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How do the Australian public perceive the risks and benefits of novel restoration and adaptation interventions on coral reefs?

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HIGHLIGHTS

- Ethics and safety enhance perceptions of an intervention's feasibility and impact.
- Public perceptions of risks and benefits remain consistent over time, supporting long-term intervention planning.
- Demographics, reef proximity and levels of understanding shape public risk perceptions.

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ABSTRACT

Ecosystem degradation due to climate change is driving increasing demand for innovative interventions for ecosystem protection, restoration, and adaptation. Understanding public perceptions of risks and benefits associated with these interventions is crucial for their successful implementation. This study examines Australian residents' perceptions of risks and benefits associated with the potential deployment of six novel coral reef interventions on the Great Barrier Reef, including marine cloud brightening, fogging, rubble stabilization, coral seeding, natural breeding, and genetic engineering. Using longitudinal survey data collected in 2018, 2022, and 2024 from over 8000 participants, this paper investigates how perceptions of ethics and safety, feasibility, and social impact changed over time, across interventions, and between demographic groups. All interventions were perceived as beneficial. However, restorative interventions (rubble stabilization and coral seeding) received lower risk scores across all risk/benefit domains, while genetic engineering was viewed as slightly less ethical and safe than other interventions. Factors such as proximity to the Great Barrier Reef, age, Indigenous status, and self-reported understanding of the interventions significantly influenced public risk perceptions. Enhancing public understanding and addressing ethical concerns are critical to building support for innovative reef interventions. Empirical insights reveal the complex dynamics of public risk perceptions and their underlying factors, highlighting their role in shaping support. The methodological approach of assessing perceived risks and benefits over time offers a valuable framework for evaluating public acceptance of environmental technologies across various contexts, supporting the development of responsible management strategies for global ecosystems.

1. Introduction

Tropical coral reefs, including Australia's Great Barrier Reef (GBR), are increasingly the focus of research to develop novel protection, restoration, and adaptation interventions (hereafter, 'novel interventions') intended to alter environmental conditions at a local or regional scale (Fritz et al., 2024), improve ecosystem recovery following disturbance, and accelerate ecosystem adaptation to climate change (Anthony et al., 2020; Bay et al., 2019; Twardek et al., 2023). With existing coral restoration techniques suitable only for application at very

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small scales, novel intervention options are needed, according to Anthony et al. (2020), to increase ecosystem resilience in the face of increasingly frequent and severe climate-related disturbances. The success of such interventions will depend on parallel efforts to reduce greenhouse gas emissions and improve the effectiveness of 'conventional' environmental management practices, such as pest and water quality control (McLeod et al., 2022), reducing pressure on ecosystems, and allowing more time for recovery and adaptation (Anthony et al., 2017).

The success of novel interventions also relies on sustained public support for their development and deployment (Fritz et al., 2024; Kenny et al., 2023; Löfqvist et al., 2023). Prior research suggests that public support is associated with people's perceptions of potential risks and benefits, particularly in comparison to established management practices such as manual pest control (Mankad et al., 2021; Merk and Pönitzsch, 2017). This is especially relevant in the context of the GBR, where novel interventions are being developed through the Reef Restoration and Adaptation Program (RRAP) to supplement traditional conservation strategies (Bay et al., 2019; McLeod et al., 2022). Ensuring public confidence in these measures is critical to their future adoption. Public risk perceptions, the ways in which individuals and groups understand and interpret threats, play a critical role in the communication and management of novel interventions (Lockie et al., 2024).

Individuals often make subjective risk judgments based on personal characteristics, knowledge, experience, and cognitive processing (Finucane et al., 2000; Lockie et al., 2024). In the case of reef restoration, these perceptions can influence whether specific technologies are viewed as viable, trustworthy, or acceptable by the broader public. However, empirical research on risk perception related to intervention on the GBR and other ecosystems is still in its early stages. A significant gap to date relates to the understanding of public risk perceptions, particularly concerning the underlying aspects or dimensions of risk. Some studies bypass this level of detail and simply ask whether people perceive a specific intervention as risky or not (Tam and McDaniels, 2013). While such information is useful, it does not provide insight into which specific aspects of an intervention are perceived as problematic or why potential benefits might justify risk-taking. For example, some people may view an intervention as risky because of potential unanticipated effects. In contrast, others may consider it risky because they believe it is unlikely to succeed or because the benefits, even if it does succeed, are insignificant. Understanding these distinctions is essential for intervention research programs like RRAP, where stakeholder concerns may influence regulatory approval, investment, and implementation.

Through an inductive analysis of both the literature on risk analysis and interviews with GBR community members, Lockie et al. (2024) identified three broad ways in which public risk perceptions might shape the political acceptability and material outcomes of novel interventions. These included: (1) the ethics and acceptability of intervening in ecosystems previously treated as 'natural' or 'wild', (2) the amplification or attenuation of other risks through behavioural changes such as reef visitation and tourism, and (3) the perceived viability of interventions. Baum et al.'s (2024) conceptualisation of risk overlaps in some areas, focusing on factors such as the perceived safety, cost-efficiency, and long-term effectiveness of novel environmental interventions. However, both frameworks require broader empirical validation.

Beyond understanding how to conceptualise public risk perceptions related to novel reef restoration interventions, there is a growing need to understand how such perceptions change across time, space, intervention types, and social groups. Most studies in this space have typically focused on a single point in time, rather than elucidating how perceptions may change over time and why, and focused on single interventions or sites, with small sample sizes (Liu et al., 2023; Tam and McDaniels, 2013; Wibeck et al., 2017). An exception to this trend is the work by Baum et al. (2024) which explored risk perceptions using a large-scale, cross-country research design. Their study also examined multiple intervention types, whereas most other research, except for Tam and McDaniels (2013), focuses on a single intervention (Liu et al., 2023; Mankad et al., 2021). Baum et al.'s (2024) findings show that on a global scale, people in the Global South were generally more supportive of interventions, with the most significant factor being age - younger people tended to perceive more benefits and less risk associated with interventions. However, the extent to which these patterns hold in the Australian context, particularly regarding emerging GBR restoration technologies, remains underexplored. Beyond these findings, there is also limited knowledge about how public risk perceptions differ across social cohorts and demographics.

Our study contributes to this nascent literature on public risk perceptions of novel ecosystem protection, restoration, and adaptation interventions using a case study on the world's largest living ecosystem, the GBR in Australia. We used longitudinal data ($n = 8460$), collected over a six-year period between 2018 and 2024, to evaluate public perceptions of risks and benefits across six novel interventions – five of which are currently being explored and tested through Australia's RRAP program and one (genetic engineering) which is not part of RRAP. These six interventions represent a subset of the broader suite of approaches under consideration, which are commonly grouped into three functional categories: protecting or mitigating against risks, repairing or restoring, and/or enhancing adaptation (Bay et al., 2019; McLeod et al., 2022). We used a data-driven approach using multiple risk indicators to identify how different types of risk perception cluster together. Based on the clusters identified, we investigated: (1) how laypeople's perceptions of risks and benefits differed across the six types of reef restoration interventions, (2) how public perceptions varied across time and reef proximity, and (3) how various demographic and contextual factors influenced these perceptions. Acknowledging and understanding public perceptions of these technologies is critical for anticipating acceptance, identifying potential barriers, and informing the development of regulatory governance frameworks and risk management strategies for reef restoration.

1.1. Research context

Tropical coral reefs around the world are facing severe threats, with their condition continuously deteriorating due to the impacts of climate change. Mass coral bleaching events triggered by marine heatwaves occur more frequently (with a fourth global coral bleaching event recorded in 2024 throughout the tropics, including Florida, Australia's GBR, the Red Sea, the Persian Gulf, the Gulf of Aden and large areas of South Pacific) and last for longer durations, allowing less time for recovery (Klein et al., 2024). Restricting global warming to 1.5 °C is unlikely to protect the world's coral reefs, with evidence suggesting that ~40 % of GBR warm water coral reefs will disappear by 2050, with +2 °C of warming models predicting complete collapse of functions (Quigley and Baird, 2024).

Coral reefs provide numerous benefits to human communities globally, including food, financial resources, recreational opportunities, coastal protection, cultural settings, and various other ecological goods and services (Bartelet et al., 2024; Costanza et al., 2014; Hoegh-Guldberg et al., 2019). The decline of coral reefs can have profound consequences for the livelihoods, culture, and psychological well-being of hundreds of millions of people, posing an urgent decision challenge for management and conservation efforts (Robinson et al., 2023). Effective conservation strategies are essential to preserve these benefits and ensure the resilience of both coral reefs and the human communities that depend on them.

Numerous solutions to address the degradation of coral reefs worldwide, including the GBR, have been proposed and tested through programs such as the KAUST Coral Restoration Initiative in the Kingdom of Saudi Arabia and Australia's RRAP. RRAP, one of the largest programs of its kind, is a collaborative initiative involving academic institutions, non-profit organisations, government agencies, and private sector partners, focusing on a broad range of prospective interventions. Led by the Australian Government's Reef Trust and the Great Barrier Reef Foundation, RRAP's objective is to provide Reef managers with a set of proven, sustainable, acceptable, and feasible intervention strategies to enhance the GBR's resilience and capacity to adapt to climate change (Bay et al., 2019; McLeod et al., 2022).

The first functional group of interventions subject to research and development through RRAP, protective interventions, includes marine cloud brightening (MCB) and low-level fogging, both are solar radiation management (SRM) techniques that utilize atomised seawater to reduce surface water temperatures during marine heatwaves (Butcherine et al., 2023; Harrison, 2024). The second group focuses on restorative interventions, including the provision of more stable substrates for coral recovery (Kenyon et al., 2023), the harvesting and settling slicks of coral larvae on degraded reefs (McLeod et al., 2022) and increasing the efficiency and effectiveness of coral aquaculture and outplanting (Lippmann et al., 2023; Randall et al., 2021). The third group comprises adaptive interventions, including the identification of corals with natural heat tolerance for use in restoration plantings (Selmoni et al., 2024), pre-conditioning juvenile corals in aquaculture facilities to heat stress (McLeod et al., 2022), the introduction of heat-evolved strains of algal symbionts on which corals rely for photosynthesis (Scharfenstein et al., 2023), and selective breeding of corals for heat tolerance (McLeod et al., 2022).

While the technical viability of these approaches is being assessed by scientists, their social legitimacy depends on how they are perceived by the public. As novel interventions grow in scale and visibility, understanding public responses becomes essential for effective governance, risk communication, and long-term success (Arning et al., 2020; de Groot et al., 2020; Le et al., 2022).

2. Methodology

We designed a five-step analytical sequence to align with the research objectives and maintain methodological transparency. First, we used semantic differential scales to measure respondents' perceptions of multiple risk and benefit factors for each intervention, capturing nuanced, interval-level attitudinal data. Second, we applied Principal Component Analysis (PCA) to reduce dimensionality, identify latent constructs, and improve conceptual clarity, confirming data suitability with standard diagnostic tests. Third, we calculated and visualized descriptive statistics (means, standard deviations) to compare perception clusters across interventions. Fourth, we used Tukey multiple comparison tests to identify statistically significant differences between clusters that did not appear in the raw statistics or density plots. Finally, we examined changes in perceptions over time, by reef proximity, and other contextual variables to address questions on public perception dynamics. A flow chart outlining these key methodological steps is provided in Appendix A.

