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The public remain uninformed and wary of climate engineering

Daniel P. Carlisle[1] · Pamela M. Feetham[1] · Malcolm J. Wright[2,3] · Damon A. H. Teagle[4]

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Abstract
International CO_2 emissions reduction commitments are insufficient to avert damaging global warming and imperil a sustainable future. Climate engineering approaches are increasingly proposed as near-term intervention strategies, but deployment of these controversial techniques will require careful engagement with and the support of the public. New quantitative measurements of public perceptions for six climate engineering approaches show that the public of the United Kingdom (UK), United States (US), Australia (AU) and New Zealand (NZ) continue to have little knowledge of climate engineering. All approaches are regarded unfavourably, albeit less so for carbon dioxide removal (CDR) than solar radiation management (SRM). Knowledge and perceptions are remarkably similar between countries although UK and US respondents are more favourable towards SRM and UK respondents are more favourable towards CDR. Stratospheric aerosol injection is the most negatively perceived approach. Support for small-scale trials is also higher for CDR approaches than SRM. Statistical analyses yield mixed relationships between perceptions of climate engineering and age, political affiliation and pro-ecological views. Thus far, attempts to engage the public with climate engineering have seen little change over time and consequently, there is growing urgency to facilitate careful citizen deliberation using objective and instructive information about climate engineering.

Keywords Public engagement · Climate engineering · Geoengineering · Cross-country · Framing effects

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✉ Daniel P. Carlisle
D.Carlisle@massey.ac.nz

Extended author information available on the last page of the article

1 Introduction

Following COP 21 in Paris, 194 nations agreed to limit future global warming to less than 2 °C above pre-industrial levels, although < 1.5 °C is a preferred target for many nations. These 194 nations face significant challenges and decisions on their pathways to reducing greenhouse gas emissions. The agreed actions to date are insufficient to achieve the targets (Bawden 2016; Lawrence et al. 2018; Schleussner et al. 2016) with the current Paris pledges providing less than half the emissions reductions required (UNEP 2018). Many national net-zero ambitions rely on substantial negative emissions to balance CO_2 inputs from difficult to decarbonise sectors (e.g. cement, land-use, shipping, air travel), but remain imprecise about how this CO_2-drawdown will be achieved. The unlikelihood of reaching the Paris goals through mitigation alone has prompted new calls for globally governed research into potential large-scale climate engineering approaches (Bellamy and Healey 2018; Biermann and Möller 2019; Ki-moon 2019) including carbon dioxide removal (CDR) approaches that sequester atmospheric carbon dioxide and solar radiation management (SRM) methods that alter the radiative forcing of Earth's atmosphere (Horton 2015; Lawrence et al. 2018).

Researchers worldwide report on-going technological advances and continue to develop knowledge of climate engineering feasibility and impacts (Irvine et al. 2019; Lawrence et al. 2018; MacMartin et al. 2018; Royal Society and Royal Academy of Engineering 2018; Salter et al. 2014; Smith et al. 2018). Initiatives such as the Geoengineering Model Inter-comparison Project (GeoMIP) allow scientists to conduct multiple climate modelling simulations to estimate the likely global impacts of particular climate interventions (Kravitz et al. 2018, 2019). Interest is also building in the Harvard-based Stratospheric Controlled Perturbation Experiment (SCoPEx) project that would release aerosols from a balloon to study aerosol physics and chemistry related to some SRM approaches. Following the 2012 withdrawal of the similar UK-based 'SPICE' project, SCoPEx would be the first explicit field test of SRM technologies (Tollefson 2018). Currently, uncertainty remains around the global impacts of climate engineering as most research is restricted to computer modelling or controlled laboratory settings (Lawrence et al. 2018). Scientists are also careful to point out that climate engineering is not a panacea for failure to achieve emissions reductions, and must be deployed in concert with, rather than a distraction from accelerated improvements in energy efficiency and greenhouse gas emissions reduction efforts (Royal Society and Royal Academy of Engineering 2018).

The warnings for more action on Paris Agreement targets highlight the urgency for researchers and policy makers to engage the public in the development of potential solutions including climate engineering approaches (Burns et al. 2016; Rayner et al. 2013) before societies are confronted with the necessity of deploying such techniques at scale. Despite increasing research on public perceptions of climate engineering (Cummings et al. 2017) there are still substantial gaps in the literature. Few studies investigate public perceptions outside of developed nations in the northern hemisphere (Burns et al. 2016) or over time (Braun et al. 2018b).

The present quantitative work, therefore, examines public perceptions of climate engineering in surveys conducted across four countries and innovatively, over time. It is the first study to systematically measure public perceptions from surveys conducted in the United Kingdom (UK), United States (US), Australia (AU) and New Zealand (NZ) in December 2018, against previous measurements derived from surveys conducted in AU and NZ in December 2012 (Wright et al. 2014). The method draws on well-established psychological theory and marketing techniques to elicit and measure cognitive associations with new product concepts or brands (Anderson 1983; Anderson and Bower 1974; Romaniuk 2013; Wright et al. 2014). The present work substantively expanded the original study with fresh fieldwork that drew on new knowledge and technological advancements within the field of climate engineering, as well as further understanding of framing effects raised in recent literature. We also examine the associations with demographics, ecological views and political party affiliation on public perceptions of climate engineering and whether the public would support small-scale trials for each of the six approaches. The resulting analysis provides a robust system that quantifies public perceptions of climate engineering and provides a benchmark for future comparisons of public opinions by sampling across multiple countries and over time. Tracking public opinion, whether changed or stagnant, over time, provides imperative information for policy makers and those organisations responsible for collaborating and communicating with the public on potential climate solutions.

