Coral Reefs
https://doi.org/10.1007/s00338-026-02813-2

RESEARCH

Quantitative assessment of knowledge gaps and research priorities for understanding and managing population irruptions of crown-of-thorns starfish (*Acanthaster* cf. *solaris*) on Australia's Great Barrier Reef

Morgan S. Pratchett[1] · Peter C. Doll[1] · Christopher Cvitanovic[2] · Shaun K. Wilson[3] · Russell C. Babcock[4] · Yves-Marie Bozec[5] · Deborah Burn[6] · Maria Byrne[7] · Carolina Castro-Sanguino[6] · Carla C. M. Chen[1] · Scott A. Condie[8] · Zara-Louise Cowan[9] · Dione Deaker[7] · Amelia A. Desbiens[5] · Lyndon DeVantier[10] · Peter J. Doherty[6] · Mick Haywood[11] · Anne Hoggett[12] · Lone Høj[6] · Bethan J. Lang[1] · Samuel A. Mattthews[6] · Hamish McCallum[13] · Camille Mellin[14] · Benjamin Mos[5] · Cherie A. Motti[6] · Sven Uthicke[6] · Lyle Vail[12] · Kennedy Wolfe[5,15] · Ciemon F. Caballes[1,16]

Received: 21 August 2025 / Accepted: 2 January 2026

Abstract Despite extensive research on the western Pacific crown-of-thorns starfish (CoTS; *Acanthaster* cf. *solaris*), especially from Australia's Great Barrier Reef (GBR), there are persistent knowledge gaps that constrain understanding and management. Given renewed population irruptions of CoTS on the GBR, alongside escalating climate impacts and direct anthropogenic pressures, a quantitative assessment of knowledge gaps was undertaken to identify research priorities and guide future efforts. In this study, 27 experts independently scored 206 research questions across seven *Themes* and 39 topics, based on four different criteria (*Knowledge gap*, *Feasibility*, *Urgency*, and *Applicability*). These questions were ultimately rationalized into 170 distinct questions, with scores aggregated across merged questions. Management was the highest scoring *Theme* for *Urgency*, *Applicability*, and overall. All but six of the 20 top-ranked questions were from the Management *Theme* and mainly related to Culling and/ or Monitoring. Most questions (158 out of 170) also scored highly for *Feasibility*, suggesting that there are existing methods and technical capability available to advance the extensive and diverse range of research questions that were posed, if resources were made available. This quantitative assessment provides guidance on the prioritization of potential research that could improve management of CoTS populations to improve coral

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00338-026-02813-2.

✉ Morgan S. Pratchett
morgan.pratchett@jcu.edu.au

1 College of Science and Engineering, James Cook University, Bebegu Yamba campus, Townsville, QLD, Australia

2 School of Business, University of New South Wales, Canberra, Australia

3 Australian Institute of Marine Science, Crawley, WA, Australia

4 CSIRO Environment, St. Lucia, QLD, Australia

5 School of the Environment, University of Queensland, St Lucia, QLD, Australia

6 Australian Institute of Marine Science, Townsville, QLD, Australia

7 Marine Invertebrate Futures Group, School of Life and Environmental Sciences, The University of Sydney, New South Wales, Australia

8 CSIRO Environment, Hobart, TAS, Australia

9 Department of Biological and Environmental Sciences, Kristineberg Center, University of Gothenburg, Fiskebäckskil, Sweden

10 Coral Reef Research, Townsville, QLD, Australia

11 O2 Marine, Fremantle, WA, Australia

12 Australian Museum Research Institute, Australian Museum, Sydney, NSW 2010, Australia

13 Griffith University, Queensland, Australia

14 The Environment Institute and School of Biological Sciences, University of Adelaide, Adelaide, Australia

15 Marine Biology and Ecology Consultant, Geeveston, TAS 7116, Australia

16 University of Guam, UOG Station, Mangilao, GU, USA

Published online: 19 January 2026

protection outcomes on the GBR. This study also suggests that there are limited constraints to undertaking necessary research to address many of the persistent knowledge gaps relating to CoTS.

Keywords Coral reefs · Disturbance · Expert elicitation · Management · Outbreaks · Prioritisation

Introduction

Managing coral reefs in the face of escalating disturbances and increasing anthropogenic pressures represents a considerable challenge, especially given that most major disturbances (in particular, those linked with environmental change) cannot be effectively managed locally and directly (e.g., Bellwood et al. 2019). Population irruptions (commonly referred to as outbreaks; Babcock et al. 2020) of crown-of-thorns starfish (CoTS; *Acanthaster* spp.) are one of the few major disturbances on coral reefs that may be amenable to direct intervention, either by increasing the timeliness, efficacy and/ or extent of direct control (Castro-Sanguino et al. 2023; Rogers et al. 2023; Matthews et al. 2024), and/ or effectively addressing the anthropogenic factors (e.g., increased land runoff or overfishing) that cause or exacerbate population irruptions (Babcock et al. 2016a, b; Hoey et al. 2016, Pratchett and Cumming 2019). There have been substantial advances in the effectiveness of direct management interventions (Westcott et al. 2020, Matthews et al. 2024) to suppress CoTS densities and thereby reduce local coral loss and enhance resilience. These accomplishments have been underpinned by targeted research to address specific management priorities (e.g., Fletcher et al. 2020; Plagányi et al. 2020; Rogers et al. 2023). However, there are also extensive knowledge gaps that constrain further improvements in CoTS management (Babcock et al. 2016a, b ; Hoey et al. 2016; Pratchett et al. 2021), including uncertainty regarding the proximal and ultimate cause(s) of population irruptions (Pratchett et al. 2014), which hinders predictions regarding where and when elevated densities may occur. Rapidly changing environmental (Heron et al. 2016) and habitat conditions (Hughes et al. 2017; Byrne et al. 2025) may also lead to fundamental changes in the population dynamics of CoTS, and corresponding effects on reef ecosystems. Like many coral reef organisms, CoTS are sensitive to changing environmental and habitat conditions (Lamare et al. 2014, Uthicke et al. 2015, Caballes et al. 2017, Hue et al. 2020, Lang et al. 2022, Byrne et al. 2023). It is, however, still unclear how these changes will influence population irruptions of CoTS and their corresponding impacts on coral reef ecosystems.

On Australia's Great Barrier Reef (GBR), there have been four separate population irruptions of Pacific CoTS (*Acanthaster* cf. *solaris*) since the 1960s (Pratchett et al. 2014). Distinct population irruptions tend to start in the northern section of the GBR, but then spread (e.g., Vanhatalo et al. 2017) and affect up to 17% of reefs (Hoey and Chin 2004). Recurrent population irruptions of CoTS were a major contributor to sustained coral loss recorded up until 2016 (De'ath et al. 2012, Mellin et al. 2019). De'ath et al. (2012) estimated that coral cover on the GBR would have increased during the period 1985–2012, rather than exhibiting a 50.7% decline, were it not for population irruptions of CoTS (see also Castro-Sangino et al. 2021). Since that time, there has been further coral loss attributable to CoTS (Matthews et al. 2024) with renewed population irruptions recently detected in the northern GBR (Chandler et al. 2023, Uthicke et al. 2024b), though climate-induced coral bleaching is increasingly recognized as the foremost cause of contemporary coral mortality (Bozec et al. 2022, Emslie et al. 2024a, b). Rapid and substantial reductions in emissions are therefore needed to minimize devastating and escalating effects of environmental change (Ortiz et al. 2014). However, this also provides renewed imperative to suppress population irruptions of CoTS (e.g., Condie et al. 2021), to minimize coral loss, mitigate the effects of environmental change, and maximize opportunities for natural adaptation.

Population irruptions of CoTS have been variously attributed to particular life-history characteristics, especially very high fecundity (Babcock et al. 2016a; Pratchett et al. 2021) and variable recruitment (Wilmes et al. 2018) that predispose CoTS to pronounced fluctuations in population size (Uthicke et al. 2009, Deaker and Byrne 2022). However, major changes in population modality (from persistent low-density populations to abrupt, but short-lived population irruptions) are often ascribed to physical or biological factors that potentially disrupt normal population regulation (e.g., predatory release due to overfishing, Endean and Stablum 1973; release from nutritional constraints that otherwise limit larval development and survival, Birkeland 1982). Even if CoTS are pre-disposed to population irruptions, this does not explain the recurrence of population irruptions at seemingly regular (15–17 years) intervals on the GBR (Babcock et al. 2020). Such oscillations in the appearance of high densities of adult CoTS are most likely attributable to changes in resource availability (Caballes et al. 2016, Pratchett and Cumming 2019). For CoTS, resource limitation may occur i) among coral-feeding adults, whereby fecundity (if not growth and survival) is constrained by availability of preferred coral prey (Caballes et al. 2016), ii) during ontogenetic shifts in the diet and habitat of juvenile CoTS, which may be constrained by access to coral prey (Deaker et al. 2020, Wilmes et al. 2020), iii) for juvenile

algal-feeding CoTS, where settlement, growth, and development are affected by accessibility to different species of crustose coralline algae (Doll et al. 2023; Jensen et al. 2025, Llarena et al. 2025), or iv) during larval development, which may be constrained by availability of planktonic prey (Lucas 1982, Brodie et al. 2005, but see Olson 1987, Wolfe et al. 2015, Allen et al. 2019).