2.1. Sampling and survey design

The data presented in this manuscript were collected as part of a broader study examining community perceptions of current and emerging management interventions for the GBR, conducted under and aligned with RRAP. This study draws on longitudinal data from surveys conducted in 2018, 2022, and 2024, capturing the views of 8460 Australian residents over time.

A stratified sampling strategy was employed to target two key groups:

- Australian residents across all states and territories (national sample).
- Individuals residing within 50 km of the GBR coastline (resident sample).

In each of the three survey years, data were collected using online surveys distributed via a market research company (YouGov) using online panels. For the Australia-wide sample, we set quotas based on Australian census data (Australian Bureau of Statistics, 2021, Australian Bureau of Statistics, 2016) to match the population distribution by gender (male/female), age group, and location (Australian state or territory). For the Great Barrier Reef (GBR) sample, we applied soft quotas for Queensland using the same demographic categories as a guide. Both samples included a mix of urban and rural respondents to reflect the diversity of the target populations. Data quality was maintained by removing incomplete responses or surveys completed too quickly to ensure reliable input (e.g., by "speeders").

The surveys included a section where participants were presented with a novel GBR intervention and where asked about how they perceived its risk and benefits. Our research design used independent samples where each respondent only answered questions about one specific intervention, rather than comparing the suite of interventions. Five of these interventions are currently being explored through RRAP, while the sixth, genetic engineering, is not under active development. Detailed descriptions of these interventions are available in the Supplementary material Appendix B. Demographic and contextual information about respondents was also collected. Detailed information on the survey questions can be found in Tables 1 and 2. To minimise priming effects, questions were randomised by the survey platform, ensuring that each participant received a unique sequence of questions.

Table 1
Perceived risks and benefits of novel interventions on the Great Barrier Reef.[a]

Statement representing highest potential risk (value of 1)	Statement representing the most benefit (value of 7)
This technology is not needed for long-term health of the Reef	This technology will be critical to the long-term health of the Reef
This technology will be unsafe for people	This technology will be safe for people
The benefits of this technology will be too small to justify the cost	Likely to be cost-effective when fully developed
This sort of technology will be unsafe for ecosystems	This sort of technology will be safe for ecosystems
Use of this technology is unethical	Use of this technology is ethical
Turn the Reef into an artificial system	Protect the Reef's natural values
The technology is unlikely to work	The technology looks like a promising option to help the Reef
The technology will only help small sections of the Reef	This technology should help large sections of the Reef
Likely to have unforeseen environmental impacts if implemented	Environmental impacts can be identified and tested
This technology will compromise cultural values associated with the Reef [b]	This technology will enhance cultural values associated with the Reef [b]
This technology will damage Reef industries such as tourism [b]	This technology will provide new opportunities for Reef industries such as tourism [b]
This technology will have negative impacts on communities living near the Reef [b]	This technology will have positive impacts on communities living near the Reef [b]

[a] Outcomes are measured using a 7-point semantic differential scale in which 1 represents agreement with the statement representing the highest potential risk and 7 represents agreement with the statement representing the most benefit.

[b] Question not included in the 2018 survey, because at that time, our objective was to establish baseline perceptions of the Australian public's perceived technical and environmental evaluation of novel interventions. In subsequent waves (2022 and 2024), we expanded the scope to include cultural values, tourism, and community impacts in response to stakeholder feedback, emerging literature on social licence to operate, and policy interest in the socio-economic implications of Reef interventions.

Table 2
Factors influencing perceived risks and benefits of novel interventions on the GBR.

Variable	Description	Unit of measurement
Reef proximity	Distance of respondent's residence from the GBR.	(0) More than 50 km from GBR (1) Within 50 km from GBR
Year	Year in which the survey was conducted	(0) 2018 (1) 2022 (1.5) 2024
Gender[a]	Gender of respondent.	(0) Female (1) Male
Age Group	Respondent's age group; initially measured using six levels: (1) under 18 (terminated from survey); (2) 18 to 29; (3) 30 to 39; (4) 40 to 49; (5) 50 to 59); and (6) above 60. The binary split was based on the approximate midpoint of the age distribution in our sample, with 43 % of respondents across all survey cohorts aged 50 years and older.	(0) Below 50 years (1) 50 years and older
First Nations people	Respondent identified as Aboriginal and/or Torres Strait Islander.	(0) No (1) Yes
Education	Respondent had an undergraduate and/or postgraduate degree; initially measured using five levels.	(0) No (1) Yes
Employment	Respondent had a full-time employment status at the time of the survey	(0) No (1) Yes
Visitation (ever)	Respondent had ever visited the GBR.	(0) No (1) Yes
Knowledge (GBR)	Respondent's self-rated knowledge about the GBR.	From 1 'know very little' to 10 'know a lot'.
Understanding (technology)	Respondent's self-rated understanding of the described intervention.	From 1 'know very little' to 10 'know a lot'.

[a] In 22 out of our 8460 surveys, the respondents selected the 'other/prefer not to say' gender option. These surveys were too few for a dedicated gender category, and they were consequently excluded from our regression analysis.

2.2. Risk and benefit outcome variables

We included the twelve specific risk and benefit indicators described in Table 1. These indicators were informed by the technological risk perceptions literature (Bellamy and Lezaun, 2017; Corner and Pidgeon, 2015; Merk and Pönitzsch, 2017) and developed based on expert knowledge gained through RRAP. The indicators were developed and finalized through collaborative workshops involving subject matter experts. The indicators were measured using survey questions that consisted of two opposing statements, to which the respondent should indicate their level of support, using a semantic differential scale with verbal anchors (Osgood, 1952; Salkind, 2007). This approach allows for the interpretation of responses along a continuous spectrum between opposing evaluative statements (e.g., from "This technology is not needed …" to "This technology will be critical …"). This format assumes that each pair of opposing statements represents a coherent evaluative continuum, which is a common and empirically supported approach in risk perception research (Finucane et al., 2000). While risk and benefit judgments can be cognitively distinct, prior studies suggest that they often align along a shared evaluative dimension when items are clearly worded and contextually grounded (Salkind, 2007). In public discourse, perceptions of new technologies are often shaped not by isolated assessments of "risk" or "benefit," but by an overall sense of whether the technology is likely to do more good than harm (Mankad et al., 2021; Merk and Pönitzsch, 2017). In this study, we therefore used a semantic differential scale to measure public sentiment about novel reef interventions along a single evaluative continuum, ranging from negative (e.g., risky, harmful, unnecessary) to positive (e.g., beneficial, safe, necessary) outcomes.

This question format reflects plain-English use of the term 'risk' to denote a threat or hazard and thus the opposite of a benefit or opportunity. Respondents were asked to indicate which outcome, negative or positive, they thought most likely. For any one respondent a response of 4, the midpoint, may have indicated uncertainty, the perception that both risks and benefits are trivial, or the perception risks and benefits are both equally likely despite being of greater magnitude. Respondents were not asked to estimate the probability of any particular outcome nor the consequences of those outcomes for the Reef's Outstanding Universal Value as inscribed in the GBR World Heritage Area, as will be required during regulatory risk assessment of proposed interventions (Lockie et al., 2024).

2.3. Analysis

While the semantic differential items used in this study were framed with verbal anchors (Table 1), they were implemented as 7-point scales with evenly spaced numeric values from 1 to 7. Such scales are commonly treated as interval-level data in attitude and perception research when applied consistently (Dawes, 2008; Smith and Albaum, 2004), which allows for the use of Principal Component Analysis (PCA) as well as parametric techniques such as linear regression. Because of the large number of risk and benefit indicators we included in our survey (Table 1), we first used PCA to explore whether some indicators were clustered together. PCA was undertaken using R modelling software version 4.2.2 (R Core Team, 2013), and its in-built stats package, using the *princomp* function. Because the last three risk indicators in Table 1 were not included in the 2018 survey, the PCA was only based on the 2022 and 2024 surveys. We found that the first two principal components explained about a third (33 %) of the total variance in the 12 risks and benefits indicators. We used the scores on these first two factors to identify primary overlaps between different risk factors and verified whether these made sense conceptually. Rather than using the principal factors as new variables in our further analysis and given the first two factors explained about a third of the total variance, we decided to create novel variables based on observed clustering, which helped us retain the relevant information captured in the individual risk indicators. Clustering the risks and benefit indicators based on these first two principal components identified three primary clusters of risks and benefits in our dataset that we deemed conceptually and practically relevant (Fig. 1):

1. **Ethics and Safety** (intervention will be safe for people and ecosystems and is ethical in use).
2. **Feasibility** (intervention will be critical to the long-term health of the Reef, likely to be cost-effective when fully developed, looks like a promising option to help the Reef, and should help large sections of the Reef).
3. **Social Impacts** (intervention will enhance cultural values associated with the Reef, provide new opportunities for Reef industries such as tourism, and have positive impacts on communities living near the Reef).

For each of the three clusters, we created a novel variable using an equally weighted average of the specific risk and benefit indicators that were clustered under it. Two indicators were excluded from further analysis (whether the intervention protects the Reef's natural values and whether environmental impacts can be identified and tested) as suggested by conceptual overlap and clustering analysis (Fig. 1). We tested for the internal reliability of the three clustered risk indicators by calculating the Cronbach's alpha (α) for the variables that were used within each scale. Cronbach tests were undertaken on the combined sample, including all the novel interventions across all the survey years (2018, 2022, and 2024) for the Ethics and Safety and Feasibility clusters, and for the survey years 2022 and 2024 for the Social Impacts cluster because these indicators were not included in the 2018 survey. All scales

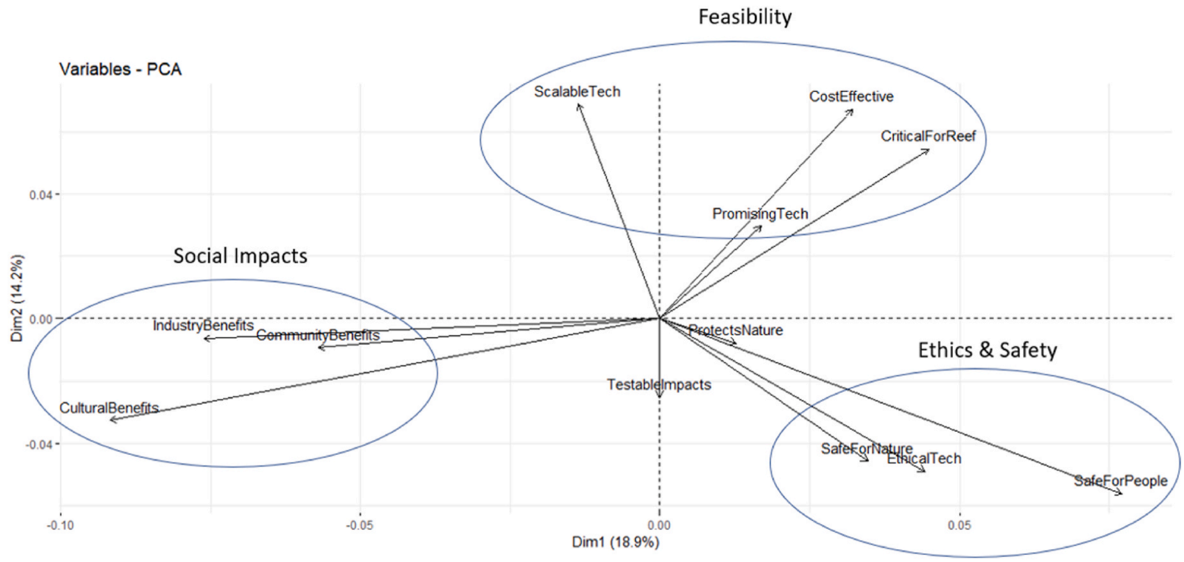

Fig. 1. Clustering of potential risks and benefits associated with six novel interventions on the Great Barrier Reef.
Note*: We used Principal Component Analysis (PCA) on the indicators (*Table 1*) to explore whether some risks and benefits were clustered together. PCA was undertaken using R modelling software version 4.2.2 (*R Core Team, 2013*), and its in-built stats package, using the princomp function. The graph shows the similarities between potential risks and benefits in terms of their relationship to the first two principal components. The first two principal components explain 33 % of the total variance in the twelve variables included in the analysis, with respectively 19 % for the first dimension (x-axis), and 14 % for the second dimension (y-axis). Analysis based on combined sample with all six novel interventions and is based on data from the 2022 and 2024 surveys only because three risk factors were not included in the 2018 survey (see *Table 1*).*

showed internal reliability with Cronbach's α values of 0.846 for Ethics and Safety, 0.873 for Feasibility, and 0.849 for Social Impacts. We also noted that the Cronbach α for the three clustered variables (Ethics and Safety, Feasibility, and Social Impacts) was 0.918, indicating significant overlap between different dimensions of risk as perceived by Australian residents.

