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Mapping public appraisals of carbon dioxide removal

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ABSTRACT

Efforts to deliver on net zero emissions targets are set to rely on carbon dioxide removal (CDR) methods. Democratic, trustworthy and socially intelligent research, development, demonstration and deployment of CDR methods in aid of net zero will be highly dependent on how different publics evaluate them, and ultimately which groups support or oppose them. This paper develops a novel, nationally representative method for the multi-criteria appraisal of five policy relevant CDR methods – plus an option not to pursue CDR at all – by members of the British public (n = 2,111). The results show that the public supports the inclusion of CDR in UK climate policy. CDR methods often characterised as 'natural' or 'nature-based' are appraised more highly than 'technological' ones, in the descending order: habitat restoration, afforestation, wood in construction, bioenergy with carbon capture and storage, and direct air carbon capture and storage. Yet, there is no significant disagreement in the appraisal of technological methods and they therefore may be less polarizing, suggesting that popular preconceptions of what is natural – and therefore more attractive – may be holding them back. CDR methods being mainly developed by public sector and non-governmental organisations are also appraised more highly than those being developed by private interests. Regional differences in option appraisal reveal where particular CDR methods are more or less likely to be supported or opposed; stressing the importance of matching physical requirements for CDR with appropriate social contexts. Demographic and socio-economic analyses show that people who appraise CDR methods most highly tend to be older respondents, male, or of a higher social grade. Finally, those with hierarchical worldviews and who voted 'leave' in the UK's referendum on EU membership are less supportive of CDR than those with egalitarian worldviews and who voted 'remain'.

1. Introduction

A growing number of countries around the world are re-orienting their climate change policies around 'net zero' emissions targets. This balancing out of emissions added to and removed from the atmosphere in theory allows for residual emissions from hard-to-abate sectors such as cement, steel, plastics, shipping and aviation, as long as they are offset in other sectors by negative emissions. Negative emissions are attainable only through methods for carbon dioxide removal (CDR), with the Sixth Assessment Report of the Intergovernmental Panel on Climate Change recently concluding that use of these mitigation methods is now 'unavoidable' (IPCC, 2022). A wide range of CDR methods have been proposed, spanning those that capture CO_2 through biological or chemical processes on land or in the oceans, and then store it in biomass, soil, geological reservoirs, minerals, or marine sediment and calcifiers (Minx et al., 2018).

In June 2019 the UK became the first country to enshrine a net zero emissions target in law, seeking to achieve the goal by 2050. Informing this decision was an influential report by the UK's Committee on Climate Change (CCC, 2019) titled *Net zero: The UK's contribution to stopping global warming*, in which the Committee laid out a number of 'core', 'further ambition' and 'speculative' scenarios for achieving net zero by 2050 (CCC, 2019). These relied upon several CDR methods, including land-based removals via afforestation and habitat (peatland) restoration, wood in construction, bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). CDR now forms a key part of the UK Government's 'Build Back Greener' Net Zero Strategy, with key policies to position the UK as a global leader in the rapidly developing sector. This includes £100 million of investment in CDR innovation, to in turn leverage private investment and demand for expertise (HM Government, 2021).

There is an urgent need develop systematic frameworks for evaluating CDR methods (Fridahl, Hansson & Haikola, 2020). The eventual deployment of any such CDR methods in aid of net zero will be highly dependent on how different publics – as segmented by demographic or political factors, for example – evaluate them, and ultimately which

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groups support or oppose them. Public participation in CDR method evaluation is normatively important to democratic process and instrumentally important to building trust and support (and hence avoiding mistrust and opposition), but it is also substantively important to generating 'social intelligence' and more robust decision making (Fiorino, 1990; Irwin, 1995).

As such, a small but growing literature on public attitudes towards CDR methods has started to emerge. Within it, a number of common themes have begun to arise, including a preference for reducing emissions over removing them (Bellamy, Chilvers & Vaughan, 2016), a preference for CDR over solar geoengineering methods (Parkhill & Pidgeon, 2011; Pidgeon et al., 2013; Wright, Teagle & Feetham, 2014; Bellamy, Chilvers & Vaughan, 2016), and a preference for natural CDR methods over technological ones (Corner & Pidgeon, 2015; Bellamy, Chilvers & Vaughan, 2016; Thomas, Pidgeon & Roberts, 2018). They also include concerns about messing with nature (Corner et al., 2013; Braun et al., 2017; Wolske et al., 2019), not addressing the root causes of climate change (Ipsos, MORI, 2010; Cox, Spence & Pidgeon, 2020), and concerns (or a lack thereof) about deterring emissions reductions (Braun et al., 2017; Cox, Spence & Pidgeon, 2020; Kahan et al., 2015; McLaren et al., 2016). They furthermore highlight the importance of socio-cultural (Kahan et al., 2015; Bellamy, Lezaun & Palmer, 2017) and geographical (Buck, 2018; Gannon & Hulme, 2018; Thomas, Pidgeon & Roberts, 2018) contexts, the development of appropriate governance (Bellamy, Lezaun & Palmer, 2017; Pidgeon & Spence, 2017), and an attention to how the technical systems of CDR are intimately coupled to social arrangements (Bellamy, Lezaun & Palmer, 2019).

At this early stage in the development of CDR methods, the literature nevertheless remains limited. First, existing research has tended to focus on a single CDR method and only once more than three at a time (Ipsos, MORI, 2010). Broadening out the framing of research into public attitudes on CDR to more options is key to avoiding a premature 'narrowing in' and 'closing down' on – and legitimisation of – certain options (Stirling, 2008; Kreuter, 2021). Second, it has tended to consider the same CDR methods, notably BECCS, DACCS and afforestation. Third, with few exceptions, it has examined these methods in isolation of a specified policy context. Fourth, with only one small-scale exception (Bellamy, Chilvers & Vaughan, 2016), it has not utilised formal decision analysis methods, which can offer a more systematic approach to option evaluation compared to typical opinion elicitation methods like surveys or deliberative workshops. This paper seeks to address these gaps by 1) undertaking a comparative analysis of no fewer than five CDR methods, plus an option not to pursue CDR at all; 2) complementing analyses of BECCS, DACCS and afforestation with those of the never-before included options: wood in construction and peatland habitat restoration; 3) examining these methods specifically in relation to the CCC's scenario analysis and the UK's net zero policy; and 4) developing a novel multi-criteria option appraisal method on a large-scale.

In developing this method, the paper draws on cultural cognition (Kahan, 2012); a conception of the cultural theory of risk, to better understand the socio-cultural basis for citizens' appraisals (Douglas & Wildavsky, 1982). Cultural cognition posits that individuals' perceptions of technological and environmental risks are shaped by the social groups of which they are part. In particular, it outlines two crosscutting dimensions of sociality – individualism-collectivism and hierarchy-egalitarianism – which give rise to four elementary worldviews: egalitarian individualism, hierarchical individualism, hierarchical collectivism, and egalitarian collectivism.