1.1 Public engagement with emerging technologies

Public engagement is increasingly sought as a key element of the governance of emerging science and technology. Over the years, three key arguments have emerged to promote public participation (Chilvers 2009; Fiorino 1990; Stirling 2008; Wilsdon and Willis 2004; Winickoff et al. 2015). The normative rationale suggests public participation is necessary in democracy and that the public have a right to be involved in policy that will affect them. The substantive rationale claims that public participation can improve decision-making and outcomes by incorporating diverse knowledge and viewpoints. Finally, the instrumental rationale suggests participation can achieve specific outcomes including increasing trust in science, enhancing legitimacy of institutions and avoiding conflict. The latter substantive and instrumental outcomes are rarely evidenced in practice (Chilvers 2009), leading to the question of what value public participation might provide beyond the tokenistic attempts at democracy. Nonetheless, the growing impetus for public engagement with science is apparent across a range of emerging technologies (Stirling 2008), such as nanotechnologies (Rogers-Hayden and Pidgeon 2007) and climate engineering (Bellamy and Lezaun 2017; Corner et al. 2012).

Social scientists also differentiate between three types of public engagement mechanisms (Rowe and Frewer 2005). *Public communication* mechanisms involve a passive process where the public receive information, but do not play an active role in informing decision making; *public consultation* mechanisms, including the current study, are used to elicit opinions from the public; and *public participation* mechanisms involve dialogue between stakeholders and the public to share knowledge and negotiate understanding. Each of these types of public engagement has inherent flaws. One main criticism relates to public communication mechanisms and the ‘deficit’ model of science communication. The deficit model assumed that educating the public through communication mechanisms would improve citizens’ perceptions of science (Corner and Pidgeon 2010). Contemporary public consultation and public participation mechanisms reject the deficit model and imply citizens can make informed judgements in the absence of technical knowledge under the right conditions (Wilsdon and Willis 2004).

Given the global significance of climate engineering, large-scale public consultation methods, are needed to provide systematic measurement of public opinion across global populations. Quantitative surveys address these needs but are typically restricted by narrow standardised measures of ‘acceptance’ or ‘support’. These attitudinal measures are criticised for disregarding more nuanced positions and overlooking participants underlying reasoning. Accordingly, there is concern among social scientists that quantitative survey research may not reflect actual public opinion and could exclude legitimate policy alternatives from future consideration (Bellamy et al. 2012). One method of addressing these concerns is small-scale participatory mechanisms that encourage citizens to engage in nuanced discussions and challenge the underlying assumptions that shape the appraisal process. For example, Bellamy et al. (2016) report a deliberative appraisal method where participants developed their own appraisal criteria that better reflect the small groups' opinions on climate engineering proposals. To address these concerns, the current study draws on participative elements in an initial qualitative phase to identify a list of citizen-generated appraisal criteria that are later applied in the quantitative phase of public consultation.

1.2 Framing the climate engineering debate

Eliciting public opinion on emerging technologies is particularly challenging as citizens are often unfamiliar with the technologies in question. One issue is that survey instruments may elicit 'non-attitudes' where participants respond to questionnaire items despite holding no genuine prior opinion on the matter (Asher 2017). These non-attitude responses are often sensitive to minor changes in questionnaire wording and may distort measures of public opinion. Researchers have therefore raised concerns about the way climate engineering is framed during public engagement.

One framing concern is that CDR and SRM approaches should not be lumped together under the broad umbrella term 'climate engineering' as CDR approaches are substantially different from SRM (Heyward 2013; Lomax et al. 2015; Minx et al. 2018). CDR approaches share greater similarities with mitigation strategies that reduce atmospheric carbon concentrations, whereas SRM approaches do not (Minx et al. 2018). Another framing concern is that the higher risk profile of SRM approaches will negatively affect perceptions of CDR approaches, forestalling their serious consideration (Colvin et al. 2019; Horton 2015). Given the substantial differences within CDR and SRM categories, Colvin et al. (2019) argue individual technologies should be considered independently to facilitate nuanced discussion and avoid sweeping generalisations. Other framing issues are the need to evaluate climate engineering approaches within the broader context of alternative strategies, such as mitigation and adaptation (Bellamy et al. 2012; Bellamy and Lezaun 2017), to ensure that linguistic frames avoid use of natural analogies, such as likening air capture to 'artificial trees' (Corner and Pidgeon 2015) and to recognise that terms such as 'insufficient mitigation' or 'climate emergency' narrow and pre-empt the direction of discussions (Bellamy et al. 2013; Bellamy and Lezaun 2017; Corner et al. 2011).

Since there is concern among social scientists that framing may have undue effects on perspectives of climate engineering, we take care to minimise such effects. We avoid the term climate engineering and instead refer to potential solutions to rising global temperatures. We avoid the use of natural analogies (Corner and Pidgeon 2015) and statements about a 'climate emergency' or 'insufficient mitigation' (Bellamy et al. 2013; Corner et al. 2011). We define responses as distinct policy options alongside adaptation and mitigation, present the approaches individually and apply new scientific knowledge to update the descriptions and images used.

2 Methods

The research method is validated in two ways. First, its theoretical foundations are well established in cognitive psychology. Second, the brand imaging techniques developed from

Table 1 Approaches for carbon dioxide removal and solar radiation management

Carbon dioxide removal		
Biochar	–	Biomass is converted into a charcoal-like product to lock-in carbon.
Bioenergy with carbon capture and storage	BECCS	Biomass is combusted to produce renewable energy and carbon dioxide emissions are captured and stored in geological reservoirs.
Direct air capture and carbon storage	DACCS	Carbon dioxide is filtered from the atmosphere using engineered structures and stored in geological reservoirs.
Enhanced weathering	EW	Materials (e.g. silicate minerals) are finely ground to accelerate chemical reactions that remove carbon dioxide from the atmosphere.
Solar radiation management		
Marine cloud brightening	MCB	Tiny seawater droplets are sprayed into low altitude marine clouds to increase their reflectivity.
Mirrors in space	MIS	Space-based materials or structures reflect a portion of incoming sunlight.
Stratospheric aerosol injection	SAI	Sulphate particles are spread in the stratosphere to reflect incoming sunlight.