For each of the six novel interventions (Supplementary material Appendix B), we then compared their mean scores and distributions on the three risk clusters (Fig. 1). We also visualized our results using ridgeline plots, which integrate both summary statistics and density information, using the *ggridges* package (Wilke, 2024) in R modelling software. We used Analysis of variance (ANOVA), through R's in-built stats package function (*aov*), to compare the mean scores on the three risk clusters between the six novel interventions. We use Tukey's honest significance test to compare pairwise differences between interventions, using the *TukeyHSD* function in R. We used Tukey's honest significance test because it compares all possible pairs of groups while controlling the overall error rate, ensuring that any detected differences are unlikely to be due to chance. This approach allowed us to detect meaningful contrasts between intervention types with confidence, even when the differences were subtle.

Finally, we used linear regression models for each of the three risk clusters to explore differences in public risk perceptions explained by demographic factors and differences in knowledge and threat perceptions between our survey participants (Table 2). Here we used separate regression models for each of the six novel interventions to compare whether these determinants vary according to intervention type. Models were fit using R, using the built-in stats package and the *lm* function. All non-binary predictors in the models were standardised using z-scores to facilitate direct comparison of effect sizes (Abelson, 1995). We assessed the assumptions of linear regression using the DHARMa residuals package in R (Hartig, 2018) and multicollinearity was assessed using variance inflation factors calculated with the performance package in R (Lüdecke et al., 2021). All predictors had a variance inflation factor below 2, indicating no collinearity in the model. We report adjusted R-squared values provided through the *lm* function, indicating the proportion of the total variability in the outcome variable that is accounted for by the model.

3. Results

As shown in Table 3, mean values for all risk clusters and interventions ranged between 4 (the midpoint of the semantic differential scale) and 5, which could be interpreted as slightly positive. Using Tukey's honest significance tests to compare pairwise differences between interventions (Supplementary material Appendix C), we found that the perceived ethics and safety of genetic engineering was significantly lower than all other interventions at the ninety-five percent level of significance (p-value = 0.05). The perceived ethics and safety of marine cloud brightening, fogging, and natural breeding were all significantly lower than both rubble stabilization and coral seeding. There were no significant differences in the perceived ethics and safety of marine cloud brightening, fogging, and natural breeding. Nor,

Table 3
Summary statistics for perceived risk indicators by novel intervention type[a].

Risk indicator	Novel intervention	Mean value (standard deviation)
Ethics and Safety	Marine cloud brightening	4.55 (1.34)
	Fogging	4.65 (1.34)
	Rubble stabilization	4.83 (1.29)
	Coral seeding	4.89 (1.31)
	Natural breeding	4.67 (1.26)
	Genetic engineering	4.30 (1.30)
Feasibility	Marine cloud brightening	4.44 (1.38)
	Fogging	4.48 (1.41)
	Rubble stabilization	4.80 (1.33)
	Coral seeding	4.85 (1.33)
	Natural breeding	4.71 (1.30)
	Genetic engineering	4.47 (1.32)
Social Impacts	Marine cloud brightening	4.51 (1.33)
	Fogging	4.44 (1.34)
	Rubble stabilization	4.68 (1.32)
	Coral seeding	4.76 (1.28)
	Natural breeding	4.67 (1.21)
	Genetic engineering	4.46 (1.28)

[a] *Based on 8460 Australian resident surveys across years 2018, 2022, and 2024 for Ethics & Safety and Feasibility risk indicators and based on 6440 Australian resident surveys across years 2022 and 2024 for Social Impacts risk indicator. Fogging and Coral seeding interventions only have data for the years 2022 and 2024.*

similarly, was there a significant difference in the perceived ethics and safety of rubble stabilization and coral seeding. There were no significant differences in the perceived feasibility of marine cloud brightening, fogging, and genetic engineering, but all attracted significantly lower assessments of feasibility than did rubble stabilization, coral seeding, and natural breeding. There were no significant differences in the perceived feasibility of rubble stabilization, coral seeding, and natural breeding. In relation to perceived social impacts, the same significant relationships were found as described for feasibility.

Differences in mean value aside, Fig. 2 demonstrates a similar pattern of results for all interventions and risk/benefit domains, with the shape and density of the ridgeline plots skewed to values above the midpoint of 4. Most notably, the findings show that the value of 4 on the semantical differential scale was consistently the modus across all risk and benefit factors and intervention types. Mimicking the findings from Table 3, the graph also highlights the strong similarity in risk and benefit perceptions across risk types and intervention types. In terms of perceived Feasibility, finally, the figure shows that for the natural breeding, coral seeding, and rubble stabilization interventions, the distribution starts to lean more strongly from the middle value of 4 towards the more beneficial outcomes (values of five and six).

Significant results from our linear regression analysis are provided below. Given the semantic differential scale we used for the perceived risk and benefit questions, regression coefficients (effect sizes) should be interpreted in terms of a predictor's linear effect on the seven-point differential scale. For example, a significant negative effect of −0.5 for a binary predictor indicates that, while holding other predictors constant, that predictor led to perceptions of interventions being 0.5 more risky/less beneficial. Because we used a 7-point semantic differential scale, the effect size (−0.5) would equate to the intervention being perceived as 7 % riskier/less beneficial. As shown in Fig. 3, the perceived ethicality and safety of novel interventions on the GBR were most substantially associated with the age of the respondent, First Nations status, and the self-reported understanding of the intervention. Except for fogging and genetic engineering, older respondents perceived interventions to be more ethical and safer than did younger respondents, and this effect was substantial for rubble stabilization (β = 0.32, *p*-value <0.001) and moderate for coral seeding (β = 0.22, *p*-value = 0.012). Aboriginal and Torres Strait Islander respondents perceived coral seeding (β = −0.42, *p*-value = 0.008), natural breeding (β = −0.42, *p*-value <0.001), and rubble stabilization (β = −0.30, *p*-value = 0.008) as substantially less ethical and safe. Respondents with a higher self-reported understanding of the described intervention perceived all interventions except genetic engineering to be moderately to substantially more ethical and safer, with respective standardized effect sizes (β) of 0.36 for coral seeding, 0.33 for rubble stabilization, 0.26 for fogging, 0.24 for marine cloud brightening, and 0.23 for natural breeding, all significant with a *p*-value below 0.001.

Other less substantial effects were also identified, which were only significantly associated with a specific intervention. Residents located within 50 km of the GBR coastline perceived coral seeding as moderately more ethical and safer (mean effect size (β) = 0.22, *p*-value = 0.016). Perceptions of the ethicality and safety of rubble stabilization decreased slightly over time (β = −0.13, *p*-value = 0.010). Male respondents perceived genetic engineering as slightly more ethical and safer (β = 0.15, *p*-value = 0.026). Respondents with higher self-reported knowledge levels about the GBR perceived rubble stabilization (standardized β = −0.09, *p*-value = 0.009) and coral seeding (standardized β = −0.12, *p*-value 0.001) as slightly less ethical and safe. Finally, education levels, employment status, and reef visitation did not have a significant effect on any of the interventions.

The perceived feasibility of novel interventions on the GBR was most substantially associated with the year in which the survey was conducted, the gender of the respondent, First Nations status, and the stated understanding of the intervention (Fig. 4). The perceived feasibility of fogging decreased substantially over time (β = −0.56, *p*-value = 0.001), while the perceived feasibility of marine cloud brightening (β = 0.11, *p*-value = 0.044) and natural breeding (β = 0.12, *p*-value = 0.023) increased slightly over time. Male respondents perceived fogging (β = −0.26, *p*-value = 0.004), rubble stabilization (β = −0.21, *p*-value = 0.002), and coral seeding (β = −0.19, *p*-value = 0.021) as moderately less feasible. Aboriginal and Torres Strait Islander respondents perceived

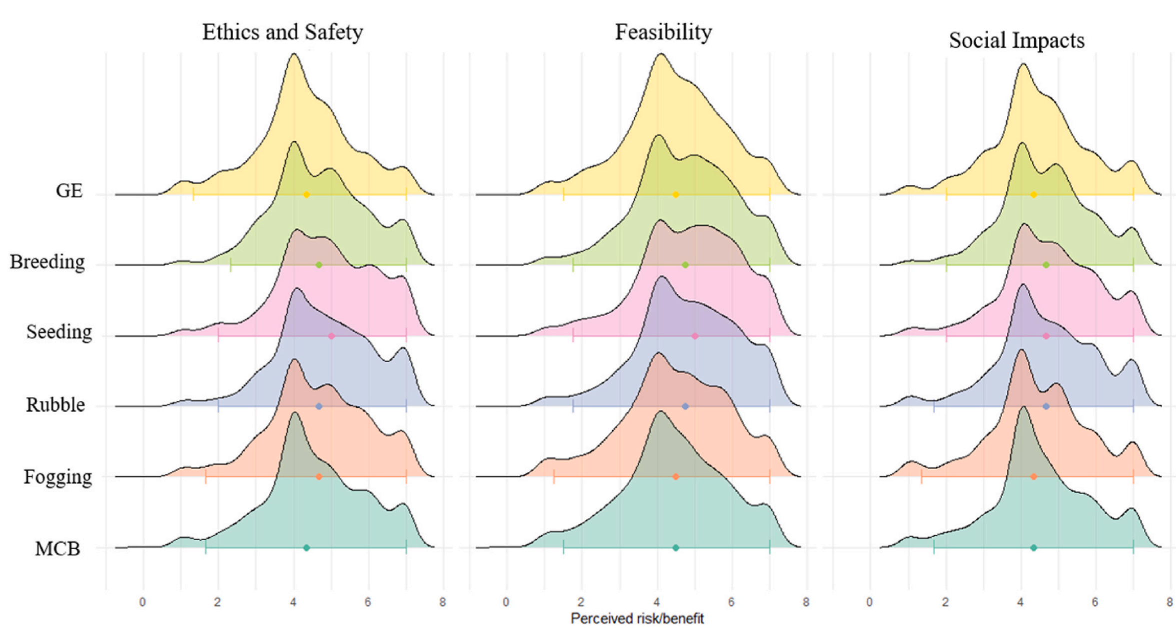

Fig. 2. Differences in distribution and average perceived risks and benefits of six novel interventions on the Great Barrier Reef.
Note: Based on 8460 Australian resident surveys across years 2018, 2022, and 2024 for Ethics and Safety and Feasibility risk indicators and based on 6440 Australian resident surveys across years 2022 and 2024 for Social Impacts risk indicator. Fogging and Coral seeding interventions only have data for the years 2022 and 2024. Figure shows distribution of risk/benefit levels according to density curves, with the round dot showing the median value and the vertical line showing the 95th quantiles.