Evidence for the formation of perceptions consistent with these worldviews has been gathered in relation to a wide range of risks, and explains variation better than other individual characteristics such as education, income, personality types and political ideology (Kahan, 2012). As the values of individuals become concurrently more egalitarian and collectivist, they become more concerned about climate change and other environmental risks such as nuclear waste and air pollution. In contrast, as individuals become concurrently more hierarchical and individualist, they become less concerned about such things. Indeed, research has shown that hierarchical individualists are more in favour of climate geoengineering ideas than egalitarian collectivists (Kahan et al., 2015). This said, the cultural cognition thesis does not come without criticism, including the fact that empirical testing has been largely limited to the United States (van der Linden, 2015). Although it has been successfully used in England also (see Kahan et al., 2015), questions remain about its wider applicability to other cultures around the world.

The paper proceeds by describing the novel multi-criteria public appraisal mapping method before reporting and then discussing its results. It shows that the British public supports the inclusion of CDR in the UK's climate policy. CDR methods that have elsewhere been characterised as 'natural' or 'nature-based' are appraised more highly than 'technological' ones. And yet, technological methods are found to be less polarizing than natural ones, suggesting that popular preconceptions of what is natural – and therefore more attractive – may be holding them back. Regional, demographic, socio-economic, political and cultural differences are also revealed to show how certain types of people are more or less likely to support or oppose particular CDR interventions.

2. Method

2.1. Growing deliberative mapping

The study developed a novel method of participatory multi-criteria option appraisal inspired by deliberative mapping (Burgess et al., 2007), which has been successfully used in relation to a variety of contested science policy domains including xenotransplantation (Davies et al., 2003), nuclear power (Burgess et al., 2004), climate geoengineering (Bellamy, Chilvers & Vaughan, 2016) and sustainable energy futures (Bellamy et al., 2022). Deliberative mapping engages diverse publics in-depth in framing the issue to be addressed; considering alternative options for addressing it; developing criteria with which to appraise the options; evaluating the performance of the options against the criteria; and weighting the criteria in terms of their relative importance. One of the main limitations of the deliberative mapping method is that it is expensive and time intensive, owing to its emphasis on participants themselves setting these framings in-depth. These factors limit the number of people who can participate to small numbers of citizens – typically 6–10 in each panel. This study is an attempt to significantly grow the numbers of citizens who can participate, and their representativeness of the population in terms of demographics, socio-economic status, geography, politics and culture. It is hoped that this approach can provide the basis for rolling out the core aspects of deliberative mapping to other contested science policy issues on a large scale.

The study is inspired by deliberative mapping rather than a direct usage because while several core features are retained, for better or worse there are also a number of notable differences. Like deliberative mapping, the method involves diverse members of the public in the appraisal of a common set of options against a range of weighted evaluation criteria. Unlike deliberative mapping, it elicits individual judgements from isolated respondents rather than from group deliberations. Furthermore, additional options to be appraised and the criteria with which to appraise options are predefined for respondents rather than elicited from participants. These trade-offs in methodological flexibility, however, allow for the core features of deliberative mapping to be rolled out on a scale hitherto unseen. As discussed above, deliberative mapping takes place with small numbers of citizens – whereas the present method raises this to 2,111. While this leaves a much-reduced qualitative dataset of participant reasonings, it increases the quantitative dataset over two hundredfold, along with its reach to – and representativeness of – the population at large.

A nationally representative sample of the British public (n = 2,111) was recruited through YouGov to complete the online appraisal process (see Supplementary Note A). The sample was sought to be representative of the country's make-up in terms of age, gender, social grade (socio-economic classification produced by the UK Office for National Statistics [ONS]), geographical region, and political orientation (as measured by vote given in the 2017 general election and in the 2016 EU referendum). The appraisal process consisted of three stages (see Supplementary Note B).

2.2. Cultural mapping

The first stage sought to measure respondents' cultural worldviews as described by cultural cognition. Blending the insights of cultural cognition with those of deliberative mapping permit us to label the method a 'cultural mapping'. Cultural worldviews were measured using the short-form individualism-collectivism and hierarchy-egalitarianism scales (British subjects wording) developed by Kahan et al. (2015). The individualism-collectivism scale measured attitudes towards social arrangements that expect individuals to attain their own well-being without interference from society versus those that expect society to ensure collective welfare. The hierarchy-egalitarianism scale measured attitudes towards social arrangements that link authority to stratified social roles based on attributes such as gender, ethnicity and class. For each scale item, subjects indicated agreement or disagreement on a 7-point Likert scale. Cronbach's alpha coefficients showed very reliable internal consistencies for both the individualism-collectivism ($\alpha = 0.70$) and the hierarchy-egalitarianism ($\alpha = 0.85$) scales.

2.3. Appraisal criteria

The second stage of the appraisal process introduced respondents to the topic of CDR and asked them to select three criteria with which to appraise CDR methods, and to weight their importance on an 11-point scale (where relative weights were later derived by calculating relative shares). Eight technical and social criteria were made available for selection and were based on groupings of criteria elicited from members of the public in a previous deliberative mapping appraisal of climate geoengineering options (Bellamy, Chilvers & Vaughan, 2016). The criteria included: effectiveness at tackling climate change; technical feasibility; environmental impacts; cost effectiveness; political feasibility; safety; social acceptability; and ethical concerns. The criteria were purposefully broad in meaning to accommodate a diversity of interpretations. While in this appraisal process it was not possible to attribute individual interpretations of these criteria to individual respondents, the earlier study – which involved amalgamating diverse criteria into these categories – provides us with a good sense of the range of interpretations likely to exist beneath each criterion (see Table 1).

2.4. Appraisal options

The third stage of the appraisal process introduced respondents to six common options for appraisal (see Table 2). Presented in a tabular format, the option definitions included the name of the option, a brief description of how it would remove CO_2 from the atmosphere, information on who is mainly developing it, and an image of what it might look like. Information on who is developing the idea was taken from real world examples, including private start-up companies in the case of DACCS (e.g. Climeworks, Carbon Engineering); existing private energy companies in the case of BECCS (e.g. Drax Group, Stockholm Exergi); existing private construction companies in the case of wood in construction (i.e. the wood construction industry); and public sector and non-governmental organisations in the case of afforestation (e.g. Forestry Commission, Woodland Trust) and habitat restoration (e.g. Natural England, Yorkshire Wildlife Trust). The options were presented as 'ideas' to avoid giving the impression that they were ready to deploy, and carefully avoided framings known to skew public attitudes, such as describing them as 'natural' or otherwise (Osaka, Bellamy & Castree, 2021). Given the format of the method, the information provided was necessarily limited, but is designed to capture to some extent the limited depth with which publics are likely to encounter the ideas in the real world. Nevertheless, CDR remains a topic of low salience among members of the public and caution should be taken when interpreting the results.

