). When it comes to CDR strategies in particular, members of the public and key stakeholder groups may not yet have strongly formed opinions. As a consequence, they may rely on pre-existing mental schemas and cognitive associations in deciding whether or not to support a given strategy for removing carbon dioxide from the atmosphere (Shrum et al. 2020).

1.2 Soil Carbon Storage

As CDR strategies have gained attention in scientific circles, a growing number of studies suggest that sequestering carbon in soils may be a worthwhile approach to addressing climate change (Christoff 2016; García-Tejero et al. 2020; Lal 2004; Minasny et al. 2017; Vermeulen et al. 2019). One such approach involves managing land, such as farm and grazing lands, forests, and wetlands, in ways that store increased amounts of carbon in the soil, thus keeping it out of the atmosphere (i.e., Soil Carbon Storage) (Bossio et al. 2020; Doetterl et al. 2015). Another approach receiving recent attention (Minx et al. 2017) involves the same land management approaches mentioned above plus the use of heat to convert unused plant material or manure on farms into a form of charcoal called biochar (Demirbas and Arin 2002; Gurwick

et al. 2012; Lehmann and Joseph 2015), which is then mixed into the soil in order to store carbon for long periods of time (i.e., Soil Carbon Storage with Biochar) (Winsley 2007; Laird 2008; Woolf et al. 2010).

Although sequestering carbon in soil to mitigate climate change is scientifically feasible (Lal et al. 2003; Sykes et al. 2020), some have argued there may be significant political barriers to implementing Soil Carbon Storage in the USA, given that key stakeholders, such as farmers, tend to be lean politically conservative and may be resistant to government regulations aimed at addressing climate change (Amundson and Biardeau 2018; Amelung et al. 2020). Also, while a small number of studies have investigated public perceptions of Soil Carbon Storage as a climate change mitigation strategy (Glenk and Colombo 2011; Kragt et al. 2016; Shrum et al. 2020), few have examined how the public reacts to the use of biochar as a component of the process (Wright et al. 2014). Moreover, past research on this topic has been conducted almost entirely outside of the USA (e.g., Jobin and Siegrist 2020), where attitudes toward climate change mitigation may be less politicized or controversial.

To address this gap, the present study examines public support for Soil Carbon Storage—with and without biochar—using a national probability survey of US adults, allowing us to estimate the overall level of US public support as well as the factors that best predict support for soil carbon strategies. In doing so, we build on recent research into public perceptions of CDR strategies besides Soil Carbon Storage, which suggests that public support may be driven to a substantial degree by whether a given strategy is perceived as "natural" (Wolske et al. 2019; Raimi et al. 2020).

1.3 The role of perceived naturalness in public support for CDR strategies

Although limited research has examined public support for Soil Carbon Storage specifically, recent research suggests that US public support for CDR strategies may depend on the extent to which the strategy is perceived to "tamper with nature." Specifically, Wolske et al. (2019) randomly assigned survey respondents to read about one of the following CDR strategies: Afforestation and Reforestation (AR), which involves planting trees in previously unforested and previously forested areas; Bioenergy plus Carbon Capture and Storage (BECCS), which involves growing and harvesting plants as a fuel source and which removes CO_2 from the air and stores it deep underground after the fuel is burned; and Direct Air Capture (DAC), which involves the passing of air over or through chemicals that absorb CO_2, typically using large fans, and depositing the recovered CO_2 into long-term geologic storage. To the extent that the public perceives some strategies as more natural than others, we might expect positive receptivity and support to follow suit, given that a preference for naturalness has been documented in various domains (Rozin et al. 2004, 2012). For instance, Wolske et al. (2019) found lower support for strategies that were perceived to tamper more with nature (e.g., BECCS and DAC) as compared to strategies that were perceived to tamper less with nature (e.g., AR).

2 Current research

We pursued two primary objectives in the present study. First, we sought to build on recent research on the role that perceptions of naturalness and attitudes toward tampering with nature play in US public support for CDR strategies (Wolske et al. 2019) with an expanded set of carbon

removal options that included Soil Carbon Storage (SCS) and Soil Carbon Storage with Biochar (SCSB), which limited research has examined in the US context. Second, we examined these questions using a national level, probability-based sample of the US public. Prior research on this topic has recruited respondents from online opt-in samples with quota sampling to match US demographic categories. While research finds that such non-probability methods sometimes yield estimates that cohere with those from probability surveys (see Motta et al. 2019 for a discussion of measurement effects in climate change surveys), others have noted that these different sampling approaches can yield different results (Goldberg et al. 2019). Given the policy implications of public opinion surveys on this topic, it is important to examine whether associations between perceptions of naturalness and public support for CDR strategies emerge in probability-based surveys, which may better enable researchers to generalize survey results to the overall US public on this timely environmental issue.

We pursued two primary hypotheses based on previous research. First, we expected that perceiving SCS as more "natural" would predict increased public support, given prior evidence that perceptions about tampering with nature predict public support for CDR strategies (i.e., AR, BECCS, and DAC) (Wolske et al. 2019). Second, we expected that respondents scoring higher on a scale measure of discomfort with altering the natural world—Aversion to Tampering with Nature (ATN) (Raimi et al. 2020)—would report more support for strategies that may be seen as more "natural" on average (e.g., SCS), and less support for strategies seemingly less "natural" on average (e.g., DAC). Finally, as an exploratory research question, we sought to test whether respondents reacted differently to soil carbon strategies depending on whether they did or did not include the use of biochar, a more technical component that may result in the strategy being perceived as less "natural." We addressed this question by embedding a between-subjects experiment in which respondents were randomly presented with either SCS or SCSB.