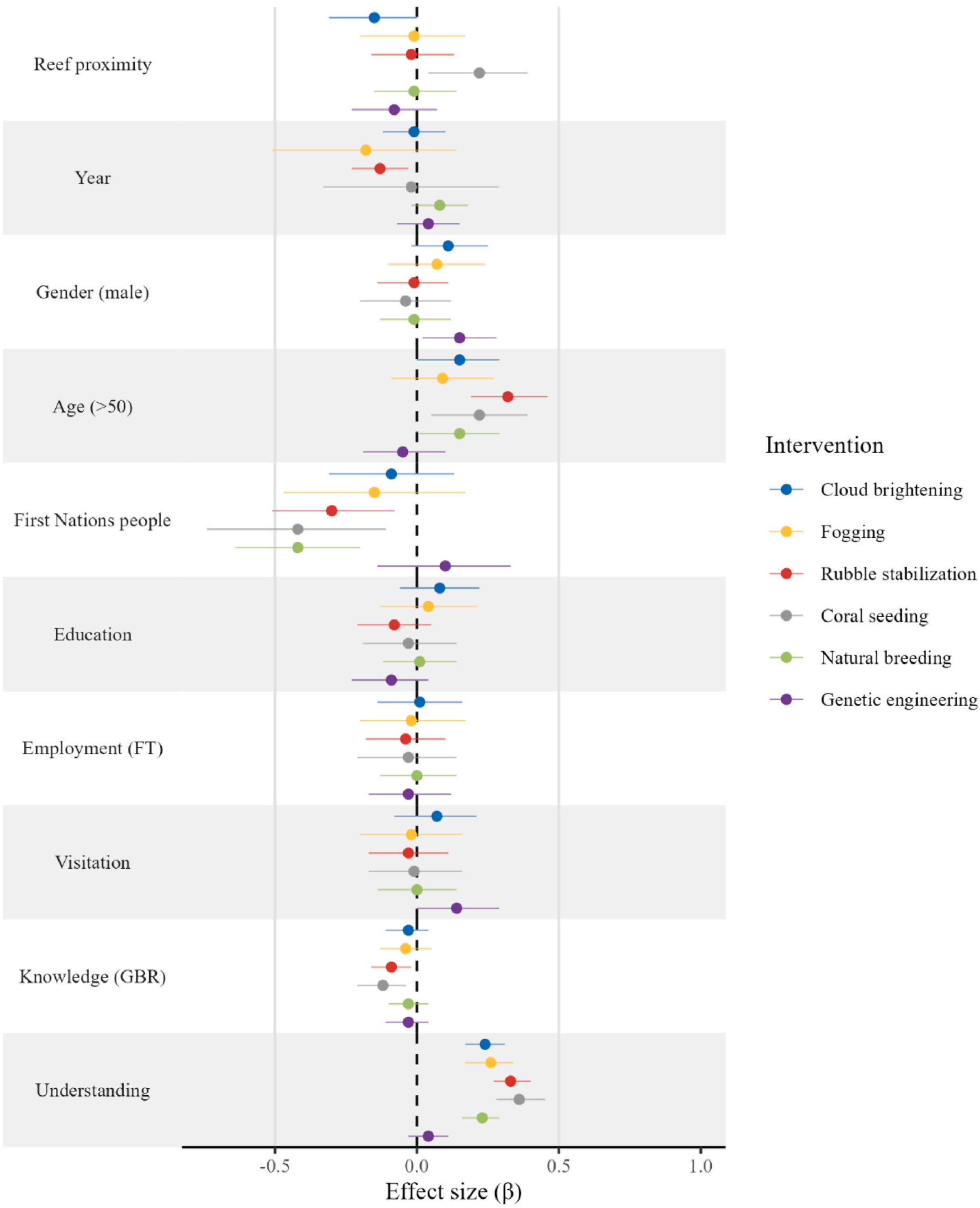

Fig. 3. Regression statistics (effect sizes at 95 % confidence intervals) for linear regression model outcomes associated with the perceived ethics and safety of novel GBR interventions.

Note: Fogging and Coral seeding interventions only have data for the years 2022 and 2024. Significant predictors are those that do not cross the dotted '0' line. Non-binary predictors (knowledge about GBR and understanding of described intervention) were standardized using z-scores. Effect sizes for non-binary predictors shown in this Figure and discussed in the text can be de-standardized by multiplying with the standard deviation of the respective indicator (Appendix D, Sample Description Table).

both natural breeding ($\beta = -0.44$, *p*-value <0.001) and rubble stabilization ($\beta = -0.37$, *p*-value = 0.001) as substantially less feasible. Finally, respondents with a higher self-reported understanding of the described intervention perceived all interventions to be moderately more feasible, with respective standardized effect sizes (β) of 0.34 for rubble stabilization (*p*-value <0.001), 0.31 for coral seeding (*p*-value <0.001), 0.26 for fogging (*p*-value = 0.002), 0.23 for marine cloud brightening (*p*-value <0.001), and 0.12 for genetic engineering (*p*-value = 0.001).

Other less substantial effects were also identified, that were only significantly associated with a specific intervention. Residents located within 50 km of the GBR coastline perceived coral seeding as slightly

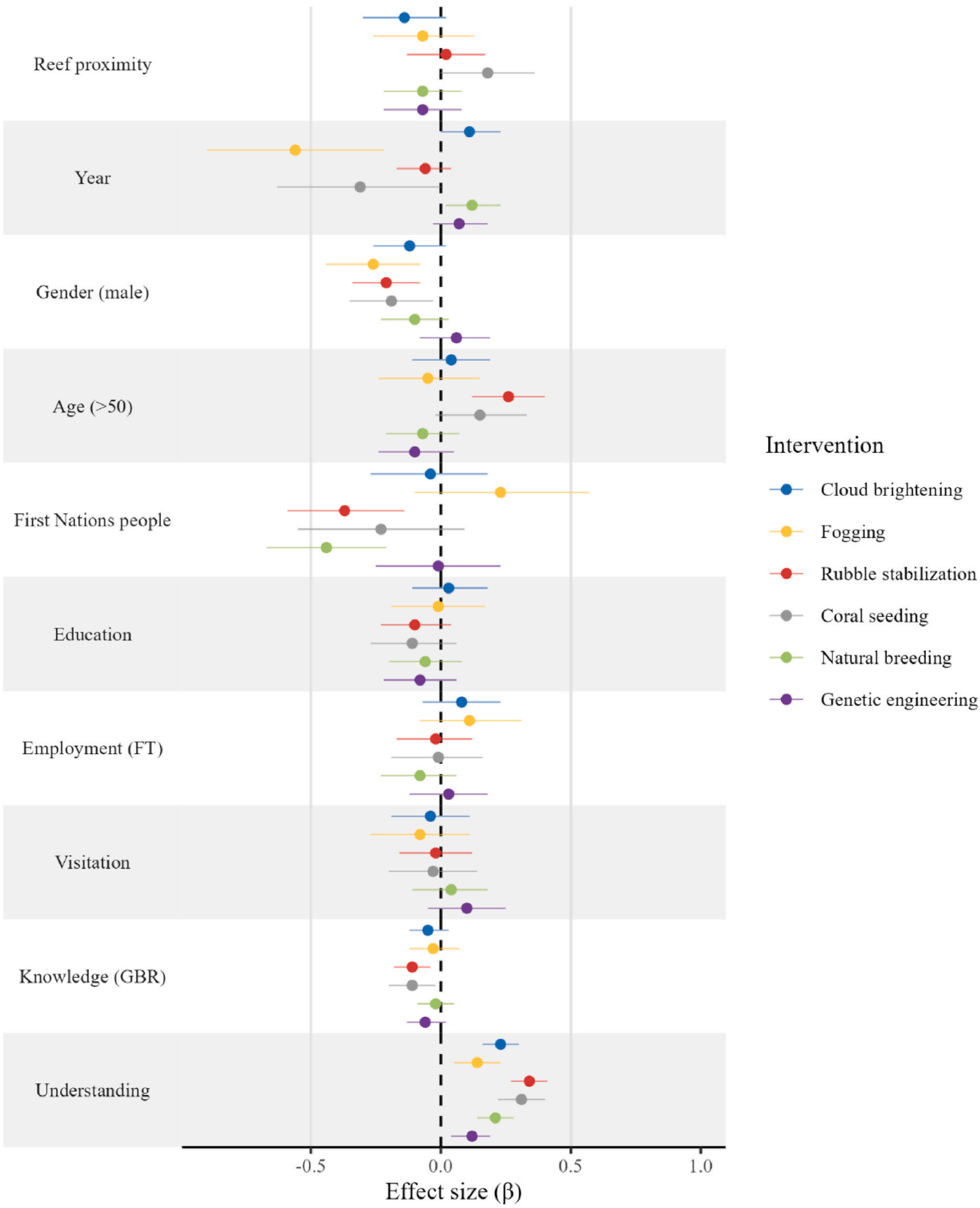

Fig. 4. Regression statistics (effect sizes (β) at 95 % confidence intervals) for linear regression model outcomes associated with the perceived feasibility of novel GBR interventions.

Note: Fogging and Coral seeding interventions only have data for the years 2022 and 2024. Significant predictors are those that do not cross the dotted '0' line. Non-binary predictors (knowledge about GBR and understanding of described intervention) were standardized using z-scores. Effect sizes for non-binary predictors shown in this Figure and discussed in the text can be de-standardized by multiplying with the standard deviation of the respective indicator (**Appendix D**, Sample Description Table).

more feasible (β = 0.18, *p*-value = 0.049). Older respondents perceived rubble stabilization as moderately more feasible (β = 0.26, *p*-value <0.001). Respondents with higher self-reported knowledge levels about the GBR perceived rubble stabilization (standardized β = −0.11, *p*-value = 0.003) and coral seeding (standardized β = −0.11, *p*-value = 0.020) as slightly less feasible. Education levels, employment status, and reef visitation did not have a significant effect on any of the interventions.