With the table visible to the respondents for the remainder of the appraisal process, respondents were then asked to score each of the options against their three chosen criteria on an 11-point scale ranging from 'very poor' to 'very good', with 'don't know' as a twelfth possibility. The rank performance of the options was calculated as the sum of weighted scores using the simple linear additive weighting aggregation model: $R_i = \sum_c S_{ic} \bullet W_c$ where overall performance rank for a given option (R_i) is the sum of performance scores for that option under a given criterion (S_{ic}), multiplied by the corresponding criterion weighting (W_c) (see Stirling and Mayer, 1999).

Five CDR options were selected for inclusion in the appraisal for their policy relevance and diversity. First, each plays a role in scenarios set out by the Committee on Climate Change for reaching net zero in the UK (CCC, 2019). Second, each has different technical and social characteristics. Some, like afforestation, would remove CO_2 from the atmosphere through increased biological uptake whereas others, like DACCS, would involve engineered removal. Some, like habitat restoration, would store CO_2 in living vegetation, while others, like BECCS or wood in construction, would store CO_2 geologically or in the built environment, respectively. Some, like DACCS and BECCS are being developed mainly by private companies, whereas others, like habitat restoration, are being developed by a combination of public sector and non-governmental organisations. Third, each of the options has a distinct expert evaluation profile. For example, the carbon removal potential of some options, like DACCS and BECCS, is expected to be high, while for others, like wood in construction and habitat restoration, it is expected to be relatively very low. Technical readiness levels also vary between options, as do anticipated costs, benefits and risks. A sixth option – no CDR – was included to elicit appraisals of seeking to reach net zero in the absence of CDR.

The subsequent quantitative data analysis followed the established analytical procedures for deliberative mapping (Burgess et al., 2007), in addition to statistical tests described in the main text.

Table 1
Criteria and their interpretations (from Bellamy et al., 2016).

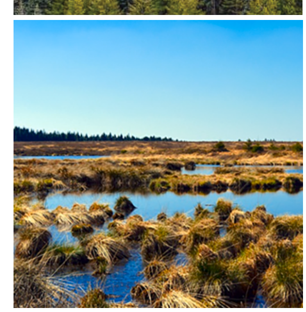
Criterion	Interpretations
Effectiveness at tackling climate change	Global temperature reduction, climatic response time, duration of effects
Technical feasibility	Technical feasibility
Environmental impacts	Environmental impacts, environmental side effects, carbon footprint
Cost effectiveness	Cost effectiveness, cost, public investment, return on investment, cost-benefit ratio
Political feasibility	Political viability, political acceptability, (inter) governmental cooperation
Safety	Side effects on people
Social acceptability	Social acceptability, impacts on people
Ethical concerns	Ownership and control, distributive justice, availability, misuse, morality, availability

3. Results

3.1. Overall option performance

Fig. 1 shows the final ranks of options overall, and four tiers of performance. It shows two options performing relatively higher, albeit with a greater variability between appraisals: habitat restoration and afforestation. It shows one option with a more middling performance and variability: wood in construction. It shows two options performing relatively lower, and with a lower variability between appraisals: BECCS

Table 2
Option definitions.

Idea for removing carbon dioxide from the air	How does the idea work?	Who is mainly developing the idea?	What might it look like?
Direct air carbon capture and storage (DACCS)†	Uses engineered processes to suck carbon dioxide out of the air and store it in rock formations underground or under the sea	Private start-up companies	
Bioenergy with carbon capture and storage (BECCS)	Uses trees and plants to produce energy, capture the carbon dioxide emissions and store them in rock formations underground or under the sea	Existing private energy companies	
Wood in construction	Stores the carbon captured by trees in infrastructure and makes space for new trees to absorb and store carbon dioxide	Existing private construction companies	
Afforestation	Grows new trees to capture more carbon dioxide and manages existing forests to maximise the amount captured	Public sector and non-governmental organisations	
Habitat restoration	Restores damaged peatlands to reduce the amount of captured carbon dioxide being released back into the air	Public sector and non-governmental organisations	
No carbon dioxide removal	Focuses attention on reducing carbon dioxide emissions rather than removing them from the air	N/A	N/A

† Image reproduced with permission of Carbon Engineering.

and DACCS. And it shows one option performing markedly lowest, and with a relatively low variability between appraisals: no CDR. It should be noted, however, that the performance of all the options overlap to differing degrees, with the poorer options under their more positive appraisals able to outperform the better options under their more negative appraisals. Indeed, the appraisal is not designed to identify a single best option – either from an individual perspective or from all perspectives taken together – but to map the performance of the options

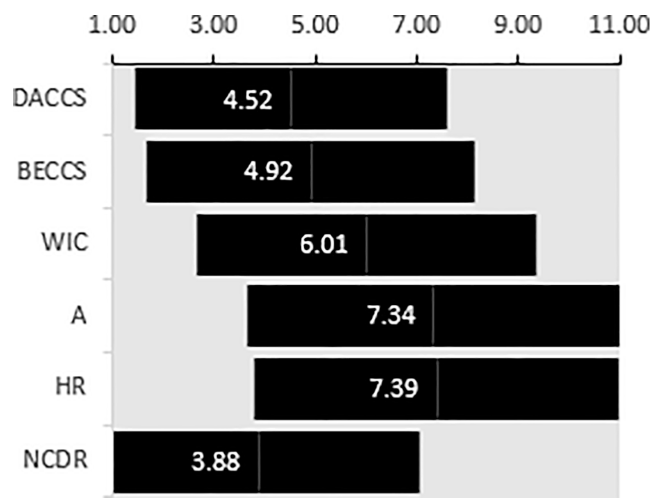


Fig. 1. Final ranks of options overall showing mean scores of option performance across all criteria and standard deviation error bars. Acronyms: direct air carbon capture and storage (DACCS); bioenergy with carbon capture and storage (BECCS); wood in construction (WIC); afforestation (A); habitat restoration (HR); no carbon dioxide removal (NCDR).

under different framing assumptions.

The proportion of respondents who indicated 'don't know' and did not participate in option specific appraisals was slightly higher for BECCS (25.7 %) and DACCS (25.3 %) than it was for no CDR (23.7 %) and wood in construction (22.1 %), with afforestation (19.9) and habitat restoration (18.9 %) affected the least. This echoes other research that has shown publics to have a low degree of knowledge and/or awareness of CDR (Bellamy, Lezaun & Palmer, 2019; Cox, Spence & Pidgeon, 2020). Moreover, of those who indicated 'don't know', 65.1 % were female and 34.9 % were male, showing a clear difference in knowledge – or willingness to admit lack of knowledge – about CDR. This is consistent with previous deliberative mapping exercises that have shown greater uncertainties in option performance among women (see Davies et al., 2003; Burgess et al., 2004; Bellamy, Chilvers & Vaughan, 2016). These statistics suggest that many members of the public have not yet made their minds up about CDR, and that therefore there remains considerable latitude for influence and change. As with any research on perceptions during this 'upstream' phase of CDR, the findings that follow are subject to incertitude (Corner, Pidgeon & Parkhill, 2012).