3 Methods

3.1 Setting and participants

We analyzed survey data from a probability-based sample of 1222 US adults recruited by the National Opinion Research Center (NORC) at the University of Chicago using the AmeriSpeak® Panel (http://amerispeak.norc.org/Pages/default.aspx) from September 19 to October 4, 2019. AmeriSpeak® randomly samples households using area probability and address-based sampling with a known, non-zero probability of selection from the NORC National Sample Frame. The panel provides sample coverage of approximately 97% of the US household population. This study was offered in English-only and was administered exclusively as a Web survey, due to the use of images as well as text in our research materials.

Because our main survey questions pre-supposed that climate change is a real phenomenon, we screened for belief in climate change using the question "Do you believe climate change is really happening?" with response options being "Yes, definitely," "Yes, somewhat," and "No." Of the original sample of 1393 respondents who agreed to take the survey, eligibility was limited to those indicating they "definitely" or "somewhat" believe climate change is happening (1284, or 92% of the sample); of these, 64 respondents did not qualify as completes according to NORC, leaving $N = 1222$ for the analytic sample. A summary of sample demographics appears in Table 1.

Table 1 Summary of unweighted sample demographics for the analytic sample ($N = 1222$), including the number (N) and proportion (%) of valid respondents

	N	%		N	%
Age			Education		
18–29	193	15.8	Less than high school	36	2.9
30–44	363	29.7	High school equivalent	199	16.3
45–59	298	24.4	Some college	561	45.9
60+	368	30.1	Bachelor's degree or above	426	34.9
Sex			Household income		
Male	589	48.2	Less than $5000	28	2.3
Female	633	51.8	$5000 to $19,999	120	9.8
Race/ethnicity			$20,000 to $34,999	207	17.0
White, non-Hispanic	792	64.8	$35,000 to $59,999	292	23.9
Black, non-Hispanic	142	11.6	$60,000 to $99,999	315	25.8
Other, non-Hispanic	18	1.5	$100,000 to $199,999	223	18.2
Hispanic	201	16.4	$200,000 or more	37	3.0
2+, non-Hispanic	33	2.7	Political ideology		
Asian, non-Hispanic	36	2.9	Very liberal	104	8.5
Political affiliation			Liberal	200	16.4
Democrat	484	39.6	Slightly liberal	152	12.4
Republican	268	21.9	Moderate/middle of the road	388	31.8
Independent	326	26.7	Slightly conservative	159	13.0
Other	134	11.0	Conservative	147	12.0
			Very conservative	54	4.4

3.2 Measures

3.2.1 Perceptions of naturalness and support for Carbon Dioxide Removal strategies

Building on the study by Wolske et al. (2019), we solicited respondents' perceptions of naturalness and policy support for five CDR strategies: Afforestation and Reforestation (AR), Bioenergy plus Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), Soil Carbon Storage (SCS), and Soil Carbon Storage with Biochar (SCSB). We polled respondents immediately after providing them with brief and scientifically accurate descriptions of each strategy that were created or adapted from multiple sources (e.g., Campbell-Arvai et al. 2017; Meko 2016; Wolske et al. 2019; see Supplementary Material). We provided these descriptions because we expected, based on prior work, that many members of the public would be unfamiliar with CDR strategies (Campbell-Arvai et al. 2017; see also Corner et al. 2012).

To minimize respondent burden, respondents viewed just three out of these five CDR strategies, which were presented in random order to account for possible order effects. Because of our focus on the Soil Carbon Storage strategies, all respondents viewed one of the two versions of this strategy (i.e., SCS or SCSB) as part of a between-subjects experimental design; in addition to this, respondents evaluated two of three strategies from the remaining set (i.e., AR, BECCS, and DAC), selected at random. This design allowed us to examine how public support for Soil Carbon Storage compared to other, previously polled CDR strategies, while testing the replicability of previous findings (Wolske et al. 2019) in a probability-based sample. To measure perceived naturalness, respondents were asked to rate how much a given CDR strategy "is natural," "tampers with nature," and "disturbs the natural order" on a scale ranging from 1 = *Strongly disagree* to 7 = *Strongly agree* (the latter two being reverse-coded

for analysis). We combined these three items to form the composite variable, perceived naturalness, for each of the five CDR strategies (αs .68 to .77).

3.2.2 Support for CDR strategies

To assess our main dependent variable, support, respondents were asked how likely they would be to support each CDR strategy using the question: "How likely are you to support [...] as a Carbon Dioxide Removal strategy?" where 1 = *Very unlikely*, 2 = *Somewhat unlikely*, 3 = *Neutral*, 4 = *Somewhat likely*, and 5 = *Very likely*.

3.2.3 Aversion to tampering with nature

To assess individual differences in attitudes toward human intervention in natural systems, near the end of the survey, respondents completed the Aversion to Tampering with Nature (ATN) scale from Raimi et al. (2020). Specifically, respondents were asked to rate their level of agreement with each of the following five statements: "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" (reverse-coded); "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" (1 = *Strongly disagree* to 5 = *Strongly agree*) (Wolske et al. 2019). A numerical average was computed to yield an ATN score for each respondent (M = 3.96, SD = 1.02, α = .72).