The perceived social impacts of novel interventions on the GBR were less consistent across interventions (Fig. 5) than were the perceived ethics and safety (Fig. 3) and feasibility (Fig. 4) of those interventions. Most generally, respondents with a higher self-reported understanding of the described intervention perceived all interventions except genetic

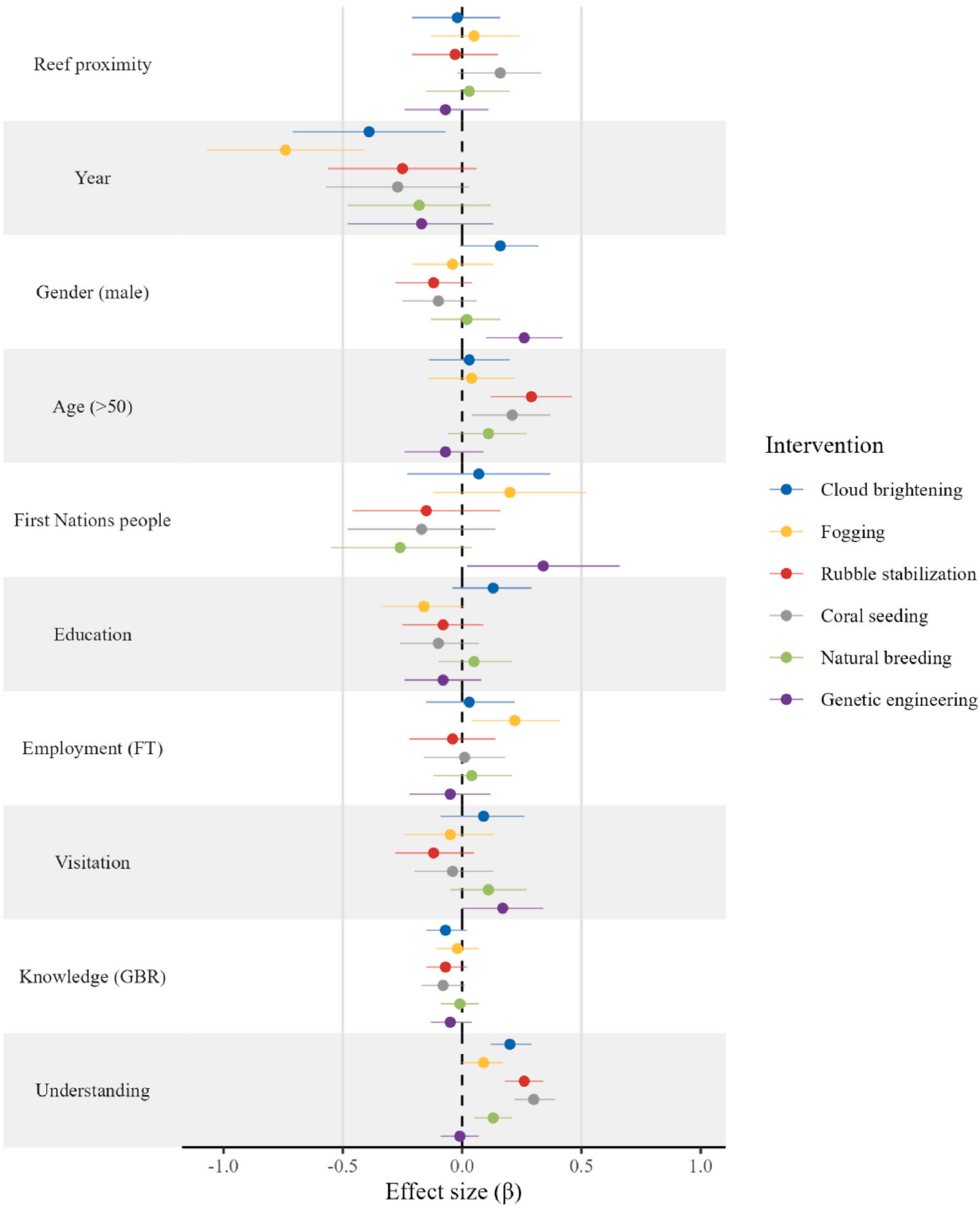

Fig. 5. Regression statistics (effect sizes (β) at 95 % confidence intervals) for linear regression model outcomes associated with the perceived social impacts of novel GBR interventions.

Note: Based on survey years 2022 and 2024 because social impact questions were not included in 2018 survey (see Table 1). Significant predictors are those that do not cross the dotted '0' line. Non-binary predictors (knowledge about GBR and understanding of described intervention) were standardized using z-scores. Effect sizes for non-binary predictors shown in this Figure and discussed in the text can be de-standardized by multiplying with the standard deviation of the respective indicator (Appendix D, Sample Description Table).

engineering to be more socially beneficial, with the most substantial effect sizes for coral seeding (standardized $\beta = 0.30$, *p*-value <0.001) and rubble stabilization (standardized $\beta = 0.26$, *p*-value <0.001). We also found a substantial effect specifically for protective interventions, with people perceiving substantially fewer social benefits of fogging ($\beta = -0.74$, *p*-value <0.001) and marine cloud brightening ($\beta = -0.39$, *p*-value $= 0.017$) across time. Male ($\beta = 0.26$, *p*-value $= 0.001$) and Aboriginal and Torres Strait Islander ($\beta = 0.34$, *p*-value $= 0.038$) respondents perceived moderately more social benefits from genetic engineering. Older respondents perceived moderately more social benefits from rubble stabilization ($\beta = 0.29$, *p*-value $= 0.001$) and coral seeding ($\beta = 0.21$, *p*-value $= 0.016$). Respondents with full-time employment at the time of the survey perceived moderately more social benefits from fogging ($\beta = 0.22$, p-value $= 0.017$), while respondents who had ever visited the GBR perceived slightly more social benefits from genetic engineering ($\beta = 0.17$, p-value $= 0.047$). Reef proximity, education levels and self-reported knowledge about the GBR did not have a significant effect on any of the interventions.

4. Discussion

Our study marks one of the first attempts to provide a comparative and comprehensive analysis that highlights shared and divergent risk dimensions across six different environmental intervention types within the protective, restorative, and adaptive categories (Anthony et al., 2017; Bartelet et al., 2025a). Previous research has typically focused either on individual interventions (Liu et al., 2023; Tam and McDaniels, 2013) or broader cross-national baselines (Baum et al., 2024), so our comparative design adds to this emerging literature. Our findings reveal significant differences in how laypeople perceive risks across the six types of novel intervention. The clustering of perceived risks and benefits into three core domains, ethics and safety, feasibility, and social impacts (Fig. 1), suggests that people tend to view these dimensions as interrelated, which aligns with theoretical models of risk perception (Finucane et al., 2000; Slovic, 2000; van der Linden, 2015) and with empirical evidence that risk–benefit judgments often cluster across domains (Arning et al., 2020; Connor and Siegrist, 2016). This insight has important implications for communication strategies, as improving understanding or trust in one domain may positively influence others. This may be due to the low prior knowledge and experience with these interventions among many respondents, which was reflected in responses indicative of a general predisposition to the idea of intervention rather than well-formed beliefs about the implications of specific interventions or the potential for variability in risks and benefits among interventions. Alternatively, it is also possible that even among respondents with well-formed views, the perceived ethics and safety of an intervention positively influenced perceptions of its feasibility and social impacts.

Across the sample, most respondents expressed cautious optimism about the potential benefits of all six interventions, with average ratings above the midpoint of the scale (Table 3 and Fig. 2). This generalized acceptance is consistent with prior findings that novel environmental interventions are often met with cautious support, reflecting underlying uncertainties (Liu et al., 2023; Merk and Pönitzsch, 2017). Statistically significant variation was evident across interventions, with the restorative interventions, rubble stabilization, and coral seeding, eliciting the highest level of confidence in delivering benefits across all three domains. Similar patterns have been observed in past studies showing that interventions framed as natural or restorative often attract higher support than those perceived as technological (Corner and Pidgeon, 2015; Le et al., 2022). Differences, however, were small. Unlike studies that ask respondents to compare and/or rank interventions, our research design used independent samples (each respondent answering questions about only one intervention). This revealed a similar pattern across all interventions and risk/benefit domains, with most people believing interventions will deliver benefits that are either modest or slightly outweigh risks, a reasonable minority believing benefits will be substantial, and a smaller minority thinking the interventions will cause harm.

Genetic engineering, importantly, followed the same broad pattern despite a statistically significantly lower assessment of potential benefits when compared with all other interventions. However, it is important to note that our data do not allow us to differentiate between respondents who simply associated minimal risk and reward with genetic engineering from those who weighed what they perceived as potentially serious negative impacts against possibilities for comparatively greater benefit – both lines of reasoning that would lead respondents to arrive at a low but still positive score. We can safely conclude that relatively few respondents believed, with certainty, that genetic engineering will cause significant harm, but more research is needed to understand whether people are unconvinced of the potential benefits of genetic engineering or rather weigh these against significant outstanding risks. Mankad et al.'s (2021) finding that public support for genetically engineered coral is significantly mediated by perceived risks and benefits, with higher support contingent on demonstrable efficacy and minimal ecological disruption, suggests such research ought to be prioritised ahead of any attempts to initiate active research and development using genetic engineering in the GBR. That said, the same is true, albeit to a lesser degree, of the other five interventions currently subject to research and development in the GBR. Comparable ambivalence has been observed, for example, in geoengineering studies, where support is strongly mediated by perceived safety and reversibility (Bellamy and Lezaun, 2017; Merk and Pönitzsch, 2017).

Our findings also explored how public perceptions differ across time, revealing that most risk perceptions remained consistent over the observed period (Figs. 3–5). The most notable exception to this generalisation was the protective interventions fogging (with perceived feasibility and social benefits both declining over time) and marine cloud brightening (the perceived social benefits of which also declined over time). The perceived feasibility of marine cloud brightening, by contrast, increased slightly over time. Such mixed dynamics mirror prior research showing that perceptions of solar radiation management technologies are volatile and shift with exposure to new information (Merk and Pönitzsch, 2017; Wibeck et al., 2017).

Our analysis of how public perceptions differ with reef proximity shows that residents living within 50 km of the GBR coastline perceived coral seeding as more ethical, safer, and feasible (Figs. 3 and 4). Living proximate to the GBR, however, had no influence on the perceived social impact of coral seeding nor on the perceived risks and benefits of other interventions (Fig. 5). It is possible that residents of the GBR coastline have been more exposed than others to popular media coverage of coral seeding trials. With coral seeding trials underway in the GBR since 2016 (McLeod et al., 2022) and receiving regular media coverage (coverage often couched in everyday terms such as 'coral IVF', 'coral babies', and 'coral nurseries' (Miller, 2020) it is possible residents have grown more familiar and comfortable with this intervention. This finding aligns with research showing that familiarity and perceived local relevance tend to increase public acceptance of novel interventions (de Groot et al., 2020; Le et al., 2022).

Among the factors influencing risk perceptions, demographic variations reveal nuanced differences in public perceptions of reef restoration interventions, particularly considering age and gender effects, Indigenous perspectives, and knowledge and understanding of interventions. Age of the respondent was mostly associated with lower perceived feasibility (Fig. 4), while age was overall associated with higher perceived ethicality and safety (Fig. 3). Our findings that older respondents perceived interventions as more ethical and safer is in direct contradiction of recent findings by Baum et al. (2024), in a global survey, where those living in a country with a younger population expressed greater support for climate intervention technologies that are usually considered as riskier (like large-scale geoengineering). Both the nature of the interventions and the global nature of Baum et al.'s (2024) sample design may explain the difference from our results. This contrast highlights how contextual and cultural factors shape demographic effects, a point also emphasised by Wibeck et al. (2017) in cross-country studies of geoengineering perceptions.