3.2. Criteria selection and weighting

This overall pattern of option performance arose from appraisals of each option under different individual criteria, which were selected and weighted differently by different respondents. Table 3 shows that effectiveness at tackling climate change and environmental impacts were, on average, the most selected. Cost effectiveness, safety and technical feasibility were the next most selected, and ethical concerns, social acceptability and political feasibility were the least selected.

Table 3
Criteria selection and weighting by respondents.

Criterion	Selected (%)	Weight (%)	
		Mean	SD
Effectiveness at tackling climate change	23.9	34.1	3.37
Technical feasibility	13.3	33.3	3.52
Environmental impacts	22.4	33.6	3.18
Cost effectiveness	14.7	32.5	4.72
Political feasibility	1.5	29.6	7.59
Safety	13.4	34.2	3.83
Social acceptability	4.8	31.1	5.53
Ethical concerns	6.0	32.5	4.42

3.3. Option performance by criteria

Fig. 2 shows that the four-tiered pattern of option performance was broadly present at the level of individual appraisal criteria too. Under the effectiveness at tackling climate change and technical feasibility criteria, the rank order changed slightly, with afforestation being appraised more highly than habitat restoration. Both options remained the highest performing, however, and with lower variability between appraisals. Under the environmental impacts' criterion, habitat restoration regained its edge over afforestation with both options maintaining a lower degree of variability between appraisals. Under the cost effectiveness criterion, afforestation overtakes habitat restoration once more, but perhaps more notably, the no CDR option performed more highly than DACCS, albeit with a greater degree of variability between appraisals. Under the political feasibility criterion, the four tiers are replaced with just two and a similarly high degree of variability between appraisals in each case: with DACCS and no CDR being outperformed by the rest. Under the remaining safety, social acceptability and ethical concerns criteria the four-tiered pattern re-emerged with lower variability between appraisals of habitat restoration and afforestation, and with afforestation edging into the lead under the social acceptability criterion and habitat restoration doing so under the safety and ethical concerns criteria. However, it should be noted once again that the performance of all the options overlap to differing degrees for each of the criteria, with the poorer options under their more positive appraisals able to outperform the better options under their more negative appraisals.

The same four-tiered pattern of option performance was also broadly present among different respondent attributes: age, gender, social grade, geographical region, political orientation and cultural worldview (see Supplementary Note C).

3.4. Option performance by region

Fig. 3 shows the final ranks of options overall by geographical region. Perhaps what is most striking is that the differences in option performance by region are quite marginal. Indeed, this is later borne out in the statistical analyses where no significant differences were found. Nevertheless, Fig. 3 shows the stark differences between the overall performance of the different options, as well as some more subtle differences between regions. DACCS was appraised more highly by those in the North, West Midlands, London and Northern Ireland. BECCS was appraised more highly by those in the North West, London and Northern Ireland. Wood in construction was appraised more highly by those in the North, South West, London, Scotland and Northern Ireland. Afforestation was appraised more highly by those in the North East and West, South West and Northern Ireland. Habitat restoration was appraised more highly by those in Northern Ireland, the North East and South West. No CDR was appraised more highly by those in the North West and East of England.

3.5. Differences between groups

Following a Shapiro-Wilk test for normality of distribution, a series of nonparametric analyses of variance were performed to test the differences between the mean scores of option performance under each attribute. A nonparametric Levene's test verified homoscedasticity (i.e., groups having the same or similar variances, also called homogeneity of variance) in most of the samples, for which a series of Kruskal–Wallis H tests were performed. For the remainder that showed heteroscedasticity (i.e., groups having different variances, also called heterogeneity of variance), a series of Mood's median tests were performed (unlike the Kruskal–Wallis H test the Mood's median test does not assume homogeneity of variance). Table 4 shows the results of these tests.

Age. Kruskal–Wallis H tests showed significant differences between age groups for DACCS, BECCS, afforestation and habitat restoration. A