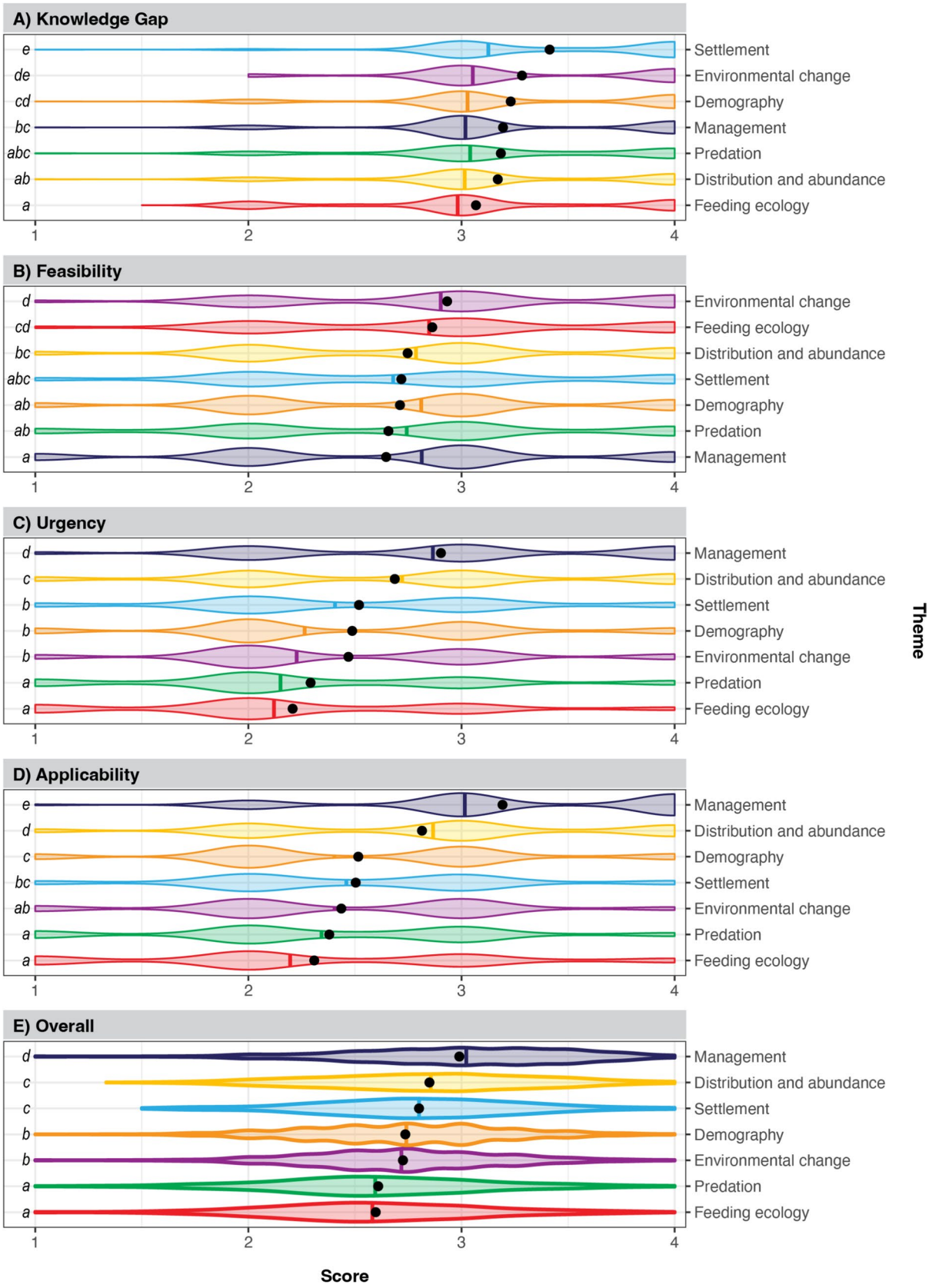
The purpose of this study was to quantitatively assess different knowledge gaps and potential research opportunities pertaining to the understanding and management of recurrent population irruptions of CoTS on Australia's GBR. This study builds upon the compilation of extensive and diverse research questions that were posed by invited experts, who were actively involved in CoTS research on the GBR (Pratchett et al. 2021). The scale and scope of research questions were constrained by asking experts to articulate distinct knowledge gaps that would improve understanding and management of CoTS and thereby help to reduce (or reverse) declining coral cover on the GBR. When originally presented (Pratchett et al. 2021), distinct research questions were arranged into 48 topics across seven *Themes*, highlighting extensive opportunities for further research and offering a roadmap to guide future research efforts. There was not, however, any attempt to assess the relative importance or prioritization of these different questions, topics, or *Themes*. Such quantitative analyses are a critical next step to rationalize and prioritize the extraordinary breath of proposed research. In this study, original participants (from Pratchett et al. 2021) were invited to score each distinct research question (from 1 to 4) for each of four different criteria (Table 1). The scores were analyzed and ranked across each of the four different criteria to facilitate prioritization of a broad and diverse range of perceived knowledge gaps, following established quantitative horizon scanning methods (e.g., Wilson et al. 2010, Cvitanovic et al. 2021). A systematic, data-driven prioritization of research needs can help focus scientific efforts, guide funding allocation, and ensure that management actions are grounded in the best available evidence. By integrating ecological, environmental, and social dimensions, such assessments support the development of targeted, adaptive, and scalable responses to mitigate the impacts of CoTS outbreaks.

Methods

An extensive and diverse set of research questions was posed by 38 (out of 50 invited experts) that were actively undertaking research or have previously published peer-reviewed international journal articles on Pacific CoTS

Table 1 Prioritization criteria and categories for scoring individual research questions

Discrete categories for each of the four different criteria (in bold)	Score
A. Extent of knowledge gap	
We know everything on this topic	1
We know enough on this topic	2
We know a little bit on this topic	3
We know nothing about this topic	4
B. Feasibility/achievability	
None out of three of these components: i.) resource availability; ii.) knowledge of system and technical capability; iii.) existing and validated methodology	1
One out of three of these components: i.) resource availability; ii.) knowledge of system and technical capability; iii.) existing and validated methodology	2
Two out of three of these components: i.) resource availability; ii.) knowledge of system and technical capability; iii.) existing and validated methodology	3
Three out of three of these components: i.) resource availability; ii.) knowledge of system and technical capability; iii.) existing and validated methodology	4
C. Urgency	
Not urgent, can be addressed within the next 30 years	1
Somewhat urgent, can be addressed within the next 15 years	2
Urgent, needs to be addressed within the next 5 years	3
Very urgent, needs to be addressed within the next 2 years	4
D. Applicability/relevance to management	
Has academic value, but limited application to management (i.e., blue sky research)	1
Mainly pure science, but has potential to be applied in management	2
Has some relevance and application for management, but challenging to implement	3
Immediately relevant and implementable within current management regimes	4


A) Knowledge Gap
e
de
cd
bc
abc
ab
a
Settlement
Environmental change
Demography
Management
Predation
Distribution and abundance
Feeding ecology
1
2
3
4
B) Feasibility
d
cd
bc
abc
ab
ab
a
Environmental change
Feeding ecology
Distribution and abundance
Settlement
Demography
Predation
Management
1
2
3
4
C) Urgency
d
c
b
b
b
a
a
Management
Distribution and abundance
Settlement
Demography
Environmental change
Predation
Feeding ecology
1
2
3
4
D) Applicability
e
d
c
bc
ab
a
a
Management
Distribution and abundance
Demography
Settlement
Environmental change
Predation
Feeding ecology
1
2
3
4
E) Overall
d
c
c
b
b
a
a
Management
Distribution and abundance
Settlement
Demography
Environmental change
Predation
Feeding ecology
1
2
3
4
Score
Theme

◂**Fig. 1** Scoring of questions within *Themes* for criteria: **A** Knowledge Gap, **B** Feasibility, **C** Urgency, **D** Applicability, and the pooled **E** Overall score. Means are indicated by solid black circles, and medians are indicated by the colored solid line. Different lowercase letters on the left-hand side are significantly different based on pairwise post hoc comparisons of means. Themes on the y-axis are arranged in descending order of means

(*Acanthaster* cf. *solaris*) within, or collected from, Australia's GBR. These 38 researchers posed a total of 251 distinct and concise research questions (either independently or part of a consortium), though five questions were considered out of scope and/ or not relevant to the GBR and thus removed from the sample (Pratchett et al. 2021). The restricted geographic focus of this study, on Australia's GBR, was justified, given the seemingly unique manifestation and proliferation of recurrent population irruptions in this region (Pratchett et al. 2014), and because the vast majority of research on CoTS was conducted on the GBR (Uthicke et al. 2024a), thereby helping to align the research priorities with management objectives and opportunities specific to this jurisdiction (GBRMPA 2024). Moreover, it is now understood that *Acanthaster* is a species complex (Haszprunar et al. 2017, Wörheide et al. 2022) and that the Pacific species that occurs on the GBR, nominally *Acanthaster* cf. *solaris*, is ecologically distinct (Foo et al. 2024; Uthicke et al. 2024a).

To organize the 246 discrete and concise questions originally posed, questions were allocated to one of 48 topics across seven different *Themes* (Fig. 1), which revealed notable similarity among some questions posed by different researchers (Pratchett et al. 2021). This was rationalized by simply removing seemingly redundant questions (based on independent assessment by the core groups of researchers), without altering the wording of any individual questions. In the current study, however, to verify this process we asked the original proponents to identify any apparent overlap (redundancy) between individual questions that they proposed versus the broader set of research questions (following Cvitanovic et al. 2013). This reduced the total number of distinct research questions to 206, though it was apparent that there was still significant overlap among some questions (as explained below). To assess the relative priority of different research questions, the original contributors were then asked to score each of the 206 seemingly distinct questions against four different criteria: *Knowledge gap*, *Feasibility*, *Urgency*, and *Applicability* (Table 1). Experts were required to score each of the different criteria to just one of the discrete categories (Table 1), which were ordered from 1 (lowest priority) to 4 (highest priority). Proponents were also asked to self-assess their expertise across each of the seven *Themes*, indicating whether they did or did not have relevant expertise. In some instances, proponents did not score questions outside of their stated area of expertise. Of the 38 experts that submitted questions, 27 scored the distinct research questions (hereafter referred to as proponents), scoring between 37 and 204 questions, depending on their research expertise and capacity to effectively assess different research topics. In total, we obtained 3917 independent scores across all 206 research questions, with a minimum of 15 scores for each question.