Our large sample of Aboriginal and Torres Strait Islander respondents allowed for deeper insight into First Nation peoples' perspectives, an area often underrepresented in public perception research. On average, Aboriginal and Torres Strait Islander respondents expressed concerns toward several interventions, perceiving them as less ethical and safe (Fig. 3), feasible (Fig. 4), and socially beneficial (Fig. 5) than did non-Indigenous respondents. While our results cannot be generalized to Reef Traditional Owners (that is, to those specific Aboriginal and Torres Strait Islander peoples with custodianship rights in the GBR), they illustrate the potential for these groups to perceive risks differently due to their unique cultural, spiritual, and socio-environmental connections to the Reef. This aligns with growing recognition of Traditional Owners' rights to active participation in the management of the GBR (Nursey-Bray and Jacobson, 2014) and suggests the importance of culturally sensitive approaches to risk communication, intervention design, and governance processes in order to foster trust, respect, and shared decision-making (Correia et al., 2024). Furthermore, including Traditional Owners in these processes can enhance the legitimacy and effectiveness of interventions (Bartelet et al., 2025b), as demonstrated in other co-management frameworks for Indigenous lands and waters (Ban et al., 2018; Sloane et al., 2018). Such collaborative efforts are essential for advancing equitable, inclusive, and sustainable risk management strategies for the GBR. Comparable insights from Indigenous co-management frameworks elsewhere show that inclusion enhances legitimacy and effectiveness (Ban et al., 2018, p. 201; Bartelet et al., 2025b; Correia et al., 2024; Sloane et al., 2018).

Perceptions of interventions were strongly influenced by levels of self-reported knowledge and understanding of interventions. Higher understanding of specific technologies led to more favourable evaluations of ethics and safety (Fig. 3), feasibility (Fig. 4), and social impacts (Fig. 5) across most interventions. On the other hand, higher perceived knowledge of the GBR itself led to less favourable views, particularly for rubble stabilization and coral seeding. Past findings also show a positive correlation between the public's understanding of novel interventions and their acceptance (Liu et al., 2023). Higher perceived quality of educational information was associated with increased trip satisfaction and perceived beauty of reef sites, indirectly influencing risk perceptions (Le et al., 2022). Similarly, Mankad et al. (2021) found that recognising the perceived relative advantages of using novel approaches to address reef degradation increased support for genetically engineered coral. These findings highlight the need for effective communication and education strategies in improving the understanding of interventions (Baum et al., 2024).

Interestingly, we found no significant relationship between formal education levels and risk perceptions across the three domains. This is notable given the technical complexity of several interventions. Drawing on dual-process theory, when people encounter unfamiliar environmental technologies with limited direct experience, they may rely more on heuristic processing, using mental shortcuts based on intuitive judgments, values, and trust, than they do on systematically analysing technical information (Kahneman, 2011). Such reliance can reduce the typical advantages associated with higher education. However, the processing pathway may depend on how information is presented. Zheng et al. (2025) found that even in complex environmental decision-making contexts (i.e. carbon offsetting), people preferred and engaged with systematic information when it was presented clearly and transparently, rather than relying on psychological shortcuts. This suggests that the plain-English descriptions we used may have reduced comprehension barriers, enabling participants across education levels to engage systematically, as also observed in environmental communication research more broadly (Le et al., 2022; Merk and Pönitzsch, 2017). Risk perceptions for novel environmental interventions are often shaped more by domain-specific understanding, personal values, trust, and perceived naturalness than they are by general educational attainment (Mankad et al., 2021). This reinforces the importance of designing communication tools that are inclusive and resonate across diverse educational backgrounds.

The main limitation of our study is the novelty of the interventions studied, which may have limited respondents' familiarity and understanding. To address this, we provided plain-English descriptions of each intervention. However, as public experience and knowledge of these interventions grow, perceptions of risk may evolve, and further monitoring will be required. A minor limitation was the absence of our social impact indicators from the 2018 survey, limiting longitudinal comparisons for this risk domain. These limitations should be considered when interpreting findings, and future research could address this by expanding the scope of data collected over time. Future studies should also explore risk perceptions in more depth. Moving beyond plain-English understanding of risk as a negative outcome or threat and toward treatment of risk as a calculus of probability and consequence (Lockie et al., 2024), future research might investigate how members of the public perceive: (1) the likelihood of adverse and positive outcomes independently; (2) secondary risks associated with failure to deliver planned ecological and social benefits; (3) the feasibility of potential risk management strategies; and (4) risks associated with specific applications of novel interventions (recognising that, in practice, interventions will be combined, deployed at varying scales, and deployed within specific ecological, social, and economic contexts). An intervention perceived generally as beneficial might be considered unacceptably risky in certain contexts, while the risks of other interventions, by contrast, may be seen to decrease.

5. Conclusion and policy implications

The findings of our study have direct implications for policy and practice in implementing protective, restorative, and adaptive interventions for the GBR. Addressing public concerns related to the feasibility and environmental impacts of protective interventions, particularly fogging, is critical. Policies should prioritize transparency regarding the scalability of these technologies and strategies to mitigate unintended side effects. Public communication efforts should aim to build confidence in the potential of these interventions to effectively protect the GBR from climate-related threats. The perceived benefits of restorative measures such as rubble stabilization and coral seeding highlight the need to prioritize and scale up these projects. Policies could emphasize their ecological benefits and demonstrated effectiveness to maintain public trust. Practitioners could integrate these interventions into broader conservation strategies, ensuring alignment with public expectations and ethical standards.

Lastly, in the event interventions based on genetic engineering were to be progressed, careful attention to ethical concerns would be required in policy development and practice. These concerns are heightened by public scepticism regarding the "unnaturalness" of genetic modifications and the potential for unintended long-term ecological consequences (Mankad et al., 2021). Efforts would need to focus on fostering public understanding and acceptance by highlighting genetic engineering's role within a broader adaptive strategy that includes interventions perceived as safer, including natural breeding. Emphasizing ethical safeguards, ecological benefits, and complementarity of approaches could support informed decision-making and public trust in adaptive interventions. As Sandler (2020) argues, a purely instrumentalist view (that is, considering these interventions solely as tools to achieve conservation goals) is insufficient and ethical considerations and diverse perspectives must also be acknowledged. Meaningful opportunities for participation in intervention design, policy, and decision-making are needed to ensure Traditional Owners, stakeholders, scientists, and the broader public are actively engaged. Such inclusive processes not only promote transparency and trust but also help ensure interventions align with cultural values, ethical principles, and ecological priorities, fostering long-term legitimacy and acceptance.

By enabling participants to consider the possibility of both harm and success, this research aligns with the core purpose of risk assessment: supporting safe and effective action. This conceptualisation recognises that risk is not inherently negative but a spectrum of outcomes that includes uncertainty, opportunity, and trade-offs (Lockie et al., 2024; Vella et al., 2021). The clustering of risk dimensions—ethics and safety, feasibility, and social impacts— allows for a more granular analysis of public perceptions, facilitating targeted strategies for risk communication and responsible intervention design. By incorporating factors such as proximity to the reef, demographic variables, and levels of understanding, our study offers nuanced insights into how different stakeholder groups perceive risks. This contributes to the emerging discourse on the interplay between ecological and social risks, particularly in culturally sensitive contexts involving Indigenous communities and local stakeholders.

CRediT authorship contribution statement

Csilla Demeter: Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation. **Henry A. Bartelet:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Stewart Lockie:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Brent W. Ritchie:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Rana Dadpour:** Writing – review & editing, Writing – original draft.

Research ethics

This research adheres to the National Statement on Ethical Conduct in Human Research. Human ethics approval was granted prior to data collection by the University of Queensland Human Research Ethics Committee (ref: 2018/HE001183 and 2021/HE002586). Reciprocal approval was granted by the James Cook University Human Research Ethics Committee (ref: H9172).

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Declaration of competing interest

The authors declare no competing interests that could influence the work in this paper.

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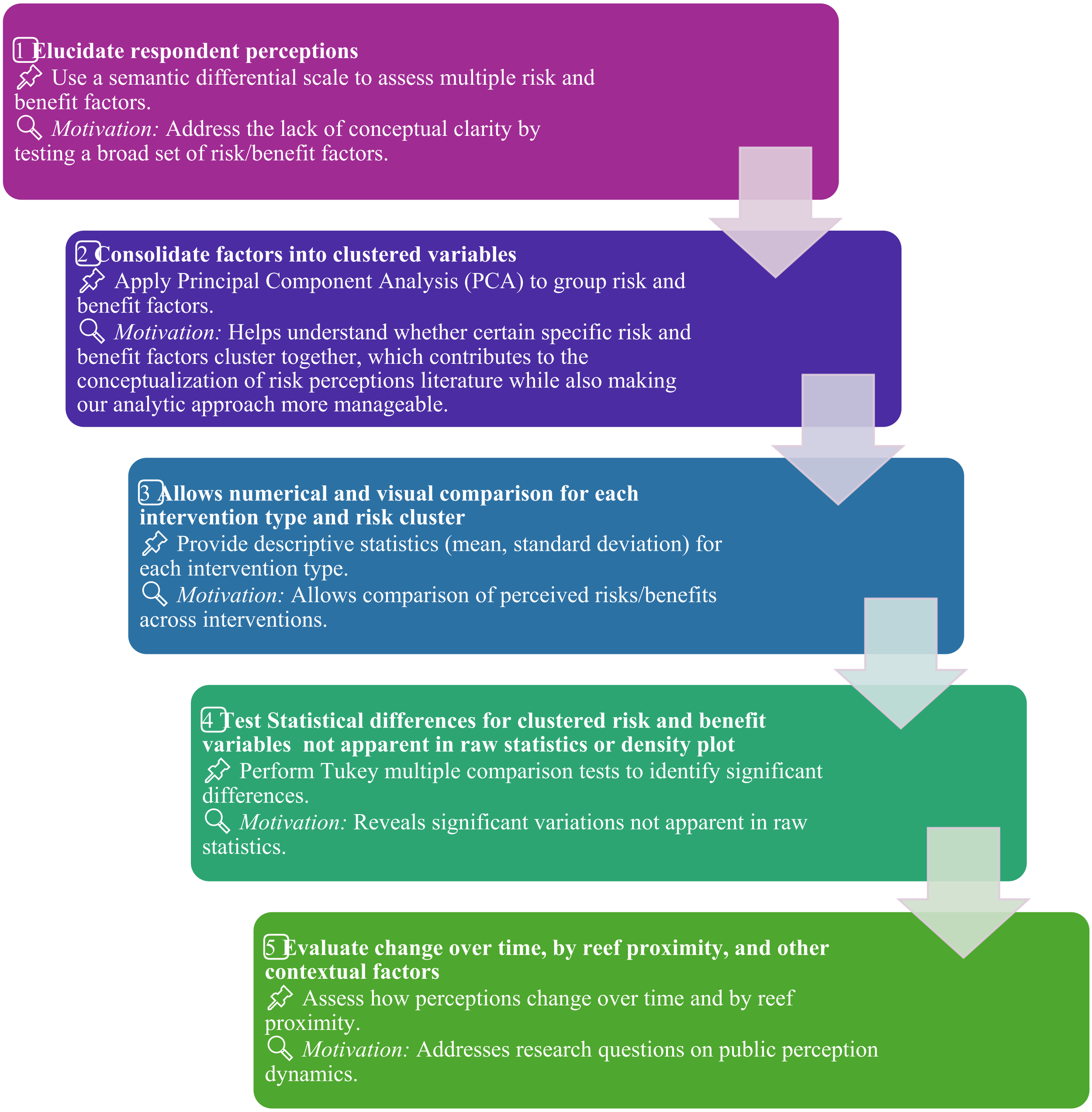
Appendix A. Analytical approach



Appendix B. Description of novel interventions

These descriptions were identical to those used and described in Bartelet et al. (2025a).