3.3 Analytic strategy

Our analysis begins by examining how public opinion toward Soil Carbon Storage approaches compares to other Carbon Dioxide Removal strategies. In doing so, we report analysis of variance (ANOVA) models testing for the experimental effect of including biochar on perceptions of naturalness and support. We then turn to a set of regression models examining the extent to which perceptions of naturalness and tampering with nature attitudes predict public support for the different Carbon Dioxide Removal strategies.

In each of the main regression models, we regressed the support variable onto respondents' perceived naturalness rating for that CDR strategy and their Aversion to Tampering with Nature (ATN) score. In addition, as covariates, we include political ideology (1 = *Very liberal* to 7 = *Very conservative*),[1] education (four-category; dummy-coded with the lowest category, *Less than high school*, as the reference group), sex (coded as 1 = *Male* and 2 = *Female*), and age (as a continuous variable in years) given their examination in prior research on climate change public opinion. Finally, for the purposes of generalizing results to the segment of the US adult public that reports believing in climate change, we present weighted analyses unless otherwise noted.

---

[1] We analyze political ideology rather than party affiliation because of our conceptual interest in political worldview rather than political identity and because of ideology's stronger association with climate change opinions that has been documented in prior research (e.g., Fielding et al. 2012; Cruz 2017). Nevertheless, when party affiliation (Democrat, Republican, Independent/Other; dummy-coded with Republican as the referent group) is substituted for political ideology in our main regression models, the findings involving perceived naturalness and aversion to tampering with nature remain substantively unchanged.

4 Results

4.1 Reactions to Soil Carbon Storage in comparison to other CDR strategies

To examine how the public's reactions varied across each of the five CDR strategies, we first computed mean-level perceived naturalness scores and mean-level support for each strategy: Afforestation and Reforestation (AR), Bioenergy plus Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), Soil Carbon Storage (SCS), and Soil Carbon Storage with Biochar (SCSB) (Table 2). Perceived naturalness scores varied substantially across strategies, with AR ($M = 5.24$, $SD = 1.27$), SCS ($M = 4.54$, $SD = 1.21$), and SCSB ($M = 4.36$, $SD = 1.13$) being perceived as more natural in comparison to the scale midpoint (i.e., $4 = $ *Neither agree nor disagree*), and with BECCS ($M = 3.62$, $SD = 1.26$) and DAC ($M = 3.60$, $SD = 1.18$) being perceived as less natural in comparison to the scale midpoint ($|t|s \geq 7.9$, $ps < .001$ for the midpoint comparisons). Support varied similarly across strategies, with AR ($M = 3.97$, $SD = 1.06$), SCS ($M = 3.68$, $SD = 1.09$), and SCSB ($M = 3.49$, $SD = 1.04$) receiving greater support in comparison to the scale midpoint (i.e., $3 = $ *Neutral*), and with BECCS ($M = 2.83$, $SD = 1.21$) and DAC ($M = 2.66$, $SD = 1.17$) receiving less support in comparison to the scale midpoint ($|t|s \geq 4.0$, $ps < .001$ for the midpoint comparisons). Expressed in percentage terms, whereas a majority of respondents reported being "somewhat" or "very" likely to support AR, SCS, and SCSB (73%, 62%, and 55%, respectively), only a minority indicated the same level of support for BECCS and DAC (32% and 25%, respectively).

4.2 Testing reactions to different Soil Carbon Storage strategies

While the above results suggest that both soil carbon strategies (SCS and SCSB) were perceived as highly natural and supported by a majority of respondents, did these reactions nevertheless differ significantly across the two versions (i.e., with vs. without biochar)? Following Miratrix et al. (2018), we report unweighted sample average treatment effects to examine this question.[2] Indeed, ANOVA testing for the experimental effect revealed that SCS was both perceived as more natural ($F(1,1211) = 7.24$, $p < .01$) and received greater support ($F(1,1212) = 5.82$, $p < .05$) than SCSB.

4.3 Perceived naturalness and aversion to tampering with nature as predictors of support for CDR strategies

To better understand the predictors of public support for the different CDR strategies, we turn to the regression results. Recall that we conducted a set of five regression models, and in each, support for a given CDR strategy was regressed onto perceived naturalness, ATN score, and the aforementioned covariates. The results for each of the five models are displayed in Table 3. As expected, perceived naturalness was a significant positive predictor in all models ($Bs \geq .299$, $ps < .001$). ATN, in contrast, was a significant negative predictor in three of the five models, namely, for DAC ($-.109$, $p < .01$), BECCS ($B = -.078$, $p < .05$), and SCSB ($B = -.149$, $p < .001$).

---

[2] Weighted analyses revealed substantively unchanged treatment effects on both perceived naturalness (F $(1,1217) = 6.98$, $p < .01$) and support ($F (1,1220) = 9.97$, $p < .01$).