During scoring and analyses for the 206 questions, a further 34 research questions were identified that were potentially redundant by the various proponents, which largely reaffirmed the opinions of the core team from the previous assessment (Pratchett et al. 2021). We therefore undertook to re-write relevant questions to redress apparent overlap and redundancy, and scores provided for each of the original questions were averaged for overarching analyses. For example, there were three distinct questions relating the microbiology or microbiome of CoTS larvae, albeit emphasizing different components, that were merged into a single question Q3 (How variable is the microbiome of larval CoTS and does this influence survival when food-limited?). A further two questions published in Pratchett et al. (2021) were not scored and therefore disregarded, either because they were seemingly resolved (What is the natural diet of CoTS larvae?) or the meaning and underlying assumptions were not clear (Where are juveniles between outbreaks?). Relative ranking of questions and *Themes* was based on the average of raw scores. There was a weak, but significant, effect of the number of proponents that scored each question and the raw score ($r^2 = 0.12$, $df = 168$, $p < 0.01$), but detrending raw scores did not affect the ranking of topics or *Themes*, and residuals ranged from −0.12 to 0.28 among questions.

To examine differences in the *Scores* between *Themes* (overall and under each criterion), we modeled proportional score data using beta regression. The original score variable ranged from 1 to 4 and was rescaled to the open interval (0, 1) using a standard transformation: $\text{Score}_\beta = (\text{Score} - 1)/3$. To avoid exact 0 or 1 values—problematic for beta distributions—we applied a continuity correction following the approach of Smithson and Verkuilen (2006): $\text{Score}_\beta = [\text{Score}_\beta \times (n-1) + 0.5]/n$, where n is the sample size. Beta regression was implemented using the *betareg* package (Cribari-Neto & Zeileis 2010) in R version 4.3.2 (R Core Team, 2023). This method is appropriate for modeling dependent variables that are continuous and bounded between 0 and 1, particularly when the distribution is asymmetric or heteroskedastic. We then fitted a model with *Theme* as the predictor of the rescaled scores and compared it to a null model (intercept only) using a likelihood ratio test to evaluate the significance of thematic differences in scoring. Pairwise post hoc comparisons between *Themes* were conducted using estimated marginal means with Benjamini–Hochberg (BH) adjustment for multiple testing

using the *emmeans* package in R. To visualize shifts in perceived importance of research *Themes* across different scoring criteria, we constructed a bump chart using the *ggplot2* and *ggbump* packages in R. Mean scores per *Theme* were compiled and ranked for each criterion. Faceted plots were used to display score distributions (mean score ± SD) across criteria, enabling comparison of *Topic* prioritization within and across *Themes*.

Results

A total of 170 distinct research questions were analyzed in this study (Table 2), across seven *Themes* and 39 topics (Fig. 1). The distribution of questions among distinct *Themes* and specific research topics has been presented previously (Pratchett et al. 2021), but ranges from 13 to 38 questions among *Themes* and from 1 to 12 questions per topic. The range of scores assigned for each topic and *Theme* generally encompassed the full range of possible scores (from 1 to 4), though there were conspicuous differences in the mean and mode, especially when considering different criteria (Figs. 1 and 2). For *Knowledge gap*, the mode was ≥ 3 for all *Themes*, indicating incomplete or insufficient knowledge. Very few respondents suggested we had complete (score = 1; 0.55%) or even sufficient (score = 2; 10.84%) knowledge for any of the 170 questions. The two questions where most respondents suggested that there was sufficient knowledge (scores ≤ 2) were Q16 (How do local impacts of COTS vary with their population size and structure?) and Q83 (Can we identify COTS DNA in gut samples of putative predators on juvenile and adult starfish?). Conversely, 163 (out of 170) questions were assigned the maximum score (4) by at least one of the proponents. The mean and mode for the *Feasibility* were also consistently high (≥ 2.5) across all *Themes* (Fig. 1), indicating that necessary resources, capability, and methods already exist to address many of the current research questions. For 158 of the questions, at least one proponent (and up to 13 out of 27 proponents) suggested that there were no constraints (score = 4), whereas at least one proponent suggested that there were comprehensive constraints (score = 1) for some questions ($n = 108$ questions), especially in the Management theme. The specific questions for which ≥ 10 proponents scored *Feasibility* as 1 were Q87 (What are the natural predation rates on COTS gametes and larvae?) and Q132 (Is genetic control of COTS a viable option for COTS control and are associated risks socially acceptable?).

The mean and mode of scores for the *Urgency* criteria (where scores ≥ 3 indicate that research needs to be conducted within next 5 years) and *Applicability* (where scores ≥ 3 indicate question with direct application for improved management) were much more variable than for *Knowledge* and *Feasibility*, among *Themes* (Fig. 1), topics (Fig. 3), and questions (Table 2). There was also generally close alignment in the ranking of *Themes* based on *Urgency* and *Applicability*, which had a major influence on overall rankings (Fig. 2). For *Urgency*, the range of scores for individual questions and research topics (among proponents) was particularly pronounced (Fig. 1), and the mode was ≤ 2 for 103 (out of 170) questions. Overall scores were much lower for questions related to Feeding ecology and Predation on CoTS, compared to Management (Fig. 1). For *Applicability*, scores were consistently high (modes mostly 3 or 4) for questions related to Management. The only question within this *Theme* where most proponents suggested that *Applicability* was limited (≤ 2) was Q145 (How can giant triton be cultured for the purpose of suppressing low-density populations of COTS?). By contrast, most of the questions within the *Theme* of Feeding ecology were considered to have very limited application, with two notable exceptions: Q6 (Are CoTS larvae more abundant in areas with elevated nutrients and/ or higher abundance of phytoplankton?) and Q11 (Can fluctuations in availability of coral prey explain boom and bust cycles of COTS populations?).

Overall, there was significant variation in scores among *Themes* ($\chi^2 = 242.96$, $df = 6$, $p < 0.001$), reflective of significant differences for each of the individual criteria: *Knowledge Gap* ($\chi^2 = 43.58$, $df = 6$, $p < 0.001$), *Feasibility* ($\chi^2 = 52.14$, $df = 6$, $p < 0.001$), *Urgency* ($\chi^2 = 318.83$, $df = 6$, $p < 0.001$), and *Applicability* ($\chi^2 = 637.31$, $df = 6$, $p < 0.001$). The ranking of different *Themes* varied depending on the specific scoring criteria (Fig. 2), with questions related to Settlement (mean score = 3.41) and Environmental change (mean score = 3.29) considered the foremost priorities when considering the extent of current knowledge. Environmental change was also the highest priority (mean score = 2.93) based on *Feasibility*. Questions relating to the Feeding ecology of CoTS ranked very high (mean score = 2.84) in terms of *Feasibility*, but scored very poorly for *Knowledge gap*, *Urgency*, and *Application* (Fig. 2). The top-ranked *Theme* for both *Urgency* and *Applicability* was Management, though the *Feasibility* of many of these research questions was considered very low (as described above).

Within most *Themes* (Settlement, Demography, Environmental change, Predation, and Feeding ecology), the scoring and ranking of different research topics was fairly consistent across different criteria (Fig. 3). However, for Predation, the extent of current knowledge and research constraints varies depending on the specific life stage of CoTS being considered. In particular, scores for questions on predation of larvae were high for *Knowledge gap*, but lower for *Feasibility*, compared to questions on adult predation (Fig. 3). Within the Management *Theme*, there were marked differences among specific topics; questions on the topic of Culling scored very high (mean = 3.74) for *Applicability*, and high

Table 2 Mean scores for each of the top 20 questions (based on overall expert scores) within corresponding *Themes and Topics* and mean scores for each criterion: Knowledge gap (KNW), Feasibility (FSB), Urgency (URG), and Applicability (APP). Scores ≥ 3.00 (75th percentile) are shown in bold, and scores ≥ 3.6 (90th percentile) shown in red. Overall mean scores (column 4) are calculated based on the overall scores of each expert, not the mean criteria scores (columns 5–8). *n* indicates the maximum number of proponents (out of 27) that scored each question against one or more different criteria

Theme	Topic	Question	n	Overall	KNW	FSB	URG	APP
Management	Culling	Q124·What changes in surveillance techniques and culling procedures will further enhance the efficiency and effectiveness of manual control?	**25**	**3.40**	2.88	**3.21**	**3.46**	**3.88**
Management	Culling	Q128·Does the culling program release the juveniles from competition with adults thereby triggering a transition to corallivory?	**26**	**3.40**	**3.92**	2.84	**3.44**	**3.42**
Management	Culling	Q125·What is the optimal allocation of current control capacity to maximize reef-wide ecological benefits?	**24**	**3.36**	**3.09**	2.81	**3.08**	**3.75**
Management	Culling	Q127·Are there potential negative effects (e.g., creating chronic population irruptions) of ineffective culling?	**25**	**3.36**	**3.32**	2.92	**3.58**	**3.76**
Management	Culling	Q126·What proportion of COTS are detected or missed during culling at a given reef location?	**25**	**3.35**	2.88	**3.24**	**3.60**	**3.88**
Management	Monitoring	Q116·What proportion of CoTS are detected/missed using different surveillance methods, and in different habitats?	**26**	**3.33**	**3.08**	**3.28**	1.87	**3.69**
Management	Monitoring	Q122·Can changes in settlement rates or juvenile densities in the lead up to initiation of population irruptions be detected?	**26**	**3.32**	**3.50**	2.73	**3.12**	**3.58**
Distribution and abundance	Incidence of population irruptions	Q58·Where exactly do primary outbreaks initiate in the northern GBR?	**26**	**3.31**	**3.04**	**3.00**	**3.46**	**3.73**
Management	Monitoring	Q117·Can we use eDNA as an early warning tool in conjunction with other monitoring?	**25**	**3.30**	**3.08**	**3.13**	**3.20**	**3.60**
Management	Monitoring	Q115·Do current surveillance methods provide an accurate representation or suitable proxy for the overall abundance of CoTS at individual reefs?	**26**	**3.25**	2.73	**3.28**	2.83	**3.77**
Management	Monitoring	Q120·Can COTS larval sampling be used to detect the early onset of new and renewed population irruptions?	**25**	**3.21**	**3.32**	**3.00**	**3.00**	**3.40**
Distribution and abundance	Connectivity	Q80·Are predictions of connectivity models supported by empirical data on the differential occurrence of population irruptions of COTS among reefs and regions?	**23**	**3.19**	**3.18**	**3.32**	2.95	**3.43**
Management	No-take marine reserves	Q148 Will increasing the spatial extent of no-take areas serve to prevent or delay recurrence of population irruptions of COTS?	**27**	**3.19**	**3.15**	2.96	2.83	**3.59**