For further reading on CDR and SRM see Lawrence et al. (2018), National Academies of Science (2015a), National Academies of Science (2015b), Royal Society and Royal Academy of Engineering (2018)

these theories by branding experts are widely applied commercially. The method's founding theories of Associative Network Theory of Memory (ANTM) and the Adaptive Control of Thought model (Anderson 1983; Anderson and Bower 1974) describe how a concept is encoded, retrieved and stored in memory. When humans are faced with an external stimulus such as an image or concept description, information stored in memory actively cascades through a network of associated nodes to help with interpretation and problem solving (Wright et al. 2014). Brand experts developed these theories to systematically and quantitatively elicit cognitive associations with concepts or brands that are mapped in images (Romaniuk 2013; Wright et al. 2014). The 2012 study demonstrated that this system adapts to other domains such as emerging science by measuring the attributes associated with climate engineering proposals and is replicated in this study.

The surveys undertaken in 2012 commenced with qualitative research on climate engineering associations ($n = 30$) followed by quantitative data collection ($n = 2028$) on the public perceptions of three CDR approaches *Biochar*, *Air Capture* and *Enhanced Weathering*, and three SRM approaches *Cloud Brightening*, *Stratospheric Aerosols* and *Mirrors in Space* (Wright et al. 2014). The 2018 surveys undertook new qualitative research ($n = 15$) followed by new quantitative data collection ($n = 2989$) for Bioenergy with Carbon Capture and Storage (*BECCS*), Direct Air Capture and Carbon Storage (*DACCS*), Enhanced Weathering (*EW*), Marine Cloud Brightening (*MCB*), Stratospheric Aerosol Injection (*SAI*) and Mirrors in Space (*MIS)*. Since the choice of climate engineering approaches can affect research outcomes (Bellamy et al. 2012), we acknowledge the current study excludes other possible climate engineering approaches (e.g. biochar, cirrus cloud thinning and afforestation) and outline the rationale behind our choices. Public perceptions of *BECCS* remain understudied (Bellamy et al. 2019) despite playing a major role in several modelling scenarios to meet 1.5 °C or 2 °C targets, in the IPCC (2014) Fifth Assessment Report. Therefore, *BECCS* replaces *Biochar* for evaluation to maintain a balance of three CDR and three SRM approaches. Replacing MIS was also considered due to issues of feasibility. However, public and policy interest in MIS has continued to be expressed, for example with American democratic candidate Andrew Yang campaigning on providing $800 million USD in funding for SRM research, including MIS.

Thus, MIS is retained in the current study. Table 1 briefly summarises the CDR and SRM approaches from the 2012 and 2018 surveys.

To reflect recent advances in scientific knowledge, we update the descriptions of each climate engineering approach used in the 2012 materials and draw on recent imagery used by the Royal Society and Royal Academy of Engineering (2018) and Lawrence et al. (2018). The concept boards use consistent formatting and content across techniques. Descriptions begin with three sentences describing the concept, method of application and advantages, including the cooling effect and other benefits. Next, two or three sentences outline the costs, possible unintended outcomes and any caveats associated with implementation. The final two or three sentences outline how the method would be implemented over time, the scale of implementation required and indicated whether the method would require international agreements. Final descriptions are between 93 and 100 words and avoid use of adjectives from the attribute list. Some similar or identical phrases are used in multiple approaches where appropriate. Imagery is designed following similar matching criteria for scale, content and colour. As in the original study, we do not attempt to evaluate visual processing of imagery. The concept boards and questionnaires were peer-reviewed within the authorship team with additional feedback solicited from two independent international experts and from citizens within the sampling frame. Minor word adjustments were applied after this feedback and the concepts boards were further validated through successful application in the qualitative interviews ($n = 15$). Figure 1 provides an example of the BECCS concept imagery and description, used in the qualitative and quantitative materials (see Supplementary Fig. 2 for all six concept boards).

2.1 Qualitative phase (2018)

The aim of the qualitative phase is to explore the ways that citizens think about the topic to identify any new constructs associated with climate engineering approaches compared to the 2012 research (Wright et al. 2014). The output of this phase is a set of common attributes that are used in the quantitative phase as criteria for evaluating climate engineering approaches. Using attributes (criteria) developed by citizens incorporates diverse and inclusive public perspectives to 'open up' the quantitative appraisal process (Bellamy et al. 2016). Whereas criteria generated by experts or researchers may not accurately reflect public perspectives and could bias appraisal outputs.

The qualitative phase includes fifteen in-depth interviews using the Kelly's Repertory Grid elicitation technique and follows the method previously applied in the qualitative phase of the

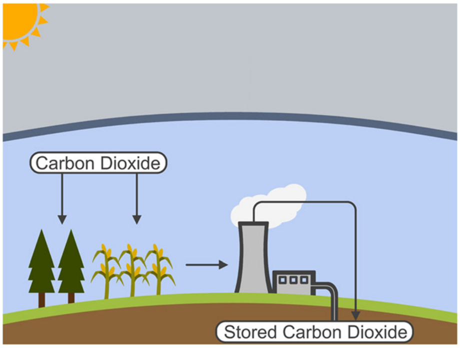

Fig. 1 Bio-energy with carbon capture and storage

2012 study (Rogers and Ryals 2007; Wright et al. 2014). The sample is purposively selected to maximise demographic diversity and consists of 53% female and 47% male New Zealanders, aged between 21 and 63 years, and with varied occupations (Supplementary Table 1). The Kelly's Repertory Grid technique invites participants to identify two concepts out of a set of three, and to explain how the pair are alike yet different from the third. The method in this case is used to identify a list of attributes associated with each climate engineering approach. Prior to the exercise, participants read all six concept boards. Participants were then sequentially presented with six sets of three concept boards to evaluate similarities and differences. Sets were predetermined to ensure each concept was evaluated three times. The presentation order of the six sets and the order of three concept boards within each set was randomised by the interviewer. Responses were audio-recorded and analysed by themes to identify attributes commonly elicited from participants. The attributes emerging from the qualitative phase in 2018 were congruent with those uncovered in the 2012 study. We therefore proceeded to the quantitative phase using the same 12 attributes as the earlier study (Wright et al. 2014).