Table 2 Summary of weighted statistics for perceived naturalness and support for each Carbon Dioxide Removal (CDR) strategy: Afforestation and Reforestation (AR); Bioenergy plus Carbon Capture and Storage (BECCS); Direct Air Capture (DAC); Soil Carbon Storage (SCS); and Soil Carbon Storage with Biochar (SCSB). Ns vary between perceived naturalness and support due to missing data. Percent support combines the two highest categories "Somewhat likely" and "Very likely"

	Perceived naturalness (index)			Support			
	N	M	SD	N	M	SD	Percent
AR	787	5.24	1.27	788	3.97	1.06	73%
BECCS	811	3.62	1.26	809	2.83	1.21	32%
DAC	827	3.60	1.18	831	2.66	1.17	25%
SCS	616	4.54	1.21	621	3.68	1.09	62%
SCSB	597	4.36	1.13	593	3.49	1.04	55%

Furthermore, we conducted an additional set of exploratory regression models that incorporated an additional predictor—namely, belief in anthropogenic climate change (to account for belief in the human vs. natural causes of climate change; Funk and Kennedy 2016)—as well as select interaction terms (e.g., the education by political ideology interaction; see Hamilton 2011; Schuldt et al. 2020) (see Supplementary Table S1).[3] Notably, perceived naturalness remained a significant predictor in all five models ($Bs > .168$, $ps < .05$). In contrast, the pattern of effects for ATN was more variable. Whereas ATN scores negatively predicted support for BECCS but not DAC in the simplified models, the opposite was observed in the expanded models ($B = -.105$, $p \leq .01$ for DAC; $B = -.064$, $p > .05$ for BECCS) (see Supplemental Table S2 for details). We return to this point about the consistency of perceived naturalness versus ATN scores as predictors of policy support in the discussion below.

4.4 Demographic predictors of support for CDR strategies

Finally, demographic variables emerged as significant predictors in all five CDR strategies (Table 3), although the patterns of association differed across models. Political ideology was a significant predictor in four out of five models—namely, for BECCS ($B = -.099$, $p < .001$), DAC ($B = -.101$, $p < .001$), SCS ($B = -.062$, $p < .05$), and SCSB ($B = -.058$, $p < .05$)—such that conservatism was associated with lower levels of support for these strategies, echoing numerous prior findings on the relationship between political ideology and climate policy support (e.g., Funk and Hefferon 2019; Gillis et al. 2021). Education was a significant positive predictor of support for AR, SCS, and SCSB ($Bs \sim .3$ to $.4$, relative to *Less than high school*), but somewhat expectedly, a negative predictor in the case of BECCS ($B = -.362$, $p < .01$ for *Some college*, and $B = -.432$, $p < .001$ for *Bachelor degree or above*, relative to *Less than high school*). Sex (female) was a significant predictor for SCSB only ($B = .108$, $p < .05$), while age negatively predicted support for BECCS ($B = -.011$, $p < .001$), DAC ($B = -.007$, $p < .001$), SCS ($B = -.005$, $p < .05$), and SCSB ($B = -.005$, $p < .05$). No other significant relationships were observed.[4]

---

[3] Belief in anthropogenic climate change was measured immediately after respondents qualified for the survey, with the item "Do you think climate change is caused more by human activities, more by natural changes in the environment, or by both equally?" The full set of interaction terms included perceived naturalness by ATN; perceived naturalness by political ideology; perceived naturalness by belief in anthropogenic climate change; and education by political ideology.

[4] For the unadjusted bivariate relationships between key study variables, see the correlation matrix in Supplemental Table S2.

Table 3 Summary of weighted regression coefficients (beta (B) and standard errors (SE)) depicting significant predictors (*p ≤ .05; **p ≤ .01; ***p ≤ .001) for support for Carbon Dioxide Removal (CDR) strategies: Afforestation and Reforestation (AR); Bioenergy plus Carbon Capture and Storage (BECCS); Direct Air Capture (DAC); Soil Carbon Storage (SCS); and Soil Carbon Storage with Biochar (SCSB). Predictors include perceived naturalness ratings for each CDR strategy, Aversion to Tampering with Nature (ATN) score, and demographic variables (i.e., political ideology, education, sex, and age)

	AR		BECCS		DAC		SCS		SCSB	
	B	SE	B	SE	B	SE	B	SE	B	SE
Perceived naturalness	.342***	.028	.469***	.030	.369***	.034	.422***	.033	.299***	.037
Aversion to Tampering with Nature (ATN)	.023	.035	−.078*	.037	−.109**	.040	−.068	.039	−.149***	.041
Political ideology	−.015	.023	−.099***	.023	−.101***	.024	−.062*	.026	−.058*	.024
Education										
High school equivalent	.301*	.147	−.236	.127	.172	.158	.427**	.154	.413**	.144
Some college	.182	.151	−.362**	.129	−.132	.159	.255	.154	.324*	.149
Bachelor's degree or above	.345*	.150	−.432***	.126	−.045	.156	.428**	.153	.322*	.146
Sex	−.025	.072	.006	.071	.011	.077	.031	.078	.187*	.078
Age	−.002	.002	−.011***	.002	−.007***	.002	−.005*	.002	−.005*	.002

5 Discussion

5.1 Perceptions of naturalness and support for Carbon Dioxide Removal strategies

Amid rising attention to Carbon Dioxide Removal strategies to help mitigate the effects of anthropogenic climate change, there is a need to better understand how the general public reacts to these approaches, as well as the psychological factors that predict public support. Soil Carbon Storage, which involves managing land in ways that increase the amount of carbon stored in soils, thus keeping it out of the atmosphere (Minasny et al. 2017), is one such strategy that is receiving increased attention from scientists and policymakers (Minx et al. 2017, 2018; Vermeulen et al. 2019). Yet, little is known about the extent to which the general public supports Soil Carbon Storage as a climate change mitigation strategy.