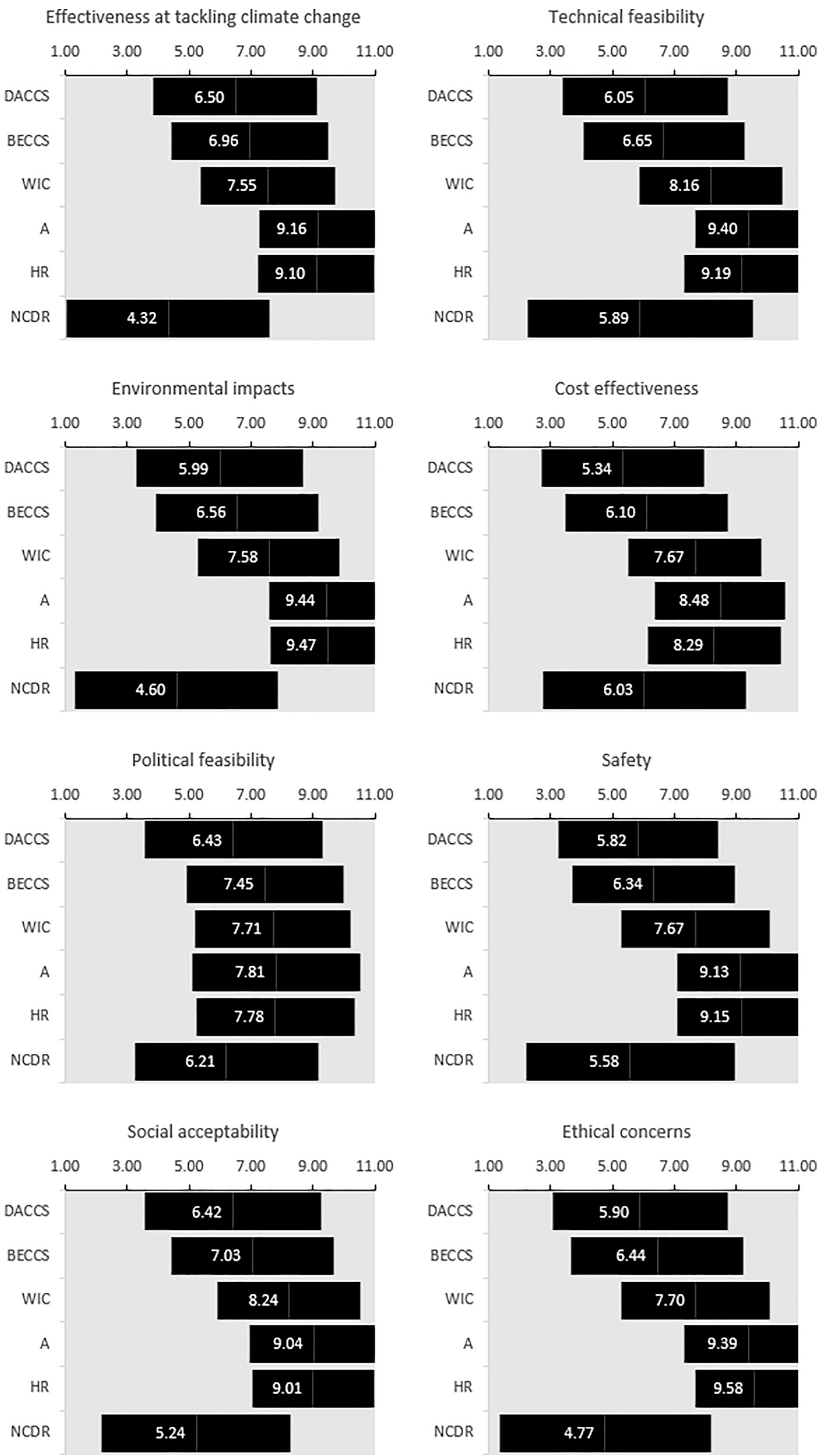


Fig. 2. Final ranks of options by effectiveness at tackling climate change (n = 1,516), technical feasibility (n = 840), environmental impacts (n = 1,418), cost effectiveness (n = 934), political feasibility (n = 97), safety (n = 847), social acceptability (n = 304) and ethical concerns (n = 383) criteria showing mean scores of option performance for each criterion and standard deviation error bars. Acronyms: direct air carbon capture and storage (DACCS); bioenergy with carbon capture and storage (BECCS); wood in construction (WIC); afforestation (A); habitat restoration (HR); no carbon dioxide removal (NCDR).

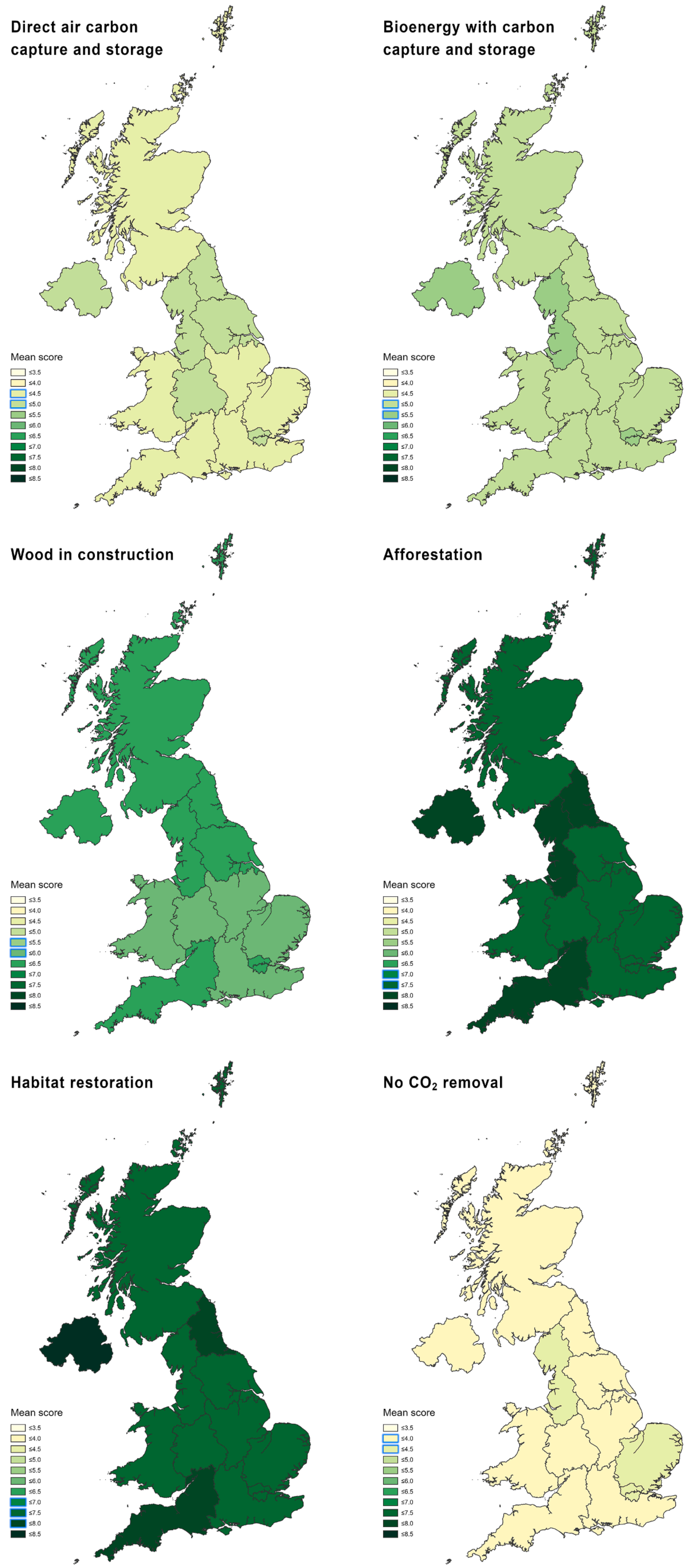


Fig. 3. Final ranks of options overall by geographical region.

Table 4
Statistical differences in option appraisal between groups by attribute.

Attribute	DACCS	BECCS	WIC	A	HR	NCDR
Age	14.90* †	18.72** †	45.52*** ‡	18.67** †	22.68*** †	n.s.
Gender	87.45*** †	60.03*** †	15.79*** ‡	6.01* ‡	n.s.	n.s.
Social grade	n.s.	n.s.	17.11** †	32.91*** ‡	23.83*** †	n.s.
Region	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
2017 election	n.s.	n.s.	n.s.	n.s.	n.s.	19.69** ‡
EU referendum	n.s.	n.s.	n.s.	4.45* †	4.15* †	8.47** ‡
Cultural worldviews	n.s.	n.s.	9.24* †	72.30*** †	76.04*** †	20.87*** ‡

* p <.05, ** p <.01, *** p <.001, n.s. = not significant.
† Kruskal–Wallis *H* statistic.
‡ Mood's median test χ^2 statistic.
Acronyms: direct air carbon capture and storage (DACCS); bioenergy with carbon capture and storage (BECCS); wood in construction (WIC); afforestation (A); habitat restoration (HR); no carbon dioxide removal (NCDR).

series of Bonferroni corrected Dunn's pairwise comparisons and Bonferroni corrected Pearson's χ^2 post-hoc tests showed between which age groups the differences lay following the Kruskal–Wallis *H* tests the Mood's median tests, respectively. Table 5 shows the results of these tests, where older respondents tended to appraise the options significantly more favourably than younger respondents.

Gender. Kruskal–Wallis *H* tests showed significant differences between genders for DACCS and BECCS where in both cases, men appraised the options significantly more highly than women. Mood's median tests showed significant differences for wood in construction and afforestation, where in both cases again, men appraised the options more highly than women.