2.2 Quantitative phase (2018)

2.2.1 Sampling

The quantitative phase consists of large-scale surveys in the UK (number of participants, $n = 751$), US ($n = 746$), Australia ($n = 763$) and New Zealand ($n = 729$) using a commercial online panel provider; Dynata (formerly ResearchNow, https://www.dynata.com). Survey invitations are topic-blind to mitigate response bias. Invitations are issued to panel members continuously until sample and demographic quotas are met. Recruitment bias is unlikely given the substantial size of the panels ($n = 1,200,000$ in the UK, $n = 11,570,000$ in US, $n = 780,000$ in Australia and $n = 260,000$ in New Zealand). Coverage bias is also minimised with high levels of internet access in all four countries.[1] The surveys were conducted in early December (week commencing 30 November) 2018, the same time of year as the 2012 study (Wright et al. 2014).

2.2.2 Participants

Supplementary Tables 2, 3, 4 and 5 report the demographic breakdown of the quantitative samples along with comparative census data or similar independent population estimates for gender, age and political support. The sample characteristics for each country show a satisfactory spread of demographics with overall only small deviations from population estimates. Therefore, sample composition is acceptable for the purposes of this research.

2.2.3 Data collection

The survey questionnaire is the same for all countries except for minor differences in demographic items. The questionnaire was pretested among several survey design experts and non-experts who experienced no major difficulties in interpreting questions, understanding the concepts or the survey flow. Minor improvements were made to the survey design after this

[1] Internet access across the four samples is as follows: 90% in the UK (Office for National Statistics 2018), 84% in the US (Ryan and Lewis 2017), 86% in Australia (Australia Bureau of Statistics 2017) and 94% in New Zealand (Díaz Andrade et al. 2018).

feedback. Prior to the survey's full launch, responses from 70 initial participants were checked to ensure the questions were not misunderstood. No further changes were made, and the full launch proceeded until quotas were achieved.

The questionnaire prepares participants to give meaningful responses by briefly introducing the topic and asking general questions about global warming (see Supplementary Fig. 1 for questionnaire wording). Respondents then move to the concept evaluation block where they are sequentially presented with concept boards for each climate engineering approach. Respondents evaluate all six climate engineering approaches individually by selecting from the pre-determined list of 12 attributes confirmed in the qualitative phase of research. The presentation order of concepts and attributes is randomised to avoid order effects. Additional questionnaire items are included to supplement the principal analysis of respondents' attribute associations, including support for small scale trials, understanding of concept boards, ecological views and prior knowledge of the climate engineering approaches (see Supplementary Tables 6 and 7 for question wording). The survey concludes with demographic items.

2.2.4 Measures

Attribute associations Public perceptions are measured from the count of attribute associations elicited from individual participants for each climate engineering approach. Responses are measured using a free choice, pick-any format and each attribute is coded as '1 = selected' or '0 = not selected' for each approach (see Supplementary Table 6 for question wording). Modelling mental associations using a binary variable is a requirement of the current method and is appropriate as an association can either exist or not exist in memory (Romaniuk 2013). Measuring attribute associations in this manner also has significant advantages over traditional attitudinal scales that are prone to 'non-attitude' responses. Rather than measuring fabricated non-attitudes, the current method relies on pre-existing memory associations. Where a respondent has no attitudes toward a climate engineering approach, the attribute selection task would yield few attribute associations compared to respondents with strong attitudes. In contrast, attitudinal scales fail to differentiate between non-attitudes and genuine responses and give each response equal weight in subsequent analysis. Consequently, attribute association measures are comparatively less prone to bias from non-attitude responding.

Following diagnostic tests (Supplementary Table 8) the final list of attributes is reduced to 10 to avoid duplicate measurement from overlapping attributes (Romaniuk 2013). The final attribute list maintains a balance of five positive and five negative attributes. To enable further analysis, a net positive variable is calculated as the sum of each respondents' positive attribute associations minus the sum of their negative attribute associations for each approach. The principal analysis involves aggregating the net positive variable by individual technique, by CDR techniques, by SRM techniques or over all six climate engineering techniques to make each relevant comparison. To enable comparisons between samples of different sizes, the net positive value is converted into a percentage where appropriate.

The statistical properties of the net positive variable are examined using aggregation by respondent. The overall net positive variable can take any value between −30 and 30 where '0' represents net-zero positive associations (mean ranging from −3.28 to −4.86 across all countries, standard deviation ranging from 6.43 to 7.19). Graphical analysis shows a close approximation to the normal distribution in all four countries (Supplementary Fig. 3 and 4) and kurtosis and skewness are also acceptable (Supplementary Table 9) indicating the net positive variable is suitable for further analysis using standard statistical methods.

Univariate tests of associations between the net positive variable and demographic variables identify statistically significant relationships with age and political party variables (see Section 3.3.1 and Supplementary Table 10). However, multivariate analysis does not reveal any significant effect of demographics on the net positive variable once 2-way interactions and Bonferroni corrections are considered (Supplementary Table 11). Therefore, neither age nor political party are deemed necessary as covariates for the principal analyses.

Understanding To check the adequacy of the concept boards, respondents are asked whether they could explain each approach to someone else using a 5-point Likert-style scale (see Supplementary Table 6 for question wording) where 1 = strongly agree and 5 = strongly disagree (mean ranges from 2.68 to 2.88 across technologies, standard deviation ranges from 0.99 to 1.03). Results show similar satisfactory levels of understanding to the 2012 study: 34–48% indicating they could explain the concept to someone else, 32–41% is neutral and only 16–27% disagree.

Support for small-scale trials For each technique, participants are asked to indicate their support for small-scale trials on a 5-point Likert-style scale (see Supplementary Table 6 for question wording) where 1 = strongly agree and 5 = strongly disagree (mean ranges from 2.71 to 3.25 across technologies, standard deviation ranges from 1.05 to 1.10). The subject of small-scale trials reflects the current state of climate engineering R&D where computer modelling research is already underway and the potential progression to outdoor trials will likely become a matter of public concern.