In a probability-based survey of the US public, we find that a majority of respondents expressed support for Soil Carbon Storage as a climate change mitigation strategy, whether or not it involved biochar—a process that converts unused plant material or manure into a form of charcoal that is then mixed into the soil—although Soil Carbon Storage received more support than Soil Carbon Storage with Biochar (62% and 55%, respectively). Moreover, the Soil Carbon Storage strategies trailed only Afforestation and Reforestation (AR) (73%) in terms of overall public support, and garnered significantly more support than either Bioenergy plus Carbon Capture and Storage (BECCS) (32%) or Direct Air Capture (DAC) (25%). Notably, this ordering of strategies in terms of policy support exactly matched their ordering in terms of perceived naturalness. Stated differently, the three strategies that enjoyed majority support (i.e., Afforestation and Reforestation, Soil Carbon Storage, and Soil Carbon Storage with Biochar) were rated significantly above the scale midpoint in terms of perceived naturalness, whereas the two strategies that garnered minority support (Bioenergy plus Carbon Capture and Storage and Direct Air Capture) were rated significantly below the scale midpoint in terms of perceived naturalness.

When the association between perceived naturalness and policy support was examined more closely in a set of regression models that included covariates, perceptions of naturalness emerged as a significant predictor of support for every CDR strategy on the survey. These associations remained robust in expanded regression models that incorporated additional main effect and interaction terms (see Supplemental Table S1), further complementing previous work suggesting that such perceptions are a critical factor in public support for techniques that remove carbon dioxide from the atmosphere (Wolske et al. 2019).

5.2 Aversion to tampering with nature and support for Carbon Dioxide Removal strategies

In addition to perceptions of Carbon Dioxide Removal strategies as "natural," we included an individual-difference measure of one's discomfort with altering the natural world—the Aversion to Tampering with Nature (ATN) scale (Raimi et al. 2020)—as a predictor of Carbon Dioxide Removal strategy support in all regression models. The ATN findings were more mixed, as this variable was a negative predictor of support for three out of the five Carbon Dioxide Removal strategies, namely, DAC, BECCS, and SCSB. Although we cannot be certain why aversion to tampering with nature predicted support for some strategies but not others, the pattern of results observed in our main regression models suggests that this attitudinal disposition may matter more when evaluating strategies that are generally perceived as less "natural," given that this variable did not predict support for Afforestation and Reforestation or Soil Carbon Storage—the top-two

strategies in terms of perceived naturalness. At the same time, we note that this pattern of effects changed somewhat in the supplemental regression models, which controlled for belief in anthropogenic climate change and select interaction effects, such that aversion to tampering with nature no longer predicted support for Direct Air Capture but *did* predict support for Soil Carbon Storage. Future research may wish to further explore the relationship between aversion to tampering with nature and support for climate dioxide removal strategies, including variability in this relationship across strategies.

5.3 Implications for building public support for Soil Carbon Storage

The present results contribute in significant ways to our understanding of US public support for Soil Carbon Storage as a climate change mitigation strategy (Shrum et al. 2020; Wright et al. 2014) and offer insights for communicators and policymakers. First, results of our embedded experiment revealed higher public support for Soil Carbon Storage than for Soil Carbon Storage with Biochar—yet, both versions of the strategy enjoyed majority support, suggesting that the role of biochar in public perceptions may be of minor practical importance. At the same time, we observed differences between the two versions that may matter for building public support for soil carbon solutions, such as the biochar version being perceived as less natural, and aversion to tampering with nature negatively predicting support for that version only. Together, these results suggest that Soil Carbon Storage that does *not* involve biochar may be especially politically feasible, something that policymakers—including President Biden, who highlighted Soil Carbon Storage on the presidential campaign trail (Gustin 2019)—may wish to note.

These results also carry implications for messengers seeking to build support for soil carbon and other CDR strategies among the public. Like with Afforestation and Reforestation, our findings suggest that the high naturalness perceptions enjoyed by both Soil Carbon Storage strategies may be a critical factor in their broad support, consistent with the documented preference for the "natural" over the "unnatural" (e.g., Rozin et al. 2004). Therefore, those seeking to bolster support for soil carbon sequestration as a climate mitigation strategy may wish to frame messaging in ways that highlight these naturalness associations—for example, by emphasizing elements of the strategy that may be perceived as most natural (i.e., the soil itself) or its co-benefits for agriculture and ecosystem functioning, and by de-emphasizing the strategy's more technical elements. At the same time, we note that the correlational nature of our regression analyses prevents us from speaking directly to any causal association that may exist between perceptions of naturalness and support for Soil Carbon Storage, or the other Carbon Dioxide Removal strategies we examined.