Table 2 (continued)

Theme	Topic	Question	n	Overall	KNW	FSB	URG	APP
Distribution and abundance	Incidence of population irruptions	Q55·Are there reefs or regions that are consistently among the least or worst affected by COTS outbreaks (i.e., bright and dark spots)?	**26**	**3.18**	2.96	**3.19**	**3.20**	**3.35**
Demography	Ontogenetic shifts	Q42·Can the density and size-structure of low-density populations provide insights into the mechanisms leading to population outbreaks?	**26**	**3.17**	**3.37**	**3.02**	**3.08**	**3.19**
Predation	Abundance of predators	Q84·Are important COTS predators more abundant on reefs closed to fishing?	**25**	**3.16**	**3.04**	**3.12**	**3.04**	**3.32**
Management	Monitoring	Q118·How does eDNA detection and levels vary with local size and abundance of COTS versus other environmental factors (e.g., current flow and sampling season)?	**19**	**3.15**	**3.53**	**3.00**	**3.32**	**3.11**
Settlement	Habitat and substrate preferences	Q105 Where do COTS settle across reefs within the outbreak initiation box?	**25**	**3.14**	**3.32**	2.68	2.59	**3.32**
Management	Monitoring	Q123·Can eDNA (or RNA) be used to assess abundance of COTS when they are very small or rare?	**24**	**3.14**	**3.23**	2.95	2.80	**3.25**
Management	Trophic cascades	Q151·How has fishing affected the abundance and function of not only target species, but also lower trophic levels that are potentially important in regulating COTS populations?	**25**	**3.14**	**3.13**	2.96	**3.08**	**3.40**

for *Feasibility* (mean = 3.00) and *Urgency* (mean = 3.43). In contrast, questions on the topic of Biocontrol were scored very low (mean = 1.78) for *Feasibility* and had moderate scores for *Applicability* (mean = 2.87). Within the Distribution and abundance theme, some topics (most notably, Connectivity) had high scores for *Feasibility* and *Applicability*, whereas the *Feasibility* of other topics (e.g., Stock-recruitment relationships) was considered to be more moderate, even though the scores for *Applicability* and especially *Knowledge gap* were high. Overall, the top-ranked topics were Culling and Monitoring, both of which are within the Management *Theme* (Fig. 3).

Individual questions that had highest overall scores came mostly from the Management *Theme* (Table 2) and mainly related to Culling and/or Monitoring (e.g., Q124. What changes in surveillance techniques and culling procedures will further enhance the efficiency and effectiveness of manual control?). All but six of the 20 top-ranked questions (where overall scores were ≥ 3.14) were from the Management theme. Of these, there were three questions from the Distribution and Abundance *Theme* and one from each of the Demography, Predation, and Settlement *Themes*. Several of these questions that were not from the Management *Theme* (Q58, 42, and 84) scored ≥ 3 across all criteria. The top-ranked question based on *Knowledge Gap* was Q128 (Does the culling program release the juveniles from competition with adults thereby triggering a transition to corallivory?). The top-ranked questions for *Feasibility* were mainly from the Environmental Change *Theme*, including Q157 (Can COTS larvae, juveniles, and adults withstand elevated temperatures associated with increasing incidence and severity of marine heatwaves?) which had the same mean score (3.42) as Q16 (Do COTS prey on the entire colony and can coral colonies recover after partial predation?). The top-ranked question for *Urgency* (Q126) and *Feasibility* (Q124, Q126) was among the top-ranked questions overall (Table 2).

The expertise of the 27 proponents relevant to each of the seven *Themes* ranged from 25.9% for Demography up to 63.0% for Distribution and Abundance (Fig. 4). While the top-ranked *Themes* (Management and Distribution and Abundance) were those that most proponents (> 50%) considered an area of expertise, the rankings for other *Themes* did not correspond to levels of expertise. Most notably, the *Theme* for which there was the lowest level of expertise (Demography; 25.9%) had higher average overall scores than several other *Themes*, including Environmental Change, where there was much greater expertise represented (Fig. 4).

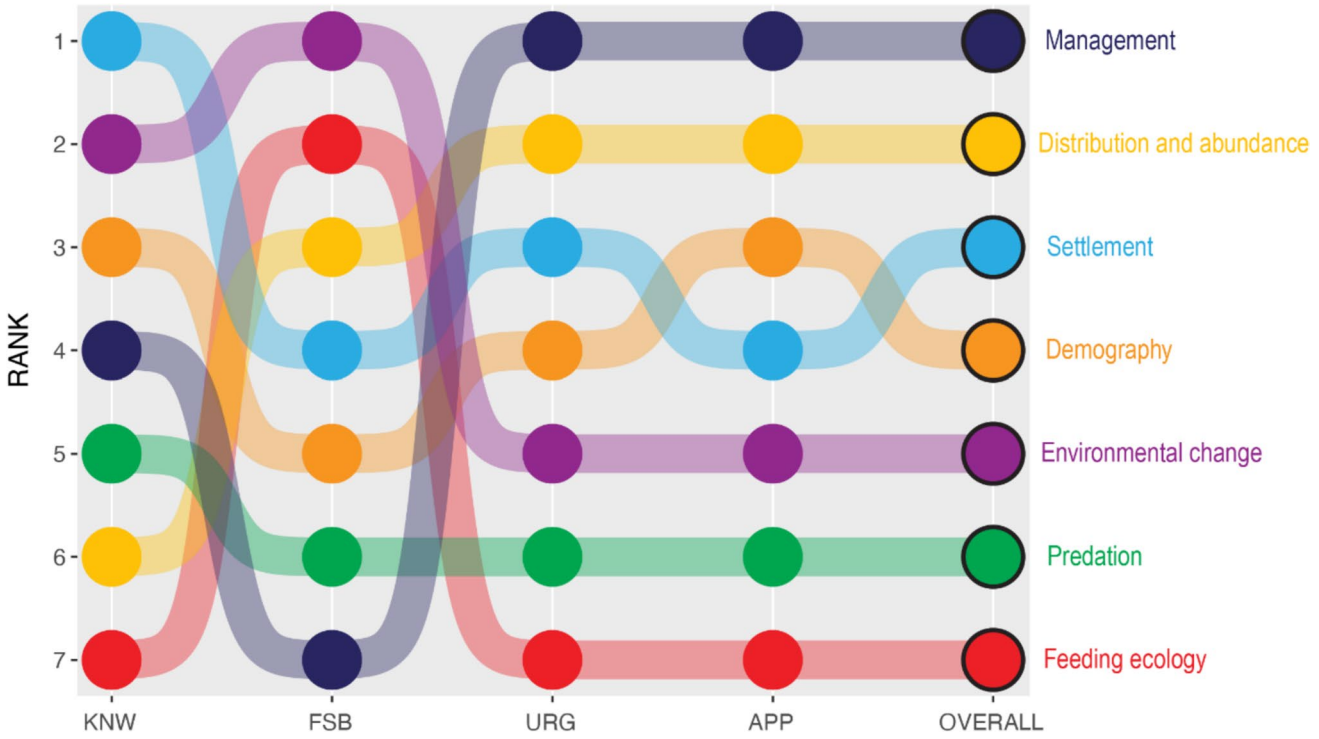


Fig. 2 Change in the ranking of *Themes* (based on mean score) for each criterion: Knowledge gap (KNW), Feasibility (FSB), Urgency (URG), and Applicability (APP). The Overall rank of each Theme is also shown (circles with black border)

Discussion

This study provides a quantitative basis for comparing among extensive research activities that have been proposed to improve understanding and management of population irruptions of Pacific CoTS (*A.* cf. *solaris*) on Australia's GBR (Supplementary Table, see also Pratchett et al. 2021). Establishing the foremost priorities for ongoing CoTS research is important given renewed population irruptions have recently been detected in the northern GBR (Chandler et al. 2023; Uthicke et al. 2024b), while climate change continues to cause extensive and widespread coral bleaching and mortality throughout the GBR (Byrne et al. 2025, McWilliam et al. in review). It is also apparent that despite the recognized importance of effective CoTS management in securing the future outlook of the GBR (e.g., GBRMPA 2024), and extensive funding for CoTS management and research (Fletcher et al. 2021), there will be inevitable constraints (both in terms of funding and research capacity) to simultaneously advance the extensive research represented across all 170 questions proposed herein. For example, the CoTS Control Innovation Program (CCIP) considered 86 knowledge gaps across 6 programs (i. Biology and ecology, ii. Population control, iii. Monitoring and surveillance, iv. Proximal causes of outbreaks, v. Social acceptability, regulatory, and institutional arrangements, and vi. Decision support and modeling), from which 12 research opportunities were selected using a structured decision-making (SDM) process (Fletcher et al. 2021). The CCIP SDM process, which involved many of the same proponents as here, was conducted independently with a much broader scope, employing a more structured approach to identify specific knowledge gaps. There are, therefore, opportunities to i) explicitly compare how these distinct processes compare in establishing the range of knowledge gaps where the research scopes overlap and ii) understand how perspectives, knowledge, and priorities of the experts contributing to this and previous works (Fletcher et al. 2021; Pratchett et al. 2021) align with and differ from those of international researchers, Indigenous Peoples, and the broader public, but these are outside of the scope of this study.