Prior awareness Following the concept evaluations, respondents are asked 'Did you know about any of these proposals before you began this survey?'. Responses are coded as '0 = no' or '1 = yes' (mean ranges from 0.14 to 0.18 across countries, standard deviation ranges from 0.34 to 0.38).

Ecological views Ecological views are measured using five items from the New Ecological Paradigm (NEP) scale (Dunlap et al. 2000). Prior public perception studies yield either mixed or non-significant relationships between NEP items and support for different climate engineering technologies (Braun et al. 2018a, b; Dütschke et al. 2016; Merk and Pönitzsch 2017; Merk et al. 2015). Responses are recorded using a 5-point Likert-style scale where 1 = strongly agree and 5 = strongly disagree. Three items are worded so that agreement indicates a strong ecological orientation, whereas agreement with the other two items indicates a weak ecological orientation (see Supplementary Table 7 for question wording). All items are recoded for analysis so that 1 = strong ecological orientation and 5 = weak ecological orientation.

Factor analysis using principal component analysis with varimax rotation identifies three positively worded items that load heavily on one factor accounting for 37.5–40.2% of the total variation, whereas the negatively worded items load on a separate factor. The scale is therefore reduced to the three positively worded items (Cronbach's α ranging from 0.679 to 0.727 across countries, average 0.715) and aggregated to form an overall NEP score where 15 represents a weak ecological orientation and 3 represents a strong ecological orientation (mean ranging from 5.73 to 6.56 across countries; standard deviation ranging from 2.14 to 2.53). The distribution of this variable is approximately normal in all four countries (skewness ranging from 0.69 to 0.87 across countries; kurtosis ranging from 0.37 to 1.27), so bivariate correlations are used to assess the relationship between the NEP variable and net positive association variables.

2.2.5 Comparisons between samples

Differences between countries in the CDR and SRM net positive variables are assessed using ANOVA (Supplementary Table 12). A Levene test indicates heterogeneous variance between samples, although the ratios of variance between samples are less than 1.5, indicating the ANOVA is still appropriate. We also test for shifts in public perceptions over time by comparing AU and NZ samples from the current 2018 study against those collected in 2012 by Wright et al. (2014). Due to the replacement of *Biochar* with *BECCS*, we test for differences in the net positive variables for *DACCS*, *EW*, *MCB*, *MIS* and *SAI* using independent sample *t* tests.

2.2.6 Construction of concept maps

To explore the nuanced differences in public perceptions between climate engineering approaches, a concept map for each approach is developed through a chi-square calculation of expected cell counts for each attribute (see Supplementary Table 13), calculation of percentage skews (deviations) between actual counts and expected values (see Supplementary Table 14), and then reporting of skews in graphical format (see Supplementary Figs. 5–8 for concepts maps of all approaches for each country). To further explore the rationale behind the perceived differences between approaches, the absolute values of attribute skews are averaged across the six approaches to produce the mean skew per attribute (see Supplementary Table 14).

3 Results

3.1 Public awareness

Despite strong arguments for early public deliberation and increasing availability of information, the public continues to demonstrate little knowledge of climate engineering approaches

Table 2 Attribute popularity (salience) for climate engineering approaches, as % of country associations

Rank	Attribute	UK 2018	US 2018	AU 2018	NZ 2018	AU 2012	NZ 2012
1	Unknown effects	22	24	24	24	24	25
2	Risky	17	19	19	18	16	16
3	Artificial	13	12	13	14	12	13
4	Understandable	9	7	7	8	8	7
5	Environmentally friendly	8	8	8	7	8	9
6	Controllable	8	7	7	7	7	8
7	Long-term sustainability	7	7	7	7	7	7
8	Quick-fix	6	6	6	6	7	6
9	Eyesore	5	5	5	6	6	6
10	Cost effective	5	5	5	4	5	3

Table 3 Memory associations for climate engineering approaches as counts and as % net positive associations

	Bioenergy with carbon capture and storage	Direct air capture and carbon storage	Enhanced weathering	Marine cloud brightening	Mirrors in space	Stratospheric aerosol injection	Total
Count of associations (2018)							
UK ($n = 751$)	1529	1513	1537	1449	1527	1507	9062
US ($n = 746$)	1456	1418	1481	1424	1535	1503	8817
Australia ($n = 763$)	1618	1664	1606	1597	1670	1696	9851
New Zealand ($n = 729$)	1683	1705	1628	1689	1692	1725	10,122
Net positive associations (2018)							
UK	4%	− 8%	− 11%	− 39%	− 48%	− 62%	− 27%
US	− 9%	− 13%	− 23%	− 41%	− 41%	− 59%	− 31%
Australia	− 6%	− 13%	− 22%	− 52%	− 53%	− 62%	− 35%
New Zealand	− 1%	− 18%	− 22%	− 44%	− 58%	− 66%	− 35%
Net positive associations (2012)	(Biochar)						
Australia	− 4%	− 13%	− 26%	− 49%	− 59%	− 54%	− 34%
New Zealand	3%	− 16%	− 32%	− 57%	− 73%	− 70%	− 40%

(Cummings et al. 2017; Wright et al. 2014). In 2012, respondents in AU and NZ surveys were asked whether they had prior knowledge of climate engineering approaches. Only 18% of the AU and NZ respondents acknowledged some awareness of these techniques (Wright et al. 2014). In the 2018 survey, the same question found only 18% (UK), 16% (US), 14% (AU), and 15% (NZ) of respondents reported prior knowledge of the climate engineering approaches tested (95% confidence intervals are plus or minus 1.2 to 1.4 percentage points).

3.2 Attribute popularity

Attribute popularity (salience) is measured as each attribute's share of all associations for that country. Although there are substantial variations in share of associations between attributes, there are negligible differences in shares of associations between countries or between years (Table 2). The shares of associations show remarkable consistency with correlations of no less than $r = 0.99$ between countries (within each year) and $r = 0.98$ between years (within AU and NZ).