Social grade. Kruskal–Wallis *H* tests showed significant differences between social grades for wood in construction and habitat restoration. A series of Bonferroni corrected Dunn's pairwise comparisons and Bonferroni corrected Pearson's χ^2 post-hoc tests showed between which social grades the differences lay following the Kruskal–Wallis *H* tests the Mood's median tests, respectively. Table 5 shows the results of these tests, where higher social grade respondents tended to appraise the options significantly more favourably than lower social grade respondents.

Table 5
Statistical differences in option appraisal between age groups and social grades.

Attribute	DACCS	BECCS	WIC	A	HR	NCDR
Age	25–34 & 65–74 (ˆ)* †	18–24(ˆ) & 25–34*; 25–34 & 45–54(ˆ) *; 25–34 & 65–74 (ˆ)*; 35–45 & 65–74(ˆ) * †	25–34 & 35–44(ˆ) *;25–34 & 45–54 (ˆ)***; 25–34 & 55–64(ˆ) ***; 25–34 & 65–74(ˆ) ***; 25–34 & 75+(ˆ) ***; 35–45 & 65–74(ˆ) * ‡	18–24(ˆ) & 25–34*; 25–34 & 45–54(ˆ) ***; 25–34- & 65–74(ˆ) * †	18–24(ˆ) & 25–34*; 25–34 & 35–44(ˆ) *; 25–34 & 45–54 (ˆ)***; 25–34 & 55–64(ˆ) **; 25–34 & 65–74(ˆ) *** †	n.s.
Social grade	n.s.	n.s.	A(ˆ) & C2*; A(ˆ) & D*** †	A(ˆ) & B*; A(ˆ) & C1*; A (ˆ) & C2***; A (ˆ) & D***; A (ˆ) & E***; C1 (ˆ) & E* ‡	A(ˆ) & C1*; A(ˆ) & C2*; A (ˆ) & D***; A (ˆ) & E*; B(ˆ) & D** †	n.s.

(* p <.05, ** p <.01, *** p <.001, n.s. = not significant).
(ˆ) indicates the group or grade in each pair that appraised the corresponding option more highly.
† Bonferroni corrected Dunn's pairwise comparisons.
‡ Bonferroni corrected Pearson's χ^2 post-hoc tests.
Acronyms: direct air carbon capture and storage (DACCS); bioenergy with carbon capture and storage (BECCS); wood in construction (WIC); afforestation (A); habitat restoration (HR); no carbon dioxide removal (NCDR).

Region. Kruskal–Wallis *H* tests showed no significant differences between regions.

2017 election. A Mood's median test showed significant differences between votes cast in the 2017 general election for no carbon dioxide removal. Bonferroni corrected Pearson's χ^2 post-hoc tests showed that the difference lay between votes cast for the Scottish National Party and votes case for the UK Independence Party (p <.05), where the latter appraised the option more highly.

EU referendum. Kruskal–Wallis *H* tests showed significant differences between votes cast in the 2016 EU referendum for afforestation and habitat restoration, where in both cases, people who voted remain appraised the option more highly than people who voted leave. A Mood's median test showed significant differences for no carbon dioxide removal, where leave voters appraised the option more highly than people who voted remain.

Cultural worldviews. Fig. 4 shows significant differences between cultural worldviews for different carbon removal options. Kruskal–Wallis *H* tests showed statistically significant differences for wood in construction, afforestation and habitat restoration. A series of Dunn's pairwise comparisons and Pearson's χ^2 post-hoc tests showed between which cultural worldviews the differences lay following the Kruskal–Wallis *H* tests the Mood's median tests, respectively. These show that those with an egalitarian worldview – of either an individualist or collectivist persuasion – are much more in favour of wood in construction, afforestation and habitat restoration than those with a hierarchical worldview. They also show that those with a hierarchical worldview – also of either an individualist or collectivist persuasion – are much more in favour of not having CDR at all. No significant differences were found between worldviews for DACCS and BECCS.

4. Discussion

This public appraisal shows that the British public supports the inclusion of CDR in the UK's climate policy. Having no CDR was consistently the lowest performing option across the board. Given the explicit link with avoiding the deterrence of emissions reductions made in the option description, this also shows that the public may be much less concerned about this matter than is often assumed. As Asayama (2021) argues, rather than being fixated on the dilemma of whether or not they may deter emissions reductions, to better situate CDR in the challenge of rapid decarbonization we should be asking how it can be used in alignment with a managed decline in fossil fuel production.

It also shows that the public appraise what are often characterised as natural CDR methods more highly than technological ones, in the