The 27 proponents, all of which have demonstrated expertise in CoTS research, varied in their assessment of individual questions, likely reflecting differential research bias and interests, as shown for horizon scans on other topics (Wilson et al. 2010). Notably, most of the proponents (> 50%) considered themselves experts in each of the top-2 ranked *Themes*, though these are arguably also among the most diverse *Themes*, which is reflected in the breath of individual questions therein. Scoring across the four criteria (*Knowledge gap*, *Feasibility*, *Urgency*, and

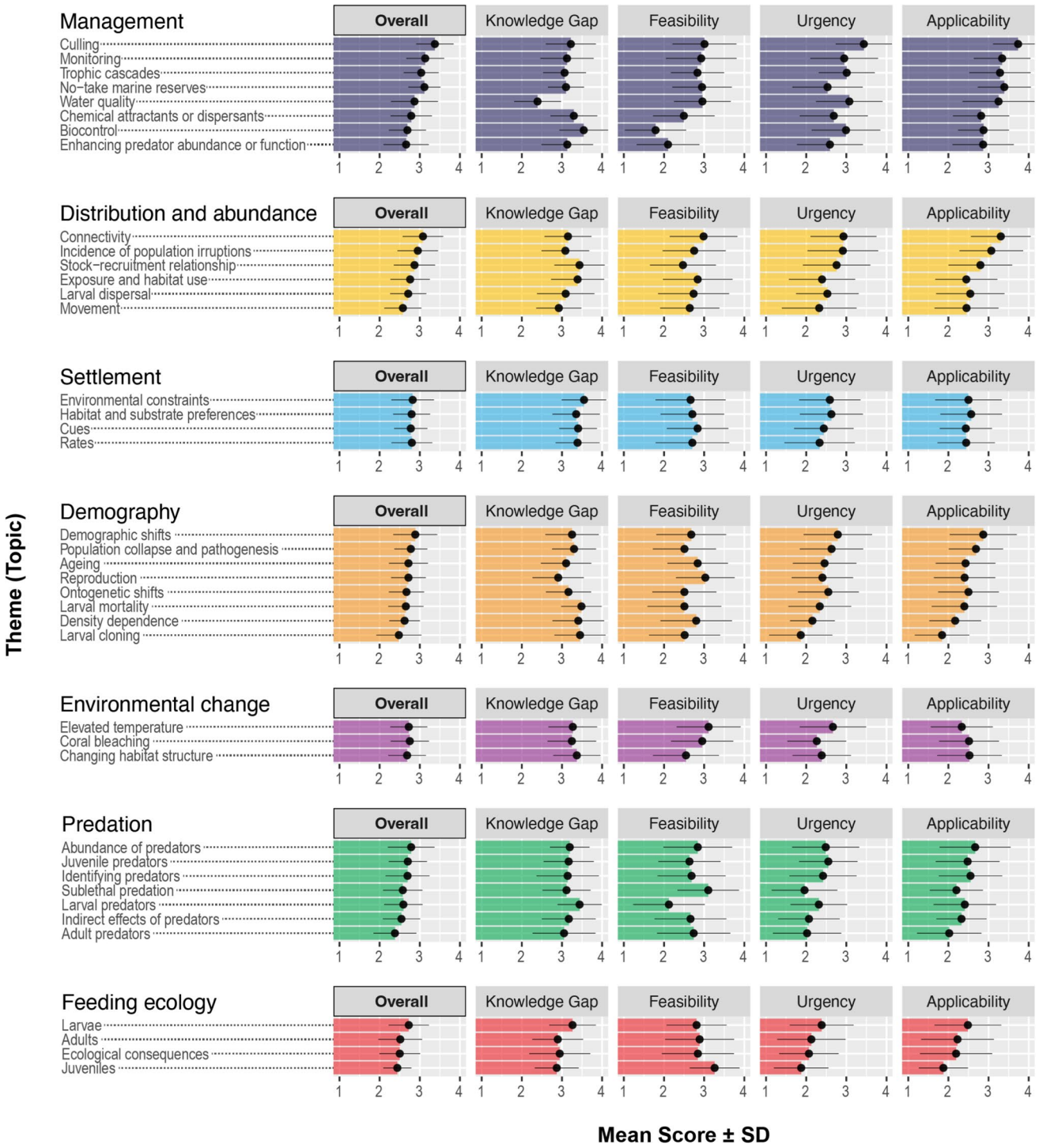


Fig. 3 Mean score for each topic (in descending order based on overall mean score) within each *Theme* (in descending order based on overall ranking of *Theme* in Fig. 2) for each criterion

Applicability) also revealed both consistent patterns and important contrasts among research *Themes* and topics. However, overall scores (averaged across proponents and criteria) highlighted the Management *Theme* as the foremost priority for additional research (Table 1). The high scores for questions within the Management *Theme*, and especially for topics of Culling and Monitoring (Fig. 1), reflect the close alignment with specific assessment components for *Urgency* and *Applicability*, where the latter explicitly considered relevance to management (Table 1). There is, however, a

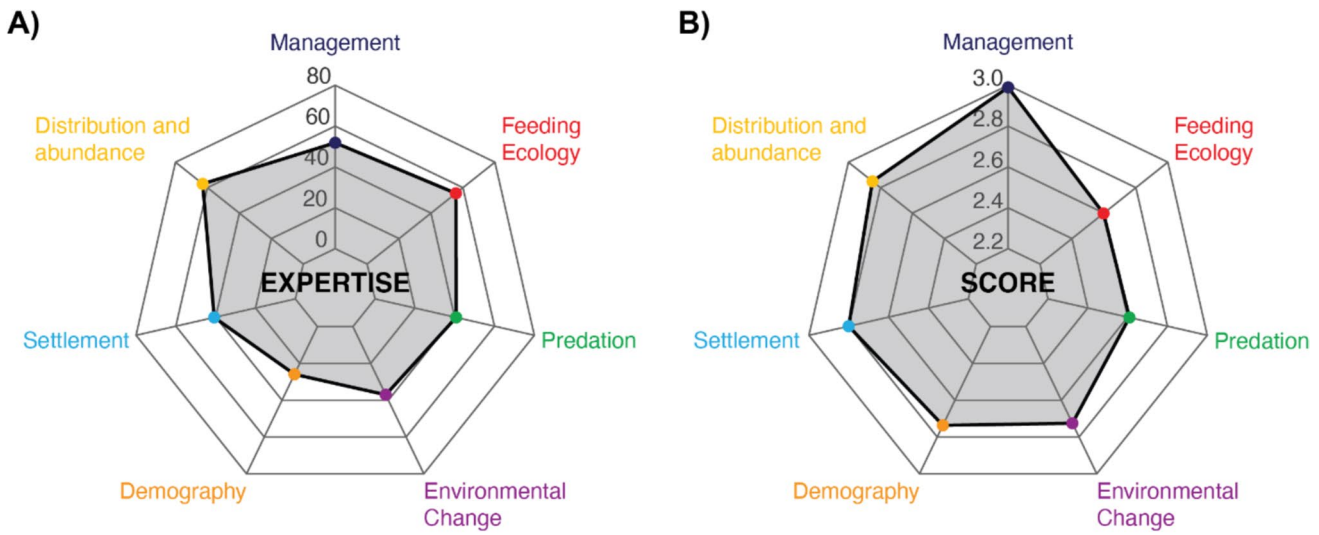


Fig. 4 **A** Variation in collective expertise of the 27 proponents that scored questions. Data shows the percentage of proponents that indicated that they had expertise relevant to each of the 7 *Themes*, based on self-assessment. **B** Average overall scores for each of the same 7 *Themes*

recognized need for additional research to further refine and enhance the efficacy of CoTS management on the GBR (Westcott et al. 2020, Castro-Sanguino et al. 2023), as well as explicitly assessing the long-term efficacy of different management approaches. Moreover, proponents (for both original questions and subsequent scoring) were explicitly asked to consider specific research activities that could improve management of population irruptions of CoTS on Australia's GBR (Pratchett et al. 2021). Even so, scores for *Urgency* and *Applicability* were generally lower than for *Knowledge gap* and *Feasibility*. *Knowledge gap* scores were uniformly high, with most questions rated ≥ 3, indicating widespread recognition of incomplete understanding across questions and *Themes*. In contrast, *Feasibility* scores, though generally high, showed greater variation, particularly for management-oriented questions where necessary tools and resources were sometimes lacking despite clear knowledge gaps. *Urgency* and *Applicability* were far less consistent, with Management questions typically ranked highest for both, while questions in *Themes* such as Feeding ecology and Predation received lower urgency and limited perceived application despite often scoring well for feasibility. This divergence highlights an important disconnect—questions that are tractable (high feasibility) are not always seen as time-critical or management-relevant, while those of greatest applied value (e.g., culling and monitoring strategies) are sometimes constrained by practical limitations. Moreover, of the 40 questions that scored ≥ 3 for *Applicability*, there were 15 (37.5%) that were outside of the Management Theme, mostly (9 questions) in the Distribution and abundance Theme. Questions within the Distribution and abundance *Theme* ranked poorly based on *Knowledge gap*, reflecting extensive and ongoing research into the abundance of CoTS on the GBR (e.g., Chandler et al. 2023, Emslie et al. 2024a,b), but this research is nonetheless considered important, especially for understanding the initiation and spread of population irruptions (Table 2). Furthermore, *Themes* such as Settlement and Environmental change consistently scored high for both *Knowledge gap* and *Feasibility*, whereas Management dominated rankings for *Urgency* and *Applicability*, driving overall priorities. These patterns suggest that while fundamental knowledge deficiencies are broadly acknowledged, research prioritization is strongly shaped by the perceived immediacy of management needs and the availability of methods to deliver actionable outcomes.

The bounds of the seven research *Themes* used to organize and assess the 170 distinct research questions are admittedly arbitrary and there are some questions that are relevant to multiple *Themes*. Notably, the high scoring research questions in the *Theme* Distribution and abundance (Table 2) had very strong relevance to Management, especially Monitoring and surveillance. The bounds of topics within *Themes* were also diffuse, with very similar questions being proposed in different topics. For example, Q116 and Q126 (Table 2) both relate to detectability of CoTS, but Q116 relates to the broad spectrum of different surveillance methods, whereas Q126 is explicitly focused on culling activities. Interestingly, both these questions scored very high (> 3.6) for *Applicability*, but Q116 was scored low for *Urgency* (mean = 1.87), compared to Q126 (mean = 3.60). It is important, therefore, to not only consider the differential scoring of specific *Themes* and topics (Fig. 3), but also differential scoring for individual questions (Table 2).