Of the ten attributes analysed. The most frequently chosen by respondents are the three negative attributes *unknown effects, risky* and *artificial*. In AU and NZ, these three attributes demonstrate little change from 2012 and still account for just over 50% of all associations. When the same data are aggregated by climate engineering approaches they yield a count of associations for each approach, together with the 'net positive' expressed as the total associations for that approach. This calculation of a 'net positive' variable enables the public perceptions of the six approaches to be ranked on that variable (Table 3).

BECCS replaces *Biochar* as the least negatively perceived approach, whereas *Stratospheric Aerosol Injection*, overtakes *Mirrors in Space* as the most negatively perceived approach. Remarkably, net positive associations for all six approaches show little variation between countries and only minor changes over time. They remain broadly negative, although CDR approaches continue to be perceived less negatively than SRM approaches.

3.3 Variables influencing public perceptions

3.3.1 Demographics

Demographic effects on the net positive variable were examined both individually, through univariate tests (Supplementary Table 10), and jointly through multivariate tests that included 2-way interactions (Supplementary Table 11) to investigate whether demographic characteristics influence individuals' evaluations of climate engineering. Univariate tests reveal statistically significant relationships between the net positive variable and age and political party variables. Age is recorded as year-born and coded in reverse to give the intuitive interpretation of increasing numbers being equivalent to increasing age, indicating older people tend to be more negative about climate engineering than younger people; however, the effect is small as indicated by r values of less than 0.30. Turning to consider political party affiliation, Republicans in the US are more negative towards climate engineering than Democrats. A significant relationship is also found in Australia, UK and NZ where respondents who selected 'Other (Please Specify):' were more negative about climate engineering; however, several of these respondents did not provide a clear affiliation (e.g. 'none', 'I don't know', 'prefer not to say'). As noted earlier, multivariate analysis does not reveal any significant effect of demographics on the net positive variable once 2-way interactions and Bonferroni corrections are considered.

3.3.2 Ecological views

For CDR proposals, strong ecological views are significantly correlated with less negative net associations in UK $r = 0.142$, ($p < 0.001$), US $r = 0.168$, ($p < 0.001$) and NZ $r = 0.117$, ($p = 0.002$). In contrast, for SRM proposals, pro-ecological views are significantly correlated with more negative net associations in UK $r = -0.103$, ($p = 0.005$) and AU $r = -0.095$, ($p = 0.009$). These results suggest ecological views influence public perceptions of climate engineering and support the proposition that the interaction between ecological and technological views are nuanced and not diametrically opposed (Scarrow 2019). Increasing pro-ecological views among the public may further increase support for CDR and reduce support for SRM.

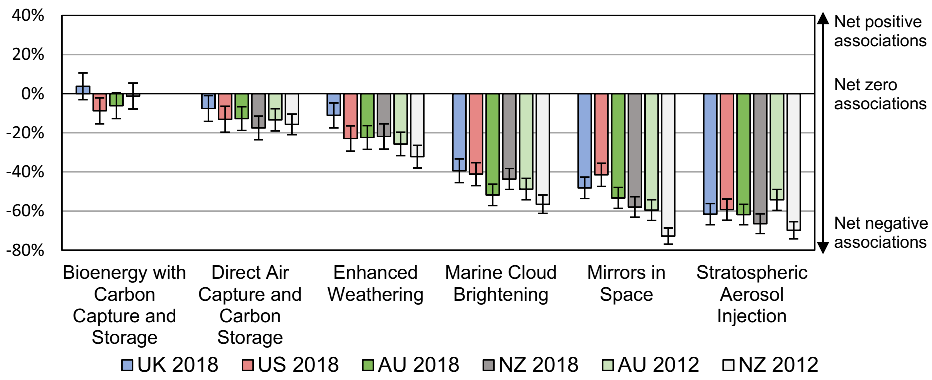

Fig. 2 Net positive memory associations for climate engineering approaches. The bar chart shows that public perceptions of climate engineering proposals are negative, although less so for CDR than SRM. For each proposal, there is little variation between countries and over time. Error bars show 95% confidence intervals

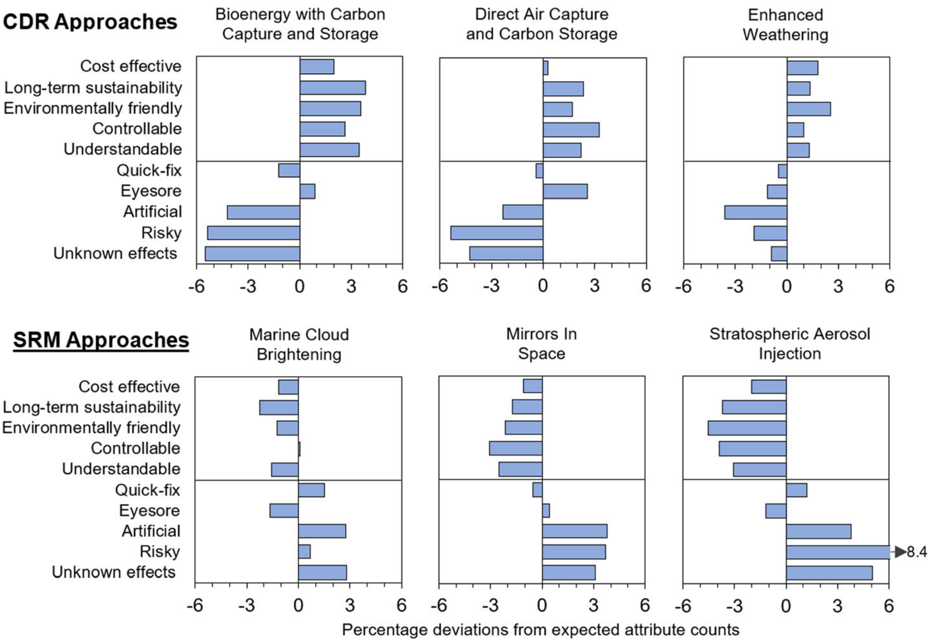

Fig. 3 Concept maps for climate engineering approaches in the UK show percentage point deviations from expected attribute counts. CDR approaches skew toward more positive attributes (top row panels), whereas SRM approaches skew toward more negative attributes (bottom row panels)

However, caution is needed when interpreting these findings as ecological attitudes are known to be poor predictors of actual behaviour (Wright and Klÿn 1998).