We classified the six interventions included in our study into: (1) protective interventions to help protect the Reef from climate extremes; (2) restorative interventions to help support the recovery of degraded reefs; and (3) adaptive interventions to help corals adapt to changing climate conditions. Within each category, we included two specific interventions. Each intervention was introduced to the participant in one paragraph, which included a description of the method used, its aims, and potential benefits and risks. Descriptions of each intervention were developed with scientists and engineers working directly on them to ensure accuracy. Most of the respondents felt that the description of their intervention was neutrally framed, and neutral responses were relatively similar across interventions with no statistical differences found (Bartelet et al., 2025a).

For protective interventions, we included marine *cloud brightening* and *fogging* (not included in 2018 survey), described to survey respondents as follows:

One approach is to help cool and **shade** the waters of the Reef by enhancing the clouds above it to reflect more sunlight and heat. This is known as **Marine Cloud Brightening**. To achieve this, very small seawater droplets are sprayed into the atmosphere using devices similar to snow making cannons placed on boats, pontoons or permanent structures in the marine environment. **Potential benefits** include cooling and shading the reef during stressful conditions that can lead to coral bleaching. Cloud brightening can be used when bleaching conditions are predicted. It can also be used only when it is required (i.e., it can be 'turned off'). **Potential risks** could include small changes to local weather patterns such as altered rainfall.

Further research is required to understand the atmospheric conditions over the Reef, the ability of this technology to be scaled up and the impacts to local weather.

One approach aims to **shade** areas of the reef using artificially generated sea mist or fog**.** This mist reduces the amount of sunlight and heat reaching the sea surface and the coral reefs beneath. **Potential benefits** include cooling and shading the reef, which prevents damage to coral and other organisms. Fogging could be deployed when coral bleaching conditions (i.e., extreme heat events) are predicted. Fogging could be effective in protecting targeted areas over short critical periods (days to weeks). It can also be used only when it is required (i.e., it can be 'turned off'). **Potential risks** include over-shading which may slow coral growth. It would be ineffective during strong wind; however, bleaching is most likely to occur during calm conditions.

For restorative interventions, we included *rubble stabilization* and *coral seeding* (not included in 2018 survey). These approaches were described to survey respondents as follows:

One approach aims to help **stabilise dead coral rubble so that new corals can grow**. Mesh structures or the application of binding agents can be used to prevent movement of the coral rubble. New coral can then naturally establish themselves and grow on this material. **Potential benefits** include providing a stable habitat to promote coral settlement and growth. This approach requires minimal human labour to maintain and would work most effectively at a local scale. **Potential risks** could include changes to natural conditions such as ocean currents, water quality, and impacts on other reef species. Further research is required to understand the effect of this technology. Similar methods are currently used overseas to fix coral reefs damaged by ships.

One approach – known as **coral seeding -** involves capturing natural, wild coral spawn/larval slicks in tanks and floating pools and then transporting them for release to help re-seed local or regional high-priority reefs. **Potential benefits** include speeding up the return of coral cover to a disturbed or damaged reef by increasing the number of available coral babies (larvae) that can settle and grow into new corals. Harvesting wild coral larval slicks is likely to have a minimal negative impact on Reef ecology, as the mortality rate of the larvae in a slick is typically high. **Potential risks** include introduced and relocated corals impacting the local coral population ecosystem. More research is needed to develop effective and efficient collection and transfer and delivery techniques.

For adaptive interventions, we included *enhancing heat resistance – natural breeding* and *enhancing heat resistance – genetic engineering.* These approaches were described to survey respondents as follows:

One approach aims to enhance the **heat resistance of corals** through the selective breeding and spread of **naturally more heat resistant corals**. This can help corals become more resilient to ocean warming and improve the overall health of coral reefs. **Potential benefits** include helping corals to become more tolerant to marine heatwaves and environmental change. **Potential risks** could include possible changes in local coral structures and species interactions. Further research is required to understand the effect of this technology. This approach may involve breeding corals in land-based nurseries, an approach that is already used in aquaculture.

One potential approach could enhance the **heat resistance of corals** using **genetic engineering.** Genetic engineering includes methods that allow very precise changes to be made to the genetic material of corals, or algae that lives in corals, to increase their ability to cope with heat stress. **Potential benefits** include helping corals to resist, repair and recover from bleaching events by improving their tolerance to heat stress. **Potential risks** could include possible disruptions to the ecosystem and spread of modified algae to other organisms. This technology is not yet sufficiently developed to be applied to corals. Further research is required to understand the effect of this technology. Similar methods have been used to genetically modify food crops including maize and canola.

Appendix C. Statistical results for Tukey multiple comparisons of means

Ethics and Safety

Table C1
Tukey multiple comparison of means tests for perceived ethics and safety of novel GBR interventions.

Comparison	Difference	Lower	Upper	Adjusted *p*-value
Fogging – MCB	0.09289107	−0.05505730	0.24083945	0.4724911
Rubble - MCB	0.27486068	0.14234379	0.40737756	0.0000001
Seeding - MCB	0.33444461	0.18727611	0.48161311	0.0000000
Breeding - MCB	0.11976039	−0.01271495	0.25223572	0.1030680
GE - MCB	−0.25586323	−0.38838011	−0.12334635	0.0000006
Rubble - fogging	0.18196960	0.03436075	0.32957846	0.0059225
Seeding - fogging	0.24155354	0.08066159	0.40244548	0.0002736
Breeding - fogging	0.02686931	−0.12070225	0.17444087	0.9954528
GE - fogging	−0.34875430	−0.49636316	−0.20114545	0.0000000
Seeding - rubble	0.05958393	−0.08724325	0.20641111	0.8572746
Breeding - rubble	−0.15510029	−0.28719634	−0.02300423	0.0106399
GE - rubble	−0.53072391	−0.66286163	−0.39858619	0.0000000
Breeding - seeding	−0.21468422	−0.36147391	−0.06789454	0.0004434
GE - seeding	−0.59030784	−0.73713502	−0.44348066	0.0000000
Ge - breeding	−0.37562362	−0.50771967	−0.24352756	0.0000000

Note: Interventions include Marine Cloud Brightening (abbreviated as MCB), fogging, rubble stabilization (abbreviated as rubble), coral seeding (abbreviated as seeding), natural breeding (abbreviated as breeding), and genetic engineering (abbreviated as GE).

Feasibility

Table C2
Tukey multiple comparison of means tests for perceived feasibility of novel GBR interventions.

Comparison	Difference	Lower	Upper	Adjusted *p*-value
Fogging – MCB	0.03853623	−0.11357869	0.19065115	0.9793090
Rubble - MCB	0.35594813	0.21969929	0.49219697	0.0000000
Seeding - MCB	0.41135552	0.26004244	0.56266860	0.0000000
Breeding - MCB	0.27218848	0.13598235	0.40839461	0.0000002
GE - MCB	0.02545571	−0.11079314	0.16170455	0.9948671
Rubble - fogging	0.31741190	0.16564606	0.46917774	0.0000000
Seeding - fogging	0.37281929	0.20739628	0.53824230	0.0000000
Breeding - fogging	0.23365225	0.08192476	0.38537975	0.0001671
GE - fogging	−0.01308052	−0.16484636	0.13868532	0.9998788
Seeding - rubble	0.05540739	−0.09555476	0.20636954	0.9022277
Breeding - rubble	−0.08375965	−0.21957581	0.05205652	0.4933547
GE - rubble	−0.33049242	−0.46635143	−0.19463342	0.0000000
Breeding - seeding	−0.13916704	−0.29009064	0.01175656	0.0905978
GE - seeding	−0.38589981	−0.53686196	−0.23493767	0.0000000
Ge - breeding	−0.24673278	−0.38254894	−0.11091661	0.0000034

Note: Interventions include Marine Cloud Brightening (abbreviated as MCB), fogging, rubble stabilization (abbreviated as rubble), coral seeding (abbreviated as seeding), natural breeding (abbreviated as breeding), and genetic engineering (abbreviated as GE).

Social Impacts

Table C3
Tukey multiple comparison of means tests for perceived social impacts of novel GBR interventions.

Comparison	Difference	Lower	Upper	Adjusted *p*-value
Fogging – MCB	−0.06643183	−0.226747855	0.09388419	0.8459976
Rubble - MCB	0.17397663	0.01458673	0.33336652	0.0230042
Seeding - MCB	0.25075256	0.091143829	0.41036129	0.0001116
Breeding - MCB	0.16076825	0.001196137	0.32034035	0.0470666
GE - MCB	−0.05038505	−0.209811271	0.10904116	0.9463733
Rubble - fogging	0.24040846	0.081094790	0.39972213	0.0002488
Seeding - fogging	0.31718439	0.157651777	0.47671700	0.0000002
Breeding - fogging	0.22720008	0.067704103	0.38669605	0.0007041
GE - fogging	0.01604678	−0.143303235	0.17539679	0.9997391
Seeding - rubble	0.07677593	−0.081825975	0.23537783	0.7392214
Breeding - rubble	−0.01320838	−0.171773434	0.14535667	0.9998975
GE - rubble	−0.22436168	−0.382779915	−0.06594345	0.0007766
Breeding - seeding	−0.08998431	−0.248769339	0.06880071	0.5882856
GE - seeding	−0.30113761	−0.459776024	−0.14249920	0.0000010
Ge - breeding	−0.21115330	−0.369754865	−0.05255173	0.0020638

Note*:* Interventions include Marine Cloud Brightening (abbreviated as MCB), fogging, rubble stabilization (abbreviated as rubble), coral seeding (abbreviated as seeding), natural breeding (abbreviated as breeding), and genetic engineering (abbreviated as GE).

Appendix D. Sample descriptions

Table D1
Sample description by survey year for Marine Cloud Brightening intervention. Indicators underlying the Social Impacts risk indicator were not included in the 2018 survey.

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Surveys	#	511	545	512	1568
Reef proximity	>50 km from the GBR	347 (68 %)	379 (70 %)	365 (71 %)	1091 (70 %)
	<50 km from the GBR	164 (32 %)	166 (30 %)	147 (29 %)	477 (30 %)
Gender	Female	271 (53 %)	293 (54 %)	256 (50 %)	820 (52 %)
	Male	239 (47 %)	252 (46 %)	255 (50 %)	746 (48 %)
Age group	<50 years	295 (58 %)	300 (55 %)	269 (53 %)	864 (55 %)
	>50 years	216 (42 %)	245 (45 %)	243 (47 %)	704 (45 %)
First Nations people	No	421 (83 %)	515 (94 %)	459 (90 %)	1395 (89 %)
	Yes	87 (17 %)	30 (6 %)	53 (10 %)	170 (11 %)
Education (graduate degree)	No	308 (61 %)	297 (54 %)	280 (55 %)	885 (57 %)
	Yes	200 (39 %)	248 (46 %)	232 (45 %)	680 (43 %)
Employment (full-time)	No	318 (63 %)	307 (56 %)	316 (62 %)	941 (60 %)
	Yes	190 (37 %)	238 (44 %)	196 (38 %)	624 (40 %)

(*continued on next page*)

Table D1 (*continued*)

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Reef visitation	No	189 (37 %)	236 (43 %)	205 (40 %)	630 (40 %)
	Yes	322 (63 %)	309 (57 %)	307 (60 %)	938 (60 %)
GBR knowledge	μ (10-scale)	5.55	4.96	5.06	5.19
	σ	2.06	2.17	2.42	2.24
Understanding (technology)	μ (10-scale)	4.57	4.62	4.57	4.59
	σ	1.51	1.50	1.50	1.50
Safety and Ethics	μ (7-scale semantic differential)	4.52	4.61	4.53	4.55
	σ	1.32	1.28	1.43	1.34
Feasibility	μ (7-scale semantic differential)	4.29	4.59	4.44	4.44
	σ	1.36	1.37	1.39	1.38
Social Impacts	μ (7-scale semantic differential)	N/A	4.60	4.41	4.51
	σ	N/A	1.24	1.42	1.33

Table D2
Sample description by survey year for Fogging intervention. Fogging intervention was not included in the 2018 survey.