The research questions proposed in this study build upon critical knowledge gaps that were identified previously (e.g., Moran 1986, Pratchett et al. 2017), but do reflect subsequent breakthroughs and technological advances (e.g., application of eDNA sampling; Doyle and Uthicke 2020, Uthicke et al. 2024b) that have facilitated new research opportunities and generated new knowledge gaps. Many of the questions proposed herein align with the questions proposed by Moran (1986) that were considered relevant to understanding the causes and consequences of population irruptions. Despite significant advances in CoTS research, many of these research questions remain unresolved (Pratchett et al. 2017). However, the major priorities revealed during this study (Table 2) highlight where there are specific management applications, rather than necessarily advancing fundamental biological knowledge or establishing the underlying cause(s) of population irruptions. This reflects widespread acceptance of conservation benefits from effectively suppressing local densities of CoTS (De'ath et al. 2012, Hoey et al. 2016, Matthews et al. 2024, but see Streit et al. 2024), regardless of their cause(s). However, this study also preferences research activities with relatively rapid and more certain application (Table 1), whereas enduring and effective management of CoTS may require a longer-term perspective and unequivocal understanding of the underlying causes(s) of, or contributors to, population irruptions (Pratchett and Cumming 2019).

Coral reef ecosystems are being subject to increasing frequency, severity, and extent of major disturbances, necessitating improvements and strengthening in established management approaches (Bellwood et al. 2019). Emerging threats posed by climate change also provide a renewed imperative to minimize, if not reverse, declining coral cover, to maximize adaptive capacity and resilience. Improved management of CoTS is recognized as one of the most important management strategies to secure the future of the GBR (GBRMPA 2024), and while there are opportunities to increase the efficiency and/ or extent of established management efforts (Matthews et al. 2024; Rogers et al. 2023), further improvements will need to be underpinned by further research to close fundamental knowledge gaps, as well as considering other forms of knowledge, such as Traditional Ecological Knowledge (TEK). This study highlights opportunities to target resources toward interventions with high perceived impact while supporting research that strengthens the evidence base for emerging control options and anticipates environmental change.

Acknowledgements This paper is dedicated to the memory of Professor Richard Kenchington, whose support for this undertaking continued until his passing on March 1, 2023. His pioneering research on the spatiotemporal dynamics of COTS populations on the GBR significantly advanced our understanding of the species.

Author contributions MSP, CFC, CC, and SKW conceptualized, led, and coordinated the study. PCD and CFC analyzed the data. MSP and PCD wrote the manuscript. All other authors (including MSP, CFC, and PCD) posed and scored research questions. All authors reviewed and edited or approved the manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. This study benefited from extensive research funding provided by the COTS Control Innovation Programme (CCIP), which is supported by the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation, though no direct funding was obtained for this study. Importantly, this project was aided by recurrent meetings and extensive engagement among researchers, to design and undertake CCIP.

Data availability Summary data are presented in Supplementary Table 1; raw data (scores by each of the individual researchers) will not be shared to protect anonymity.

Declarations

Conflict of interest Morgan Pratchett is EIC of Coral Reefs, and Ciemon Caballes is guest editor for the current Special Issue.

References

Allen JD, Richardson EL, Deaker D, Agüera A, Byrne M (2019) Larval cloning in the crown-of-thorns sea star, a keystone coral predator. Mar Ecol Prog Ser 609:271-276. https://doi.org/10.3354/meps12843

Babcock RC, Milton DA, Pratchett MS (2016a) Relationships between size and reproductive output in the crown-of-thorns starfish. Mar Biol 163:234. https://doi.org/10.1007/s00227-016-3009-5

Babcock RC, Dambacher JM, Morello EB, Plagányi ÉE, Hayes KR, Sweatman HPA, Pratchett MS (2016b) Assessing different causes of crown-of-thorns starfish outbreaks and appropriate responses for management on the great Barrier Reef. PLoS ONE 11(12):e0169048. https://doi.org/10.1371/journal.pone.0169048

Babcock RC, Plagányi ÉE, Condie SA, Westcott DA, Fletcher CS, Bonin MC, Cameron D (2020) Suppressing the next

crown-of-thorns outbreak on the Great Barrier Reef. Coral Reefs 39(5):1233–1244. https://doi.org/10.1007/s00338-020-01978-8

Bellwood DR, Pratchett MS, Morrison TH, Gurney GG, Hughes TP, Álvarez-Romero JG, Day JC, Grantham R, Grech A, Hoey AS, Jones GP et al (2019) Coral reef conservation in the Anthropocene: confronting spatial mismatches and prioritizing functions. Biol Conserv 236:604–615. https://doi.org/10.1016/j.biocon.2019.05.056

Benson AA, Patton JS, Field CE (1975) Wax digestion in a crown-of-thorns starfish. Comp Biochem Physiol B Biochem Mol Biol 52(2):339–340. https://doi.org/10.1016/0305-0491(75)90075-9

Birkeland C (1982) Terrestrial runoff as a cause of outbreaks of *Acanthaster planci* (Echinodermata: Asteroidea). Mar Biol 69:175–185. https://doi.org/10.1007/BF00396897

Birkeland C (1989) The faustian traits of the crown-of-thorns starfish. Am Sci 77(2):154–163

Bozec YM, Hock K, Mason RA, Baird ME, Castro-Sanguino C, Condie SA, Puotinen M, Thompson A, Mumby PJ (2022) Cumulative impacts across Australia's Great Barrier Reef: a mechanistic evaluation. Ecol Monogr 92(1):e01494. https://doi.org/10.1002/ecm.1494

Britton JR, Pegg J, Gozlan RE (2011) Quantifying imperfect detection in an invasive pest fish and the implications for conservation management. Biol Conserv 144(9):2177–2181. https://doi.org/10.1016/j.biocon.2011.05.008

Brodie J, Fabricius K, De'ath G, Okaji K (2005) Are increased nutrient inputs responsible for more outbreaks of crown-of-thorns starfish? An appraisal of the evidence. Mar Pollut Bull 51(1–4):266–278. https://doi.org/10.1016/j.marpolbul.2004.10.035

Byrne M, Deaker DJ, Gibbs M, Selvakumaraswamy P, Clements M (2023) Juvenile waiting stage crown-of-thorns sea stars are resilient in heatwave conditions that bleach and kill corals. Glob Chang Biol 29(23):6493-6502. https://doi.org/10.1111/gcb.16946

Byrne M, Waller A, Clements M, Kelly AS, Kingsford MJ, Liu B, Reymond CE, Vila-Concejo A, Webb M, Whitton K, Foo SA (2025) Catastrophic bleaching in protected reefs of the Southern Great Barrier Reef. Limnol Oceanogr Lett 10(3):340–348. https://doi.org/10.1002/lol2.10456

Caballes CF, Pratchett MS, Kerr AM, Rivera-Posada JA (2016) The role of maternal nutrition on oocyte size and quality, with respect to early larval development in the coral-eating starfish, *Acanthaster planci*. PLoS ONE 11:e0158007. https://doi.org/10.1371/journal.pone.0158007

Caballes CF, Pratchett MS, Raymundo ML, Rivera-Posada JA (2017) Environmental tipping points for sperm motility, fertilization, and embryonic development in the crown-of-thorns starfish. Diversity 9:10. https://doi.org/10.3390/d9010010

Castro-Sanguino C, Ortiz JC, Thompson A, Wolff NH, Ferrari R, Robson B, Magno-Canto MM, Puotinen M, Fabricius KE, Uthicke S (2021) Reef state and performance as indicators of cumulative impacts on coral reefs. Ecol Indic 123:107335. https://doi.org/10.1016/j.ecolind.2020.107335

Castro-Sanguino C, Bozec YM, Condie SA, Fletcher CS, Hock K, Roelfsema C, Westcott DA, Mumby PJ (2023) Control efforts of crown-of-thorns starfish outbreaks to limit future coral decline across the Great Barrier Reef. Ecosphere 14(6):e4580. https://doi.org/10.1002/ecs2.4580

Chandler JF, Burn D, Caballes CF, Doll PC, Kwong SL, Lang BJ, Pacey KI, Pratchett M (2023) Increasing densities of Pacific crown-of-thorns starfish (*Acanthaster* cf. *solaris*) at Lizard Island, northern Great Barrier Reef, resolved using a novel survey method. Sci Rep 13:19306. https://doi.org/10.1038/s41598-023-46749-x

Chesher RH (1969) Destruction of Pacific corals by the sea star *Acanthaster planci*. Science 165(3890):280–283. https://doi.org/10.1126/science.165.3890.280

Condie SA, Anthony K, Babcock RC, Baird ME, Beeden R, Fletcher CS, Gorton R, Harrison D, Hobday AJ, Plagányi ÉE, Westcott DA (2021) Large-scale interventions may delay decline of the Great Barrier Reef. R Soc Open Sci 8(4):201296. https://doi.org/10.1098/rsos.201296

Cribari-Neto F, Zeileis A (2010) Beta regression in R. J Stat Softw 34(2):1–24. https://doi.org/10.18637/jss.v034.i02

Cvitanovic C, Wilson SK, Fulton CJ, Almany GR, Anderson P, Babcock RC, Ban NC, Beeden RJ, Beger M, Cinner J, Dobbs K (2013) Critical research needs for managing coral reef marine protected areas: perspectives of academics and managers. J Environ Manage 114:84–91. https://doi.org/10.1016/j.jenvman.2012.10.051

Cvitanovic C, Mackay M, Kelly R, Wilson SK, Waples K, Nash KL, van Putten EI, Field S, Botterill-James T, Austin BJ, Beckley LE (2021) Thirty critical research needs for managing an ecologically and culturally unique remote marine environment: the Kimberley region of Western Australia. Ocean Coastal Manage 212:105771. https://doi.org/10.1016/j.ocecoaman.2021.105771