3.4 Differences between samples

We test for differences in perceptions of CDR and SRM proposals between countries with ANOVA and a Games Howell post hoc test (Supplementary Table 12). The analysis reveals the UK sample is slightly less negative towards CDR approaches than the US, AU and NZ samples ($F_{3,2985} = 3.659$, $p = 0.012$). Similarly, the UK and US samples were both slightly less negative towards SRM approaches than the AU and NZ samples ($F_{3,2985} = 13.464$, $p < 0.001$). Although these differences are significant, they are not substantial (see Fig. 2).

Considering other changes from the 2012 data, in 2018, NZ public perceptions are somewhat less negative towards *EW* ($t = -2.973$, $p = 0.003$), *MCB* ($t = -5.615$, $p < 0.001$), *SAI* ($t = -4.202$, $p < 0.001$) and *MIS* ($t = -6.685$, $p < 0.001$), and AU public perceptions showed no significant differences between years based on a Bonferroni-corrected critical p value of 0.01. The net positive associations for climate engineering approaches show remarkable consistency, with correlations ranging from $r = 0.96$ to $r = 0.99$ between countries (within each year), and $r = .98$ between years (for AU and NZ).

Figure 2 provides a graphical representation of the 2012 and 2018 data. Although all four countries are economically developed anglophone democracies, they retain substantial geographic, cultural, political and economic differences, and so the similarity in public perceptions is striking.

3.5 Concept maps

Concept maps for each climate engineering approach present the percentage skews (deviations) between actual counts and expected values, for each attribute, in a graphical format. Positive skews show the attribute is strongly associated with the approach. Negative skews show the attribute is weakly associated with the approach. As found in 2012 (Wright et al. 2014), the concept maps vary considerably between approaches yet are similar between countries (see Fig. 3 for UK concept map and Supplementary Figs. 5–8 for other countries).

The concept maps present attributes in inverse order of popularity with positive attributes at the top. CDR approaches skew towards the positive attributes (top row panels) whereas SRM approaches skew towards the negative attributes (bottom row panels). The sources of the overall skew can be understood by examining skew for the individual attributes (see Supplementary Table 14 for the UK example). The attributes contributing most towards negative skews are unknown effects, risky and artificial. The attributes contributing most to positive skews are *environmentally friendly*, *controllable* and *long-term sustainability*. Overall, these results show that public perceptions of climate engineering approaches continue to be negative, are very similar between the countries examined, and that CDR approaches continue to be perceived substantially less negatively than SRM approaches. Commercial branding theory indicates that substitutable brands competing within a product category tend to have highly similar rankings of attribute associations; as CDR and SRM have highly dissimilar rankings, they may be perceived as different categories, or as non-substitutable activities as far as these respondents are concerned (Romaniuk 2013). Branding theory also posits that brands with distinctive images receive more attention than brands with indistinct images (Romaniuk 2013); we therefore conclude that *BECCS* and *DACCS* with distinctively and positively skewed concept maps are likely to receive the most positive public reaction, *SAI* and *MIS* with distinctively and negatively skewed concept maps are likely to receive the most negative public reaction, whereas *EW* and *MCB* with more indistinct and minor skews in their concept maps are likely to generate more subdued public reactions.

3.6 Support for trials

Beyond perceptions of climate engineering, we also assess support for further small-scale trials for each approach. Support is measured using a 5-point scale with 1 = strongly agree and 5 = strongly disagree and is combined across countries. Responses are aggregated into agree, neutral and disagree categories for reporting (Table 4). The results show mixed support for

Table 4 Support for small scale trials 2018

	Average (1 = strongly agree)	Agree (%)	Neutral (%)	Disagree (%)	Average net positive associations (%)
Bio-energy with carbon capture and storage	2.7	45	33	21	− 3
Direct air capture with carbon storage	2.7	45	35	21	− 13
Enhanced weathering	2.8	41	34	25	− 19
Marine cloud brightening	3.0	33	36	32	− 44
Mirrors in space	3.1	30	35	35	− 52
Stratospheric aerosol injection	3.3	24	34	41	− 62

small-scale trials of individual approaches with slightly higher support for CDR trials than SRM. The final column demonstrates that the variation in average agreement for small-scale trials closely follows the variation in average net positive associations for each approach.

4 Discussion

Despite careful consideration of concerns about climate engineering frames and revising the content of the concept presentations to reflect new scientific knowledge, the net positive associations for the five climate engineering approaches of *DACCS*, *EW*, *MCB*, *SAI* and *MIS* are remarkably similar between countries in 2018 as well as between years for AU and NZ. The public remain uninformed and wary of both CDR and SRM. The consistency of these results provides strong evidence that our quantitative approach to measuring public perceptions is robust. The similarities between the 2012 and 2018 measurements also indicate that where framing effects or non-attitude responding may have impacted on public evaluations, the magnitude of impact is unlikely to substantially shift overall evaluations. Nonetheless, it is important that future work continues to track public opinion as more information emerges in the public sphere and awareness of climate engineering becomes widespread. Continued inquiry using experimental designs is also needed to explore antecedents to public opinion on climate engineering and estimate how public perceptions will develop over time.

Several researchers have raised concern that broadly categorising heterogeneous CDR and SRM technologies under the banner of climate engineering is ineffective for informing policy discussions (Minx et al. 2018) and that higher risk perceptions of SRM technologies may undermine the pursuit of CDR technologies (Colvin et al. 2019). Although perceptions of all six climate engineering techniques are predominantly negative, the substantial difference in perceptions between CDR and SRM techniques suggest that citizens do indeed perceive the two groups of technologies as conceptually distinct categories. As in the original 2012 study, we conclude that SRM technologies continue to yield comparatively negative perceptual evaluations and are more likely to elicit more negative public reactions than CDR technologies (Wright et al. 2014). The perceived polarisation provides further justification to separate CDR and SRM as distinct classes of action for addressing climate change.