6 Limitations of the study

Although our work complements and extends on previous findings (Jobin and Siegrist 2020; Visschers et al. 2017; Wolske et al. 2019) by using a probability-based sampling approach to enable greater generalizability to the US public, and by examining public support for Soil Carbon Storage as well as Soil Carbon Storage with Biochar, we note some study limitations. We anticipated that the Carbon Dioxide Removal strategies we asked about would be unfamiliar to many of our respondents and, accordingly, we provided brief, scientifically accurate descriptions of each strategy to respondents before measuring their attitudes and policy preferences. Nevertheless, it is possible that the survey responses we analyze here are less crystalized, or perhaps less enduring, than those on other topics that the US public may consider more often (e.g., presidential

approval or belief in climate change). Furthermore, although the descriptions of the Carbon Dioxide Removal strategies we provided to respondents were intended to inform and not persuade, it is possible that the presence of the descriptions, or particular elements therein (e.g., the images used to visually represent each strategy), resulted in higher levels of policy support than would be observed in everyday contexts, or otherwise affected the results. As these Carbon Dioxide Removal strategies rise on the public agenda and receive increased media coverage, it will be important to more regularly survey the public to track trends in public support and to examine whether perceptions of naturalness remain a predictor moving forward. In addition, we reiterate that while our respondents were drawn from a probability-based survey panel that is constructed to be representative of US households, respondents who indicated they did not believe climate change is really happening ($N = 109$, or 8% of the sample) were not eligible to complete the questionnaire. While this methodological choice was motivated by a desire to bolster the interpretability of our main measures, which pre-suppose that climate change is happening, we acknowledge that some who deny the reality of climate change may nevertheless feel neutral to positive about Soil Carbon Storage or other Carbon Dioxide Removal strategies—a possibility that our design cannot address. As such, the findings reported here are more accurately described as being generalizable to the portion of the US public that accepts the reality of climate change—a large and growing share of the public (Leiserowitz 2007; Leiserowitz et al. 2019).

7 Conclusions

Overall, the present study suggests that Carbon Dioxide Removal strategies centered on Soil Carbon Storage enjoy widespread support among the US public as a climate change mitigation strategy, while underscoring the role of naturalness perceptions for this support as well as public support for various Carbon Dioxide Removal strategies. The importance of perceptions of naturalness suggests that public support may be garnered for soil carbon sequestration, including biochar, based on its alignment with natural carbon cycles. International science policy and integrated assessment models must consider public perception in projections of climate mitigation, and policymakers should bear in mind the greater public support for Soil Carbon Storage compared to Direct Air Capture and BECCS in the coming years. As climate solutions continue to rise on the public agenda, future research should track how public opinion on Soil Carbon Storage evolves over time, including the extent to which naturalness perceptions remain a key predictor of support over-and-above well-established predictors of climate policy support, such as political ideology.

Author contribution   S. Sweet and J. P. Schuldt performed the statistical analysis, wrote the initial draft, and contributed equally to the work. All co-authors contributed to the design of the survey and provided comments on subsequent drafts.

Data availability Data and syntax are available at: https://github.com/sks289/US-support-for-soil-carbon-CDRs.git

Declarations

Ethics approval This research was approved by the Institutional Review Board at Cornell University.

References

Amelung W, Bossio D, de Vries W, Kögel-Knabner I, Lehmann J, Amundson R, Bol R, Collins C, Lal R, Leifeld J, Minasny B, Pan G, Paustian K, Rumpel C, Sanderman J, van Groenigen JW, Mooney S, van Wesemael B, Wander M, Chabbi A (2020) Towards implementing a global-scale soil climate mitigation strategy. Nat Commun 11:5427

Amundson R, Biardeau L (2018) Opinion: soil carbon sequestration is an elusive climate mitigation tool. PNAS 115(46):11652–11656

Bassarak C, Pfister HR, Böhm G (2017) Dispute and morality in the perception of societal risks: extending the psychometric model. J Risk Res 20(3):299–325

Borick C, Rabe B (2012) Americans cool on geoengineering approaches to addressing climate change. Issues in Governance Studies 46(4):7

Bossio DA, Cook-Patton SC, Ellis PW, Fargione J, Sanderman J, Smith P, Wood S, Zomer RJ, von Unger M, Emmer IM, Griscom BW (2020) The role of soil carbon in natural climate solutions. Nat Sustain 3(5):391–398

Brulle RJ, Carmichael J, Jenkins JC (2012) Shifting public opinion on climate change: an empirical assessment of factors influencing concern over climate change in the US, 2002–2010. Clim Chang 114(2):169–188

Caldeira K, Bala G, Cao L (2013) The science of geoengineering. Annu Rev Earth Planet Sci 41

Campbell TH, Kay AC (2014) Solution aversion: on the relation between ideology and motivated disbelief. J Pers Soc Psychol 107(5):809

Campbell-Arvai V, Hart PS, Raimi KT, Wolske KS (2017) The influence of learning about Carbon Dioxide Removal (CDR) on support for mitigation policies. Clim Chang 143(3-4):321–336

Christoff P (2016) The promissory note: COP 21 and the Paris Climate Agreement. Environ Politics 25(5):765–787

Corner A, Pidgeon N (2014) Geoengineering, climate change scepticism and the 'moral hazard' argument: an experimental study of UK public perceptions. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 372(2031):2014006

Corner A, Pidgeon N, Parkhill K (2012) Perceptions of geoengineering: public attitudes, stakeholder perspectives, and the challenge of 'upstream' engagement. Wiley Interdiscip Rev Clim Chang 3(5):451–466