Deaker DJ, Byrne M (2022) Crown-of-thorns starfish life history traits contribute to outbreaks, a continuing concern for coral reefs. Emerg Top Life Sci 6:67–79

Deaker DJ, Agüera A, Lin HA, Lawson C, Budden C, Dworjanyn SA, Mos B, Byrne M (2020) The hidden army: corallivorous crown-of-thorns seastars can spend years as herbivorous juveniles. Biol Lett 16(4):20190849. https://doi.org/10.1098/rsbl.2019.0849

De'ath G, Moran PJ (1998) Factors affecting the behaviour of crown-of-thorns starfish (*Acanthaster planci* L.) on the Great Barrier Reef 1: patterns of activity. J Exp Mar Biol Ecol 220(1):83–106. https://doi.org/10.1016/S0022-0981(97)00085-3

Doll PC, Uthicke S, Caballes CF, Diaz-Pulido G, Abdul Wahab MA, Lang BJ, Jeong SY, Pratchett MS (2023) Settlement cue selectivity by larvae of the destructive crown-of-thorns starfish. Biol Lett 19(1):20220399. https://doi.org/10.1098/rsbl.2022.0399

Doyle J, Uthicke S (2021) Sensitive environmental DNA detection via lateral flow assay (dipstick)—a case study on corallivorous crown-of-thorns sea star (*Acanthaster* cf. *solaris*) detection. Environ DNA 3(2):323–342. https://doi.org/10.1002/edn3.123

Dumas P, Fiat S, Durbano A, Peignon C, Mou-Tham G, Ham J, Gereva S, Kaku R, Chateau O, Wantiez L, De Ramon N'Yeurt A, Adjeroud M (2020) Citizen science, a promising tool for detecting and monitoring outbreaks of the crown-of-thorns starfish *Acanthaster* spp. Sci Rep 10(1):291. https://doi.org/10.1038/s41598-019-57251-8

Emslie MJ, Ceccarelli DM, Logan M, Blandford MI, Bray P, Campili A, Jonker MJ, Parker JG, Prenzlau T, Sinclair-Taylor TH (2024a) Changing dynamics of Great Barrier Reef hard coral cover in the Anthropocene. Coral Reefs 43(3):747–762. https://doi.org/10.1007/s00338-024-02498-5

Emslie MJ, Logan M, Bray P, Ceccarelli DM, Cheal AJ, Hughes TP, Johns KA, Jonker MJ, Kennedy EV, Kerry JT, Mellin C (2024b) Increasing disturbance frequency undermines coral reef recovery. Ecol Monogr 94(3):e1619. https://doi.org/10.1002/ecm.1619

Endean R, Stablum W (1973) A study of some aspects of the crown-of-thorns starfish (*Acanthaster planci*) infestations of reefs of Australia's Great Barrier Reef. Atoll Res Bull 167:1–60

Fernandes L, Marsh H, Moran PJ, Sinclair D (1990) Bias in manta tow surveys of *Acanthaster planci*. Coral Reefs 9(3):155–160. https://doi.org/10.1007/BF00258228

Fletcher CS, Bonin MC, Westcott DA (2020) An ecologically-based operational strategy for COTS control: integrated decision making from the site to the regional scale. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns, pp 65. https://nesptropical.edu.au/wp-content/uploads/2020/04/NESP-TWQ-Project-3.1.1-Technical-Report-2.pdf

Fletcher CS, Bonin MC, Caballes CF, Gómez-Cabrera MC, Kroon FJ, Mankad, A, Pratchett MS, Uthicke S, Westcott DA (2021) Design of the COTS Control Innovation Program: a technical report and recommendations. A report to the Australian Government by the COTS Control Innovation Program, pp 149. https://www.barrierreef.org/uploads/CCIP-Design-Phase-Technical-Report.pdf

Foo SA, Millican HR, Byrne M (2024) Crown-of-thorns seastar (*Acanthaster* spp.) feeding ecology across species and regions. Sci Total Environ 930:172691. https://doi.org/10.1016/j.scitotenv.2024.172691

GBRMPA (2024) Great Barrier Reef Blueprint for Climate Resilience and Adaptation. Great Barrier Reef Marine Park Authority (GBRMPA), Townsville

Goreau TF (1964) On the predation of coral by the spiny starfish *Acanthaster planci* (L.) in the southern Red Sea. Bull Sea Fish Res Stn Isr 35:23–26

Haszprunar G, Vogler C, Wörheide G (2017) Persistent gaps of knowledge for naming and distinguishing multiple species of crown-of-thorns-seastar in the *Acanthaster planci* species complex. Diversity 9(2):22. https://doi.org/10.3390/d9020022

Hayes KR, Cannon R, Neil K, Inglis G (2005) Sensitivity and cost considerations for the detection and eradication of marine pests in ports. Mar Pollut Bull 50(8):823–834. https://doi.org/10.1016/j.marpolbul.2005.02.032

Heron SF, Maynard JA, Van Hooidonk R, Eakin CM (2016) Warming trends and bleaching stress of the world's coral reefs 1985–2012. Sci Rep 6(1):38402. https://doi.org/10.1038/srep38402

Hoey J, Campbell M, Hewitt C, Gould B, Bird R (2016) *Acanthaster planci* invasions: applying biosecurity practices to manage a native boom and bust coral pest in Australia. Manag Biol Invasions 7(3):213–220. https://doi.org/10.3391/mbi.2016.7.3.01

Hoey J, Chin A (2004) State of the Reef Report 2004: Crown-of-thorns starfish. Great Barrier Reef Marine Park Authority. https://hdl.handle.net/11017/672

Hue T, Chateau O, Lecellier G, Kayal M, Lanos N, Gossuin H, Adjeroud M, Dumas P (2020) Temperature affects the reproductive outputs of coral-eating starfish *Acanthaster* spp. after adult exposure to near-future ocean warming and acidification. Mar Environ Res 162:105164. https://doi.org/10.1016/j.marenvres.2020.105164

Hughes TP, Kerry JT, Álvarez-Noriega M, Álvarez-Romero JG, Anderson KD, Baird AH, Babcock RC, Beger M, Bellwood DR, Berkelmans R, Bridge TC, Butler IR, Byrne M, Cantin NE, Comeau S, Connolly SR, Cumming GS, Dalton SJ, Diaz-Pulido G, Eakin CM, Figueira WF, Gilmour JP, Harrison HB, Heron SF, Hoey AS, Hobbs J-PA, Hoogenboom MO, Kennedy EV, Kuo C-Y, Lough JM, Lowe RJ, Liu G, McCulloch MT, Malcolm HA, McWilliam MJ, Pandolfi JM, Pears RJ, Pratchett MS, Schoepf V, Simpson T, Skirving WJ, Sommer B, Torda G, Wachenfeld DR, Willis BL, Wilson SK (2017) Global warming and recurrent mass bleaching of corals. Nature 543:373–377. https://doi.org/10.1038/nature21707

Jensen K, Doll PC, Gomez Cabrera MC, Diaz-Pulido G, Logan M, Uthicke S (2025) Feeding preferences and growth in herbivorous juvenile crown-of-thorns sea stars (*Acanthaster* cf. *solaris*). Mar Biol 172(6):86. https://doi.org/10.1007/s00227-025-04646-z

Kayal M, Vercelloni J, Lison de Loma T, Bosserelle P, Chancerelle Y, Geoffroy S, Stievenart C, Michonneau F, Penin L, Planes S, Adjeroud M (2012) Predator crown-of-thorns starfish (*Acanthaster planci*) outbreak, mass mortality of corals, and cascading effects on reef fish and benthic communities. PLoS ONE 7(10):e47363. https://doi.org/10.1371/journal.pone.0047363

Kayal M, Bosserelle P, Adjeroud M (2017) Bias associated with the detectability of the coral-eating pest crown-of-thorns seastar and implications for reef management. R Soc Open Sci 4(8):170396. https://doi.org/10.1098/rsos.170396

Keesing JK, Lucas JS (1992) Field measurement of feeding and movement rates of the crown-of-thorns starfish *Acanthaster planci* (L.). J Exp Mar Biol Ecol 156(1):89–104. https://doi.org/10.1016/0022-0981(92)90018-6

Lamare M, Pecorino D, Hardy N, Liddy M, Byrne M, Uthicke S (2014) The thermal tolerance of crown-of-thorns (*Acanthaster planci*) embryos and bipinnaria larvae: implications for spatial and temporal variation in adult populations. Coral Reefs 33:207–219. https://doi.org/10.1007/s00338-013-1112-3

Lang BJ, Donelson JM, Caballes CF, Uthicke S, Doll PC, Pratchett MS (2022) Effects of elevated temperature on the performance and survival of Pacific Ocean crown-of-thorns starfish (*Acanthaster* cf. *solaris*). Mar Biol 169(4):43. https://doi.org/10.1007/s00227-022-04027-w

Ling SD, Cowan Z-L, Boada J, Flukes EB, Pratchett MS (2020) Homing behaviour by destructive crown-of-thorns starfish is triggered by local availability of coral prey. Proc R Soc B Biol Sci 287:20201341. https://doi.org/10.1098/rspb.2020.1341

Llarena D, Gomez-Cabrera MC, Doll PC, Uthicke S (2025) (In review) Diet of herbivorous juveniles modulates growth, survival, and the timing of the ontogenetic diet shift to corallivory in crown-of-thorns sea stars. Coral Reefs https://doi.org/10.1007/s00338-025-02783-x

Lucas JS (1982) Quantitative studies of feeding and nutrition during larval development of the coral reef asteroid *Acanthaster planci* (L.). J Exp Mar Biol Ecol 65(2):173–193. https://doi.org/10.1016/0022-0981(82)90043-0