Another viewpoint argues that it is important to facilitate a nuanced discussion on individual technologies to avoid broad generalisations across heterogeneous technologies (Colvin et al. 2019). Considering the concept maps of six individual technologies (see Fig. 3 for UK concept map and Supplementary Figs. 5–8 for other countries), there are clear differences in public perceptions between individual technologies within the CDR and SRM categories. The consistency of these differences across samples demonstrates that public perceptions of climate engineering are technology specific and nuanced. A prime example is the difference in perceptions between *MCB* and *SAI*. Though both technologies fall under the category of SRM, *MCB* elicits substantially fewer negative associations than *SAI* with a difference in net positive associations of between 10 and 23 percentage points across the four 2018 samples (see Table 3). There is a risk that painting perceptions of SRM (or CDR) as broadly negative overlooks nuanced differences between individual technologies and could hinder their future development. These findings further evidence the importance of differentiating between climate engineering technologies at the individual level (Colvin et al. 2019).

Though technical understanding of climate engineering technologies has advanced, media coverage has increased (Doyle 2017; Watts 2018), and methods of public engagement are continually refined, it is clear from consistently low public awareness that current attempts at public engagement are insufficient to facilitate global discourse. A potential reason for this is the concerted effort of social scientists to move away from deficit model of science communication toward consultative and participative mechanisms of public engagement. Indeed, the deficit model is widely discredited on the grounds that public communication mechanisms are ineffective at shifting public perceptions (Corner and Pidgeon 2010). However, coordinated public communication mechanisms need not be considered a retreat toward deficit ideals if the messages are aimed at communicating objective information to increase public awareness, rather than aiming to influence public perceptions. Commercial branding theory suggests consumers rarely consider brands they are unfamiliar with (Sharp 2010) likewise, citizens are unlikely to deliberate on emerging scientific concepts they are unaware of. If a large portion of the population is excluded from climate engineering discourses due to low awareness, then the current process of public engagement can hardly be considered democratic. Increasing information on climate engineering in the public sphere would facilitate broader public discourse on the matter outside the context of structured engagement activities. By this reasoning, communicative mechanisms of public engagement still offer some value as a tool for building public awareness.

As the growing necessity for solutions to climate change continues to drive research and development of climate engineering technologies, public engagement efforts need to expand rapidly across global publics. Consultative mechanisms of public engagement, such as the current study, provide excellent tools for eliciting and comparing diverse perspectives at a global scale as well as tracking shifts in public perceptions over time. Likewise, the growth of information communication technologies also presents opportunities to administer web-based or virtual participative mechanisms across global audiences. Regardless of the mechanism, it is important that public engagement occurs sufficiently early to allow public perceptions and concerns to influence the development of climate engineering technologies prior to significant technological development and lock-in.

Since 2012, climate engineering approaches have received increasing attention in international forums. There is more information available in the public domain and the mainstream print media and increased and regular discussion in the context of the Paris Climate Agreement targets. Yet our results show that public knowledge of climate engineering approaches remains low with only small differences in public perceptions between countries and over time. Factors, including age, political affiliation and pro-ecological views, yield mixed associations with climate engineering perceptions. However, further studies are needed to observe whether these factors remain significant as climate engineering discourse develops.

Perceptions of climate engineering are increasingly relevant following the cancellation of the SPICE experiment and as momentum builds behind the SCoPEx project. Perceptions of SAI are overwhelmingly negative and less than a quarter of respondents support small-scale trials. Though the aerosol particles released through SCoPEx are relatively benign and inconsequential, there is a risk of backlash from an uninformed public toward what might be perceived as initial attempts at SAI deployment.

Even with growing warnings of the need for urgency in climate responses, and greater knowledge of potential large-scale impacts of climate change, our fresh measurement of public engagement with climate engineering approaches show that perceptions are largely unchanged from 2012. Concerns that public discussion of climate engineering could reduce pressure to cut emissions have not been realised, as there are no substantive changes to public knowledge in this area. The climate science community and policymakers can still structure public debate on these novel scientific concepts. The increasingly urgent question is how best to use this opportunity for initial engagement with the public, given the extreme challenges presented by anthropogenic-induced global warming and the associated threats to environmentally sustainable futures as partially addressed by the Paris Agreement targets.

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Additional information Correspondence and requests for materials should be addressed to DC at D.Carlisle@massey.ac.nz.

Author contributions DT conceived the original project, advised on climate engineering approaches and contributed to writing. MW raised research funds, developed the research design, advised on and checked analysis and contributed to writing. PF raised research funds, helped with research design, fieldwork, analysis, and co-wrote the main body. DC developed materials, carried out the analysis, co-wrote the main body and provided the supplementary materials.

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Compliance with ethical standards The consistency of these results provides

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Affiliations

Daniel P. Carlisle[1] • Pamela M. Feetham[1] • Malcolm J. Wright[2,3] • Damon A. H. Teagle[4]

Pamela M. Feetham
P.M.Feetham@massey.ac.nz

Malcolm J. Wright
M.J.Wright@massey.ac.nz

Damon A. H. Teagle
Damon.Teagle@southampton.ac.uk

1 School of Communication, Journalism and Marketing, Massey University, Tennent Drive, Palmerston North 4410, New Zealand

2 School of Communication Journalism and Marketing, Massey University, Dairy Flat Highway, Albany, Auckland 0632, New Zealand

3 Ehrenberg-Bass Institute for Marketing Science, University of South Australia, North Terrace, Adelaide, South Australia 5000, Australia

4 School of Ocean & Earth Science, National Oceanography Centre Southampton, University of Southampton, European Way, Southampton SO14-3ZH, UK