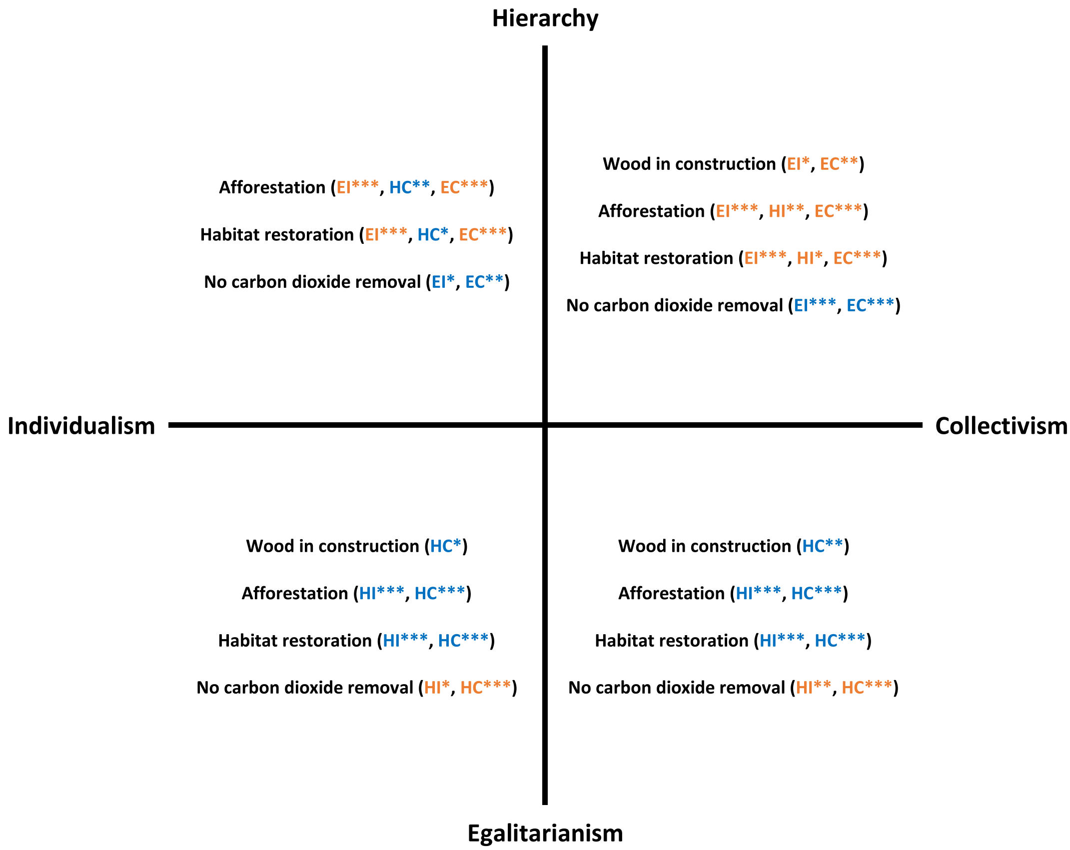


Fig. 4. Relative appraisal of options under different cultural worldviews where blue-highlighted options were appraised significantly more positively and orange-highlighted options were appraised significantly more negatively relative to other worldviews indicated in parentheses. For example, in the hierarchical individualist quadrant we can see that, with respect to no CDR, the option was appraised significantly more positively by hierarchical individualists compared to egalitarian individualists and egalitarian collectivists. This was established through Dunn's pairwise comparisons and Pearson's χ^2 post-hoc tests as appropriate (* $p < .05$, ** $p < .01$, *** $p < .001$). Acronyms: egalitarian individualism (EI); hierarchical individualism (HI); hierarchical collectivism (HC); egalitarian collectivism (EC). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

descending order: habitat restoration, afforestation, wood in construction, BECCS, and DACCS. This supports earlier research that has found a preference for more natural solutions to tackling climate change (Corner & Pidgeon, 2015; Bellamy, Chilvers & Vaughan, 2016; Thomas, Pidgeon & Roberts, 2018).

While the research design was careful to avoid natural framings in its description of the options, the imagery used to depict the options may nevertheless have evoked the Romantic view of nature, prevalent in today's society, in which certain options (particularly habitat restoration and afforestation) might have been seen as relatively pure, pristine, or otherwise free of human influence (Osaka, Bellamy & Castree, 2021). At the same time, other options (particularly DACCS and BECCS) might have been seen as relatively engineered and industrial. Such framings have been shown to have a powerful impact on public perception, with the former routinely benefitting from the ostensible naturalness of their characteristics (Corner & Pidgeon, 2015).

As noted recently, however, nature is universal and where the lines are drawn on what constitutes a natural or unnatural method is something that is defined by people acting in social groups, and is therefore eminently contestable (Osaka, Bellamy & Castree, 2021). Future research and communications would do well to finds new ways of challenging the hegemony of the Romantic view, lest the allure of a particular subset of climate solutions conceal the risks associated with 'natural' methods or detract from other vital policy options. Options include dispensing with nature as a concept altogether (ibid); emphasising the 'naturalness' in all climate solutions (ibid); or emphasising the 'technology' in ostensibly natural climate solutions (Markusson, 2022).

Another contributing factor in this rank order of option appraisals may be related to who is developing the ideas under consideration. Previous research has shown that CDR research and development taking place outside the controls of the scientific community can be highly unacceptable, and that there is a preference for independence from, or at least oversight of, private interests (Bellamy, Lezaun & Palmer, 2017; Pidgeon & Spence, 2017; McLaren et al., 2016; Wibeck, Hansson & Anshelm, 2015). Indeed, this reflects a wider mistrust of private interests in other relevant sectors, including energy companies (Demski et al., 2015). Efforts to leverage private investment in the sector should therefore be met with caution (cf. HM Government, 2021). While the options in the study were described as being developed mainly by either private, public or non-governmental organisations, the politics of their eventual deployment as complete sociotechnical systems is not a foregone conclusion (cf. Winner, 1980). It remains entirely plausible – desirable even – that often assumed social arrangements – such as the institutions, people, procedures and policies of future CDR – could be otherwise (Bellamy, Lezaun & Palmer, 2019).

While these results show that the exclusion of CDR from the UK's efforts to tackle climate change would be unwelcome, it is not to say that CDR deployment is supported unconditionally. Social science research has identified a number of conditions for the responsible governance of CDR research and development, including the independence from or oversight of private interests mentioned above, but also transparency, minimisation and monitoring of environmental impacts, accounting for controllability when thinking about scale of operations, and developing approach-specific governance protocols (Bellamy, Chilvers & Vaughan, 2016; Bellamy, Lezaun & Palmer, 2017; Pidgeon & Spence, 2017; McLaren et al., 2016; Wibeck, Hansson & Anshelm, 2015).

The selection of criteria with which to appraise the options showed a preference for 'technical' criteria (effectiveness at tackling climate change, environmental impacts, cost effectiveness, safety and technical feasibility) over 'social' ones (ethical concerns, social acceptability and political feasibility). This does not necessarily imply that respondents felt these criteria were less important; only that the constraints of the survey meant they were restricted to choosing three. Indeed, the mean relative weights assigned to each criterion by those who selected them were similar. Nevertheless, it does echo a pattern where technical criteria are often weighted more highly in similar studies (see Davies et al., 2003; Burgess et al., 2004; Bellamy, Chilvers & Vaughan, 2016). However, this may be because of the common convention where public participation exercises limit who participates to a set of ostensibly representative but ultimately narrow, sociodemographic characteristics. Recent attempts to broaden out the publics of deliberative mapping have yielded more diversity in patterns of weighting and should be explored further (Bellamy et al., 2022). Nevertheless, all attempts to find a public for CDR appraisal will be partial and should be seen as part of wider ecologies of participation (Waller, Rayner & Chilvers, 2021).

As well as performing the highest overall, habitat restoration and afforestation also performed the highest under each individual criterion. On occasion, these findings diverge from expert judgements (although these themselves on occasion diverge from one another). For example, the estimated CO_2 removal potential of wood in construction is by far the smallest of the five options included here (Royal Society & Royal Academy of Engineering, 2018), habitat restoration and afforestation are subject to greater uncertainties (ibid), and BECCS and DACCS could have much higher potential (European Academies Science Advisory Council, 2018; Minx et al., 2018). Similarly, the feasibility of habitat restoration may be smaller than thought by the public, the environmental impacts of afforestation much higher, and the costs of wood in construction much lower (Royal Society & Royal Academy of Engineering, 2018). Nevertheless, views on the costs of DACCS were in line with those of experts, with it being seen as the most expensive option (European Academies Science Advisory Council, 2018; Minx et al., 2018; Royal Society & Royal Academy of Engineering, 2018).

Regional differences in option appraisal were non-significant, but nevertheless show that certain regions could be more or less likely to support or oppose certain CDR deployments. In turn, it would be important to match up any physical requirements for siting CDR methods with appropriate social contexts. For example, those in the North West appraise DACCS and BECCS relatively higher than other regions, and happen to be adjacent to areas of significant carbon storage potential in offshore saline aquifers (Bentham et al., 2014). Similarly, those in Northern Ireland, the North East and South West appraise habitat restoration relatively higher than other regions, and happen to contain significant areas of peatland (Evans et al., 2017). Such instances may be related to relatively greater exposure to the ideas, and requires further research.