MacNeil MA, Mellin C, Pratchett MS, Hoey J, Anthony KR, Cheal AJ, Miller I, Sweatman H, Cowan ZL, Taylor S, Moon S (2016) Joint estimation of crown of thorns (*Acanthaster planci*) densities on the Great Barrier Reef. PeerJ 4:e2310. https://doi.org/10.7717/peerj.2310

Matthews SA, Williamson DH, Beeden R, Emslie MJ, Abom RT, Beard D, Bonin M, Bray P, Campili AR, Ceccarelli DM, Fernandes L (2024) Protecting Great Barrier Reef resilience through effective management of crown-of-thorns starfish outbreaks. PLoS ONE 19(4):e0298073. https://doi.org/10.1371/journal.pone.0298073

Mellin C, Matthews S, Anthony KR, Brown SC, Caley MJ, Johns KA, Osborne K, Puotinen M, Thompson A, Wolff NH, Fordham DA (2019) Spatial resilience of the Great Barrier Reef under cumulative disturbance impacts. Glob Change Biol 25(7):2431–2445. https://doi.org/10.1111/gcb.14625

Moran PJ (1986) The *acanthaster* phenomenon. Oceanogr Mar Biol Annu Rev 24:379–480

Olson RR (1987) *In situ* culturing as a test of the larval starvation hypothesis for the crown-of-thoms starfish, *Acanthaster planci*. Limnol Oceanogr 32(4):895–904. https://doi.org/10.4319/lo.1987.32.4.0895

Ortiz JC, Bozec YM, Wolff NH, Doropoulos C, Mumby PJ (2014) Global disparity in the ecological benefits of reducing carbon emissions for coral reefs. Nat Clim Chang 4(12):1090–1104. https://doi.org/10.1038/nclimate2439

Plagányi ÉE, Babcock RC, Rogers J, Bonin M, Morello EB (2020) Ecological analyses to inform management targets for the culling of crown-of-thorns starfish to prevent coral decline. Coral Reefs 39:1483–1499. https://doi.org/10.1007/s00338-020-01981-z

Plass-Johnson JG, Schwieder H, Heiden J, Weiand L, Wild C, Jompa J, Ferse SC, Teichberg M (2015) A recent outbreak of crown-of-thorns starfish (*Acanthaster planci*) in the Spermonde Archipelago, Indonesia. Reg Environ Change 15(6):1157–1162. https://doi.org/10.1007/s10113-015-0821-2

Pratchett MS, Caballes CF, Rivera-Posada JA, Sweatman HPA (2014) Limits to understanding and managing outbreaks of crown-of-thorns starfish (*Acanthaster* spp.). Oceanogr Mar Biol Annu Rev 52:133–200

Pratchett MS, Caballes CF, Wilmes JC, Matthews SA, Mellin C, Sweatman HPA, Nadler LE, Brodie JE, Thompson CA, Hoey J, Bos AR, Byrne M, Messmer V, Fortunato SAV, Chen CCM, Buck ACE, Babcock RC, Uthicke S (2017) Thirty years of research on crown-of-thorns starfish (1986-2016): scientific advances and emerging opportunities. Diversity 9:41. https://doi.org/10.3390/d9040041

Pratchett MS, Caballes CF, Cvitanovic C, Raymundo ML, Babcock RC, Doherty PJ, Doll PC, Doyle JR, Dworjanyn SA, Fabricius KE, Haywood MDE, Hock K, Hoggett A, Høj L, Keesing JK, Kenchington RA, Lang BJ, Ling SD, Matthews SA, McCallum HI, Mellin C, Mos B, Motti CA, Mumby PJ, Stump RJW, Uthicke S, Vail L, Wolfe K, Wilson SK (2021) Knowledge gaps in the biology, ecology and management of Pacific Ocean crown-of-thorns starfish, *Acanthaster* cf. *solaris*, on Australia's Great Barrier Reef. Biol Bull 241(3):330–346. https://doi.org/10.1086/717026

Pratchett MS, Chandler JF, Choukroun SM, Doll PC, Lang BJ, Kwong S, Chen CC, Emslie MJ, Caballes CF, Uthicke S, Matthews SA (2024) Biophysical processes involved in the initiation and spread of population irruptions of crown-of-thorns starfish on the Great Barrier Reef. In: Wolanski E, Kingsford MJ (eds.) Oceanographic Processes of Coral Reefs. CRC Press, pp. 290–305

Pratchett MS, Cumming GS (2019) Managing cross-scale dynamics in marine conservation: Pest irruptions and lessons from culling of crown-of-thorns starfish (*Acanthaster* spp.) Biological Conservation 238:108211. https://doi.org/10.1016/j.biocon.2019.108211

R Core Team (2023) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org

Reichelt RE, Bradbury RH, Moran PJ (1990) Distribution of *Acanthaster planci* outbreaks on the Great Barrier Reef between 1966 and 1989. Coral Reefs 9(3):97–103. https://doi.org/10.1007/BF00258219

Rogers JG, Plagányi ÉE, Babcock RC, Fletcher CS, Westcott DA (2023) Improving coral cover using an integrated pest management framework. Ecol Appl 33(8):e2913. https://doi.org/10.1002/eap.2913

Saponari L, Montalbetti E, Galli P, Strona G, Seveso D, Dehnert I, Montano S (2018) Monitoring and assessing a 2-year outbreak of the corallivorous seastar *Acanthaster planci* in Ari Atoll, Republic of Maldives. Environ Monit Assess 190(6):344

Smithson M, Verkuilen J (2006) A better lemon squeezer? Maximum-likelihood regression with beta-distributed dependent variables. Psychol Methods 11(1):54–71. https://doi.org/10.1037/1082-989X.11.1.54

Streit RP, Morrison TH, Bellwood DR (2024) Coral reefs deserve evidence-based management not heroic interference. Nat Clim Chang 14(8):773–775. https://doi.org/10.1038/s41558-024-02063-6

Trapon ML, Pratchett MS, Penin L (2011) Comparative effects of different disturbances in coral reef habitats in Moorea, French Polynesia. J Mar Biol 2011:807625. https://doi.org/10.1155/2011/807625

Uthicke S, Pratchett MS, Bronstein O, Alvarado JJ, Wörheide G (2024a) The crown-of-thorns seastar species complex: knowledge on the biology and ecology of five corallivorous *Acanthaster* species. Mar Biol 171(1):32. https://doi.org/10.1007/s00227-023-04355-5

Uthicke S, Doyle JR, Gomez Cabrera M, Patel F, McLatchie MJ, Doll PC, Chandler JF, Pratchett MS (2024b) eDNA monitoring detects new outbreak wave of corallivorous seastar (*Acanthaster* cf. *solaris*) at Lizard Island, Great Barrier Reef. Coral Reefs 43:857–866. https://doi.org/10.1007/s00338-024-02506-8

Uthicke S, Logan M, Liddy M, Francis D, Hardy N, Lamare M (2015) Climate change as an unexpected co-factor promoting coral eating seastar (Acanthaster planci) outbreaks. Sci Rep 5(1): 8402. https://doi.org/10.1038/srep08402

Uthicke S, Schaffelke B, Byrne M (2009) A boom–bust phylum? Ecological and evolutionary consequences of density variations in echinoderms Ecological Monographs 79(1):3-24. https://doi.org/10.1890/07-2136.1

Vanhatalo J, Hosack GR, Sweatman H (2017) Spatiotemporal modelling of crown-of-thorns starfish outbreaks on the Great Barrier Reef to inform control strategies. J Appl Ecol 54(1):188-197 https://doi.org/10.1111/1365-2664.12710

Weber JN, Woodhed PMJ (1970) Ecological studies of the coral predator *Acanthaster planci* in the South Pacific. Mar Biol 6(1):12–17. https://doi.org/10.1007/BF00352602

Westcott DA, Fletcher CS, Kroon FJ, Babcock RC, Plagányi EE, Pratchett MS, Bonin MC (2020) Relative efficacy of three approaches to mitigate Crown-of-Thorns Starfish outbreaks on Australia's Great Barrier Reef. Sci Rep 10(1):12594. https://doi.org/10.1038/s41598-020-69466-1

Wilmes JC, Caballes CF, Cowan ZL, Hoey AS, Lang BJ, Messmer V, Pratchett MS (2018) Contributions of pre-versus post-settlement processes to fluctuating abundance of crown-of-thorns starfishes (*Acanthaster* spp.). Mar Pollut Bull 135:332–345. https://doi.org/10.1016/j.marpolbul.2018.07.006

Wilmes JC, Hoey AS, Pratchett MS (2020) Contrasting size and fate of juvenile crown-of-thorns starfish linked to ontogenetic diet shifts. Proc R Soc Lond B Biol Sci 287(1931):20201052. https://doi.org/10.1098/rspb.2020.1052

Wilson SK, Adjeroud M, Bellwood DR, Berumen ML, Booth D, Bozec Y, Chabanet P, Cheal A, Cinner J, Depczynski M, Feary DA, Gagliano M, Graham NAJ, Halford AR, Halpern BS, Harborne AR, Hoey AS, Holbrook S, Jones GP, Kulbiki M, Letourneur Y, De Loma TL, McClanahan T, McCormick MI, Meekan MG, Mumby PJ, Munday PL, Öhman MC, Pratchett MS, Riegl B, Sano M, Schmitt RJ, Syms C (2010) Crucial knowledge gaps in current understanding of climate change impacts on coral reef fishes. J Exp Biol 213(6): 894-900. https://doi.org/10.1242/jeb.037895

Wolfe K, Graba-Landry A, Dworjanyn SA, Byrne M (2015) Larval starvation to satiation: influence of nutrient regime on the success of *Acanthaster planci*. PLoS ONE 10(3):e0122010. https://doi.org/10.1371/journal.pone.0122010

Worheide G, Kaltenbacher E, Cowan ZL, Haszprunar G (2022) A new species of crown-of-thorns sea star *Acanthaster benziei* sp. nov. (Valvatida: Acanthasteridae) from the Red Sea Zootaxa 5209(3):379-393. https://doi.org/10.11646/zootaxa.5209.3.7