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Surveys	#	N/A	555	504	1059
Reef proximity	>50 km from the GBR	N/A	390 (70 %)	353 (70 %)	743 (70 %)
	<50 km from the GBR	N/A	165 (30 %)	151 (30 %)	316 (30 %)
Gender	Female	N/A	285 (51 %)	253 (50 %)	538 (51 %)
	Male	N/A	270 (49 %)	248 (50 %)	518 (49 %)
Age group	<50 years	N/A	315 (57 %)	281 (56 %)	596 (56 %)
	>50 years	N/A	240 (43 %)	223 (44 %)	463 (44 %)
First Nations people	No	N/A	534 (96 %)	447 (89 %)	981 (93 %)
	Yes	N/A	21 (4 %)	57 (11 %)	78 (7 %)
Education (graduate degree)	No	N/A	286 (52 %)	288 (57 %)	574 (54 %)
	Yes	N/A	269 (48 %)	216 (43 %)	485 (46 %)
Employment (full-time)	No	N/A	316 (57 %)	305 (61 %)	621 (59 %)
	Yes	N/A	239 (43 %)	199 (39 %)	438 (41 %)
Reef visitation	No	N/A	219 (39 %)	181 (36 %)	400 (38 %)
	Yes	N/A	336 (61 %)	323 (64 %)	659 (62 %)
GBR knowledge	μ (10-scale)	N/A	5.11	5.10	5.11
	σ	N/A	2.20	2.34	2.27
Understanding (technology)	μ (10-scale)	N/A	4.84	4.61	4.73
	σ	N/A	1.46	1.37	1.42
Safety and Ethics	μ (7-scale semantic differential)	N/A	4.71	4.57	4.65
	σ	N/A	1.22	1.45	1.34
Feasibility	μ (7-scale semantic differential)	N/A	4.62	4.33	4.48
	σ	N/A	1.29	1.51	1.41
Social Impacts	μ (7-scale semantic differential)	N/A	4.62	4.25	4.44
	σ	N/A	1.20	1.46	1.34

Table D3
Sample description by survey year for Rubble Stabilization intervention. Indicators underlying the Social Impacts risk indicator were not included in the 2018 survey.

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Surveys	#	500	553	531	1584
Reef proximity	>50 km from the GBR	341 (68 %)	387 (70 %)	391 (74 %)	1119 (71 %)
	<50 km from the GBR	159 (32 %)	166 (30 %)	140 (26 %)	465 (29 %)
Gender	Female	279 (56 %)	296 (54 %)	273 (52 %)	848 (54 %)
	Male	221 (44 %)	257 (46 %)	256 (48 %)	735 (46 %)
Age group	<50 years	287 (57 %)	276 (50 %)	280 (53 %)	843 (53 %)
	>50 years	213 (43 %)	277 (50 %)	251 (47 %)	741 (47 %)
First Nations people	No	429 (86 %)	528 (95 %)	480 (90 %)	1437 (91 %)
	Yes	71 (14 %)	25 (5 %)	51 (10 %)	147 (9 %)
Education (graduate degree)	No	324 (65 %)	316 (57 %)	303 (57 %)	943 (60 %)
	Yes	176 (35 %)	237 (43 %)	228 (43 %)	641 (40 %)
Employment (full-time)	No	303 (61 %)	336 (61 %)	332 (63 %)	971 (61 %)
	Yes	197 (39 %)	217 (39 %)	199 (37 %)	613 (39 %)
Reef visitation	No	183 (37 %)	220 (40 %)	213 (40 %)	616 (39 %)
	Yes	317 (63 %)	333 (60 %)	318 (60 %)	968 (61 %)
GBR knowledge	μ (10-scale)	5.47	4.85	5.13	5.14
	σ	2.15	2.17	2.33	2.23

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Table D3 (*continued*)

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Understanding (technology)	μ (10-scale)	4.89	4.83	4.66	4.79
	σ	1.33	1.39	1.45	1.40
Safety and Ethics	μ (7-scale semantic differential)	4.91	4.90	4.68	4.83
	σ	1.29	1.20	1.37	1.29
Feasibility	μ (7-scale semantic differential)	4.81	4.90	4.68	4.80
	σ	1.27	1.26	1.44	1.33
Social Impacts	μ (7-scale semantic differential)	N/A	4.77	4.59	4.68
	σ	N/A	1.21	1.42	1.32

Table D4
Sample description by survey year for Coral Seeding intervention. Coral Seeding intervention was not included in the 2018 survey.

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Surveys	#	N/A	542	536	1078
Reef proximity	>50 km from the GBR	N/A	381 (70 %)	390 (73 %)	771 (72 %)
	<50 km from the GBR	N/A	161 (30 %)	146 (27 %)	307 (28 %)
Gender	Female	N/A	292 (54 %)	282 (53 %)	574 (53 %)
	Male	N/A	249 (46 %)	250 (47 %)	499 (47 %)
Age group	<50 years	N/A	290 (54 %)	290 (54 %)	580 (54 %)
	>50 years	N/A	252 (46 %)	246 (46 %)	498 (46 %)
First Nations people	No	N/A	524 (97 %)	478 (89 %)	1002 (93 %)
	Yes	N/A	18 (3 %)	58 (11 %)	76 (7 %)
Education (graduate degree)	No	N/A	291 (54 %)	279 (52 %)	570 (53 %)
	Yes	N/A	251 (46 %)	257 (48 %)	508 (47 %)
Employment (full-time)	No	N/A	296 (55 %)	312 (58 %)	608 (56 %)
	Yes	N/A	246 (45 %)	224 (42 %)	470 (44 %)
Reef visitation	No	N/A	201 (37 %)	207 (39 %)	408 (38 %)
	Yes	N/A	341 (63 %)	329 (61 %)	670 (62 %)
GBR knowledge	μ (10-scale)	N/A	5.17	5.16	5.16
	σ	N/A	2.20	2.31	2.26
Understanding (technology)	μ (10-scale)	N/A	4.86	4.79	4.82
	σ	N/A	1.35	1.44	1.40
Safety and Ethics	μ (7-scale semantic differential)	N/A	4.92	4.85	4.89
	σ	N/A	1.23	1.39	1.31
Feasibility	μ (7-scale semantic differential)	N/A	4.95	4.75	4.85
	σ	N/A	1.25	1.40	1.33
Social Impacts	μ (7-scale semantic differential)	N/A	4.85	4.67	4.76
	σ	N/A	1.18	1.37	1.28

Table D5
Sample description by survey year for Natural Breeding intervention. Indicators underlying the Social Impacts risk indicator were not included in the 2018 survey.

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Surveys	#	508	553	526	1587
Reef proximity	>50 km from the GBR	344 (68 %)	385 (70 %)	374 (71 %)	1103 (70 %)
	<50 km from the GBR	164 (32 %)	168 (30 %)	152 (29 %)	484 (30 %)
Gender	Female	277 (55 %)	292 (53 %)	268 (51 %)	837 (53 %)
	Male	230 (45 %)	261 (47 %)	254 (49 %)	745 (47 %)
Age group	<50 years	274 (54 %)	301 (54 %)	296 (56 %)	871 (55 %)
	>50 years	234 (46 %)	252 (46 %)	230 (44 %)	716 (45 %)
First Nations people	No	444 (88 %)	539 (97 %)	460 (87 %)	1443 (91 %)
	Yes	62 (12 %)	14 (3 %)	66 (13 %)	142 (9 %)
Education (graduate degree)	No	319 (63 %)	298 (54 %)	266 (51 %)	883 (56 %)
	Yes	187 (37 %)	255 (46 %)	260 (49 %)	702 (44 %)
Employment (full-time)	No	307 (61 %)	301 (54 %)	328 (62 %)	936 (59 %)
	Yes	199 (39 %)	252 (46 %)	198 (38 %)	649 (41 %)
Reef visitation	No	206 (41 %)	212 (38 %)	200 (38 %)	618 (39 %)
	Yes	302 (59 %)	341 (62 %)	326 (62 %)	969 (61 %)
GBR knowledge	μ (10-scale)	5.64	4.90	5.06	5.19
	σ	2.14	2.18	2.37	2.26
Understanding (technology)	μ (10-scale)	4.83	4.74	4.67	4.75
	σ	1.45	1.42	1.49	1.45
Safety and Ethics	μ (7-scale semantic differential)	4.60	4.68	4.74	4.67
	σ	1.25	1.19	1.33	1.26

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Table D5 (*continued*)

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Feasibility	μ (7-scale semantic differential)	4.59	4.78	4.76	4.71
	σ	1.29	1.27	1.34	1.30
Social Impacts	μ (7-scale semantic differential)	N/A	4.73	4.61	4.67
	σ	N/A	1.16	1.27	1.21

Table D6
Sample description by survey year for Genetic Engineering intervention. Indicators underlying the Social Impacts risk indicator were not included in the 2018 survey.

Indicator	Level	Frequency (fraction)			
		2018	*2022*	*2024*	*Total*
Surveys	#	501	552	531	1584
Reef proximity	>50 km from the GBR	341 (68 %)	382 (69 %)	382 (72 %)	1105 (70 %)
	<50 km from the GBR	160 (32 %)	170 (31 %)	149 (28 %)	479 (30 %)
Gender	Female	255 (51 %)	284 (51 %)	273 (52 %)	812 (51 %)
	Male	244 (49 %)	268 (49 %)	255 (48 %)	767 (49 %)
Age group	<50 years	281 (56 %)	280 (51 %)	296 (56 %)	857 (54 %)
	>50 years	220 (44 %)	272 (49 %)	235 (44 %)	727 (46 %)
First Nations people	No	436 (87 %)	537 (97 %)	476 (90 %)	1449 (92 %)
	Yes	64 (13 %)	15 (3 %)	55 (10 %)	134 (8 %)
Education (graduate degree)	No	301 (60 %)	293 (53 %)	282 (53 %)	876 (55 %)
	Yes	199 (40 %)	259 (47 %)	249 (47 %)	707 (45 %)
Employment (full-time)	No	311 (62 %)	324 (59 %)	323 (61 %)	958 (61 %)
	Yes	189 (38 %)	228 (41 %)	208 (39 %)	625 (39 %)
Reef visitation	No	175 (35 %)	201 (36 %)	217 (41 %)	593 (37 %)
	Yes	326 (65 %)	351 (64 %)	314 (59 %)	991 (63 %)
GBR knowledge	μ (10-scale)	5.32	5.11	4.97	5.13
	σ	2.12	2.05	2.31	2.17
Understanding (technology)	μ (10-scale)	4.62	4.79	4.65	4.69
	σ	1.49	1.39	1.48	1.45
Safety and Ethics	μ (7-scale semantic differential)	4.27	4.29	4.33	4.30
	σ	1.30	1.24	1.38	1.30
Feasibility	μ (7-scale semantic differential)	4.37	4.56	4.46	4.47
	σ	1.29	1.28	1.37	1.32
Social Impacts	μ (7-scale semantic differential)	N/A	4.49	4.43	4.46
	σ	N/A	1.18	1.37	1.28

Data availability

Data will be made available on request.

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