This is not to say that these regions would be supportive of such developments, however. Indeed, there is a great deal of difference between general attitudes towards the ideas presented here versus attitudes to specific deployments on the ground, as shown in relation to analogous technologies such as fracking, wind or nuclear energy (Cox, Pidgeon & Spence, 2021; Devine-Wright & Howes, 2010; Parkhill et al., 2009). While this analysis is an important first step in identifying likely places of support and opposition, detailed public engagement in specific locales will be needed to attend to specific geographical constraints and concerns. Indeed, it will be crucial for future research to understand how CDR will be taken forward in particular contexts: which methods, to what extent, when, where and by whom (Bellamy et al., 2021).

Differences between voters in the EU referendum and the 2017 general election indicate that a significant gulf lies between remain and leave voters, and between Scottish National Party and UK Independence Party (UKIP) voters, on the issue of whether or not to pursue CDR at all. While leave and UKIP voters are still much more in favour of having CDR methods than not, they are more likely to resist them than others. This suggests that the remain-leave divide in British politics continues to be salient, and in this case, even more so than the traditional political party fault lines. It also adds a further dimension to appropriate geographical siting.

Demographic and socio-economic differences in option appraisal show that certain types of people may be more likely to support or oppose CDR methods. CDR methods tend to be appraised more highly by older respondents, male respondents, and those of a higher social grade. At the same time, all options were appraised more poorly by women, and with greater uncertainty, suggesting a more cautious approach to evaluation. These findings bring into sharp focus earlier concerns voiced in relation to male dominated dimensions of geoengineering projects, and the need to attend to feminist sensibilities through value-sensitive engineering and design processes (Buck, Gammon & Preston, 2014). This said, there is a risk in considering these to be essentialised gender differences rather than 'effects made by gender' as a socio-political force (Henwood, Parkhill & Pidgeon, 2008). There are also other demographic and characteristic variables that were not included in the present study but could have an important influence on support for or opposition to CDR methods. Level of education and beliefs about climate change itself, for example, have both proven to be important factors in prior studies (Poortinga et al., 2019).

Finally, a significant gap exists between people who hold egalitarian and hierarchical cultural worldviews. Individualist and collectivist hierarchists are much more in favour of not having CDR than individualist and collectivist egalitarians, highlighting where likely resistance to CDR deployments may come from. Nevertheless, they were still more in favour of having CDR methods than not. Whereas earlier research has suggested that hierarchical individualists are more in favour of geoengineering ideas than egalitarian collectivists (Kahan et al., 2015), the present findings suggest that the line of divergence between worldviews for CDR is much broader, between hierarchists and egalitarians of both kinds. While this is consistent with the predictions of cultural cognition, the specific reasonings behind the greater support for not having CDR among hierarchists is, however, not completely clear. The no CDR option was described to respondents in terms of avoiding the deterrence of emissions reductions, but it may also have been appealing to climate sceptics believing that CDR should not be used because climate change itself is not a problem.

A significant gap also exists where egalitarians – of either an individualist or collectivist persuasion – are much more in favour of the so-called 'natural' or 'nature-based' CDR methods than hierarchists of either persuasion. Perhaps most interestingly, however, there were no significant differences between worldviews in relation to the more 'technological' CDR methods of DACCS and BECCS. This shows that there is no significant disagreement about the performance of technological CDR methods, and that they may be less likely to polarize public opinion than natural CDR methods. Coupled with the need to properly scrutinise natural CDR methods by deactivating the natural framing in public discourse discussed above, the potential contribution of technological CDR methods may be more fully realised. In seeking to maintain this lack of polarisation, technological and natural CDR methods alike must avoid becoming linked to 'greenwashing' by corporate interests or the fossil fuel industry.

5. Conclusions

Public participation in appraisal is imperative to building democratic, trustworthy and socially intelligent research, development, demonstration and deployment of CDR methods. This study has contributed to the small but growing literatures on CDR technology assessment and public attitudes to CDR by developing a novel multi-criteria option appraisal process inspired by deliberative mapping. It has significantly grown the number of people who can traditionally participate in the core process from tens to thousands of citizens. It has also fused the method with the insights of the cultural cognition thesis, alongside accounting for political and geographical factors, as well as more typical demographic and socio-economics factors. The study finds that the British public supports the inclusion of CDR in the UK's efforts to tackle climate change, though this does not equate to unconditional support. It finds a preference for 'natural' CDR methods, though this appears to be symptomatic of the Romantic view of nature prevalent in society at large. Preferred CDR methods are being mainly developed by public sector and non-governmental organisations, echoing mistrust of private interests found elsewhere. Regional differences in option appraisal reveal where particular CDR methods are more or less likely to be supported or opposed; though local research will be needed to establish attitudes towards site-specific projects. Highest support comes from egalitarian cultural worldviews, older people, men, and higher social grades, with hierarchical cultural worldviews and women appraising the options more poorly. Finally, unlike 'natural' CDR methods, 'technological' CDR methods suffer no significant disagreement between cultural worldviews, a fact which when coupled with the need to deactivate the effects of the nature framing, promises that they may be more fully realised in the future.

These findings have a number of immediate implications for national and international climate policy. The findings show that the inclusion of CDR in the UK Government's Net Zero Strategy (2021) and in the CCC's (2019) net zero scenarios is in line with how the British public is thinking about CDR. It shows that BECCS, wood in construction and afforestation – the CDR methods included in the CCC's 'core' scenario – are the 'middle' performing options in public appraisals. It also shows that DACCS and habitat restoration – the CDR methods included in the CCC's 'further ambition' scenario – are the least and highest performing options, respectively. This means that, at least in terms of public opinion, the exclusion of these options from the 'core' scenario may be an oversight in the case of habitat restoration. The method developed here can serve as a template for rolling out core principles of deliberative mapping internationally to support consideration of CDR methods in climate policy (and indeed of options in other contested science policy domains) around the world. While certain aspects of the present study are UK-specific, the cultural cognition thesis holds that the same socio-cultural patterns of worldview will be present in other countries. We can therefore expect to find higher support for CDR methods among egalitarians than among hierarchists. Depending on the dominant political cultures in any given country, CDR may have a relatively easier or harder time entering into national climate policies (Mamadouh, 1999), and if it does will likely encounter a variety of emergent policymaking styles (Schenuit et al., 2021). Nevertheless, further research is needed to test this hypothesis empirically in different national contexts.

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CRediT authorship contribution statement

Rob Bellamy: Conceptualization, Methodology, Investigation, Writing – review & editing, Funding acquisition, Formal analysis, Writing – original draft, Visualization, Data curation, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102593.

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