Corner A, Parkhill K, Pidgeon N, Vaughan NE (2013) Messing with nature? Exploring public perceptions of geoengineering in the UK. Glob Environ Chang 23(5):938–947

Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408(6809):184–187

Cruz SM (2017) The relationships of political ideology and party affiliation with environmental concern: a meta-analysis. J Environ Psychol 53:81–91

Demirbas A, Arin G (2002) An overview of biomass pyrolysis. Energy Sources 24(5):471–482

Doetterl S, Stevens A, Six J, Merckx R, Van Oost K, Pinto MC, Casanova-Katny A, Muñoz C, Boudin M, Venegas EZ, Boeckx P (2015) Soil Carbon Storage controlled by interactions between geochemistry and climate. Nat Geosci 8(10):780–783

Dryhurst S, Schneider CR, Kerr J, Freeman AL, Recchia G, Van Der Bles AM, Spiegelhalter D, van der Linden S (2020) Risk perceptions of COVID-19 around the world. J Risk Res:1–13

Dunlap RE, McCright AM, Yarosh JH (2016) The political divide on climate change: partisan polarization widens in the US. Environ Sci Policy Sustain Dev 58(5):4–23

Faran TS, Olsson L (2018) Geoengineering: neither economical, nor ethical – a risk – reward nexus analysis of Carbon Dioxide Removal. Int Environ Agreements 18(1):63–77

Field CB, Mach KJ (2017) Rightsizing carbon dioxide removal. Science 356(6339):706–707

Fielding KS, Head BW, Laffan W, Western M, Hoegh-Guldberg O (2012) Australian politicians' beliefs about climate change: political partisanship and political ideology. Env Polit 21(5):712–733

Funk C, Hefferon M (2019) U.S. public views on climate and energy. Pew Research Center

Funk C, Kennedy, B (2016). The politics of climate. Pew Research Center

Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira GW, Hartmann J, Khanna T, Luderer G (2018) Negative emissions—part 2: costs, potentials and side effects. Environ Res Lett 13(6):063002

García-Tejero IF, Carbonell R, Ordoñez R, Torres FP, Zuazo VHD (2020) Conservation agriculture practices to improve the soil water management and Soil Carbon Storage in Mediterranean rainfed agro-ecosystems. In Soil health restoration and management (pp. 203-230). Springer, Singapore

Gillis A, Vandenbergh M, Raimi K, Maki A, Wallston K (2021) Convincing conservatives: private sector action can bolster support for climate change mitigation in the United States. Energy Res Soc Sci 73:101947

Glenk K, Colombo S (2011) Designing policies to mitigate the agricultural contribution to climate change: an assessment of soil based carbon sequestration and its ancillary effects. Clim Chang 105(1–2):43–66

Goldberg MH, van der Linden S, Ballew MT, Rosenthal SA, Leiserowitz A (2019) The role of anchoring in judgments about expert consensus. J Appl Soc Psychol 49(3):192–200

Gurwick NP, Kelly C, Elias P (2012) The scientific basis for biochar as a climate change mitigation strategy: does it measure up. Union of Concerned Scientists 1-15

Gustin J (2019) These candidates see farming as a climate solution. Here's what they're proposing. Inside Climate News. Retrieved online from https://insideclimatenews.org/news/19072019/agriculture-climate-solution-election-2020-biden-warren-sanders-soil-carbon-conservation/

Hamilton LC (2011) Education, politics and opinions about climate change evidence for interaction effects. Clim Chang 104(2):231–242

Intergovernmental Panel on Climate Change [IPCC] (2018) Global warming of 1.5° C: an IPCC special report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Jobin M, Siegrist M (2020) Support for the deployment of climate engineering: a comparison of ten different technologies. Risk Anal 40(5):1058–1078

Kahan DM, Jenkins-Smith H, Tarantola T, Silva CL, Braman D (2015) Geoengineering and climate change polarization: testing a two-channel model of science communication. Ann Am Acad Pol Soc Sci 658(1):192–222

Kragt ME, Gibson FL, Maseyk F, Wilson KA (2016) Public willingness to pay for carbon farming and its co-benefits. Ecol Econ 126:125–131

Laird DA (2008) The charcoal vision: a win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. Agron J 100(1):178–181

Lal R, Follett RF, Kimble JM (2003) Achieving soil carbon sequestration in the United States: a challenge to the policy makers. Soil Sci 168(12):827–845

Lawrence MG, Schäfer S, Muri H, Scott V, Oschlies A, Vaughan NE, Boucher O, Schmidt H, Haywood J, Scheffran J (2018) Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals. Nat Commun 9(1):1–19

Lehmann J, Joseph S (Eds.) (2015) Biochar for environmental management: science, technology and implementation. Routledge

Leiserowitz A (2007) International public opinion, perception, and understanding of global climate change. Human Development Report 2008:1–40

Leiserowitz A, Maibach EW, Rosenthal S, Kotcher J, Bergquist P, Ballew M, Goldberg M, Gustafson A (2019) Climate change in the American mind: April 2019. Yale University and George Mason University. New Haven, CT: Yale Program on Climate Change Communication

McCright AM, Dunlap RE (2011) The politicization of climate change and polarization in the American public's views of global warming, 2001–2010. Sociol Q 52(2):155–194

Meko T (2016) Four ways to suck carbon out of thin air. Wash Post, February 27. https://www.washingtonpost.com/graphics/national/carboncapture/

Minasny B, Malone BP, McBratney AB, Angers D, Arrouays D, Chambers A, Chaplot V, Chen ZS, Cheng K, Das BS, Field DJ (2017) Soil carbon 4 per mille. Geoderma 292:59–86

Minx JC, Lamb WF, Callaghan MW, Bornmann L, Fuss S (2017) Fast growing research on negative emissions. Environ Res Lett 12(3):035007

Minx JC, Lamb WF, Callaghan MW, Fuss S, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira GW, Hartmann J, Khanna T (2018) Negative emissions—part 1: research landscape and synthesis. Environ Res Lett 13(6):063001

Miratrix LW, Sekhon JS, Theodoridis AG, Campos LF (2018) Worth weighting? How to think about and use weights in survey experiments. Polit Anal 26(3):275–291

Motta M, Chapman D, Stecula D, Haglin K (2019) An experimental examination of measurement disparities in public climate change beliefs. Clim Chang 154(1):37–47

Preston CJ (2013) Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and Carbon Dioxide Removal. Wiley Interdiscip Rev Clim Chang 4(1):23–37

Raimi KT, Wolske KS, Hart PS, Campbell-Arvai V (2020) The Aversion to Tampering with Nature (ATN) scale: individual differences in (dis) comfort with altering the natural world. Risk Anal 40(3):638–656

Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Handa C, Kheshgi H, Kobayashi S, Kriegler L, Mundaca L (2018) Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [In Press]

Rozin P, Spranca M, Krieger Z, Neuhaus R, Surillo D, Swerdlin A, Wood K (2004) Preference for natural: instrumental and ideational/moral motivations, and the contrast between foods and medicines. Appetite 43(2):147–154

Rozin P, Fischler C, Shields-Argelès C (2012) European and American perspectives on the meaning of natural. Appetite 59(2):448–455

Schuldt JP, Eiseman DL, Hoffmann MP (2020) Public concern about climate change impacts on food choices: the interplay of knowledge and politics. Agr Hum Val1-9

Shrum TR, Markowitz E, Buck H, Gregory R, van der Linden S, Attari SZ, Van Boven L (2020) Behavioural frameworks to understand public perceptions of and risk response to Carbon Dioxide Removal. Interface Focus 10(5):20200002

Sjöberg L (2000) Perceived risk and tampering with nature. J Risk Res 3(4):353–367

Slovic PE (Ed.) (2000) The perception of risk. Earthscan publications. Risk, society, and policy series

Smith P, Davis SJ, Creutzig F, Fuss S, Minx J, Gabrielle B, Kato E, Jackson RB, Cowie A, Kriegler E, Van Vuuren DP (2016) Biophysical and economic limits to negative CO 2 emissions. Nat Clim Chang 6(1):42–50

Solomon S, Plattner GK, Knutti R, Friedlingstein P (2009) Irreversible climate change due to carbon dioxide emissions. PNAS 106(6):1704–1709

Sykes AJ, Macleod M, Eory V, Rees RM, Payen F, Myrgiotis V, Williams M, Sohi S, Hillier J, Moran D, Manning DA (2020) Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. Glob Chang Biol 26(3):1085–1108

Van Boven L, Sherman, D (2018). Actually, Republicans do believe in climate change. New York Times. https://www.nytimes.com/2018/07/28/opinion/sunday/republicans-climate-change.html

van der Weerd W, Timmermans DR, Beaujean DJ, Oudhoff J, van Steenbergen JE (2011) Monitoring the level of government trust, risk perception and intention of the general public to adopt protective measures during the influenza A (H1N1) pandemic in the Netherlands. BMC Public Health 11(1):575

Van Vuuren DP, Stehfest E, Gernaat DE, Van Den Berg M, Bijl DL, De Boer HS, Daioglou V, Doelman JC, Edelenbosch O, Harmsen M, Hof AF (2018) Alternative pathways to the 1.5 C target reduce the need for negative emission technologies. Nat Clim Chang 8(5):391–397

Vermeulen S, Bossio D, Lehmann J, Luu P, Paustian K, Webb C, Augé F, Bacudo I, Baedeker T, Havemann T, Jones C (2019) A global agenda for collective action on soil carbon. Nat Sustain 2(1):2–4

Visschers VH, Shi J, Siegrist M, Arvai J (2017) Beliefs and values explain international differences in perception of solar radiation management: insights from a cross-country survey. Clim Chang 142(3-4):531–544

Walter D, Böhmer MM, Reiter S, Krause G, Wichmann O (2012) Risk perception and information-seeking behaviour during the 2009/10 influenza A (H1N1) pdm09 pandemic in Germany. Eurosurveillance 17(13):20131

Winsley P (2007) Biochar and bioenergy production for climate change mitigation. New Zealand Science Review 64(1):5–10

Wolske KS, Raimi KT, Campbell-Arvai V, Hart PS (2019) Public support for Carbon Dioxide Removal strategies: the role of tampering with nature perceptions. Clim Chang 152(3-4):345–361

Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. Nat Commun 1:56

Wright MJ, Teagle DA, Feetham PM (2014) A quantitative evaluation of the public response to climate engineering. Nat Clim Chang 4(2):106–110