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RESTORATION
& ADAPTATION
PROGRAM

Fogging Development (CS-07)

Final Report June 2025

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RRAP Fogging Development (CS-07) Final Report June 2025

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Copyright and Disclaimer

This Report summarises work undertaken under *Fogging Development (CS-07)* in accordance with the Reef Restoration and Adaptation Program's *Cooling and Shading* Project Agreements. It provides a summarised, point-in-time synopsis of activities, methods, findings and outcomes completed in accordance with the approved project scope up to 30 June 2025.

All information reflects project scope and outcomes as of May-June 2025. Subsequent updates, analyses, or scientific developments are not included. This report should be read alongside any associated and publicly available technical reports, datasets, and publications for full detail. This report does not provide scientific inferences, policy guidance or operational instructions beyond the project's defined scope and duration.

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Acknowledgement

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The RRAP partners acknowledge Aboriginal and Torres Strait Islander Peoples as the first marine scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on land and in sea Country. We pay our respects to Elders, past, present, and future, and their continuing culture, knowledge, beliefs, and spiritual connections to land and sea Country.

We specifically acknowledge and thank the following Traditional Owners of sea Country that this report relates to:

Location	**Traditional Owner Group**
Heron Island, One Tree Island and Gladstone	PCCC TUMRA, Gidarjil
Whitsundays	Ngaro
Broadhurst Reef and Davies Reef	Bindal and Manbarra

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1 Executive Summary

Coral reefs are facing critical threats due to anthropogenic climate change. Rising sea surface temperatures caused by increased atmospheric carbon dioxide (CO_2) levels have resulted in widespread coral bleaching events. Bleaching occurs when corals, under thermal stress, expel their symbiotic zooxanthellae, leading to a loss of colouration and energy production. Without these symbiotic algae, corals are more vulnerable to mortality and disease. These bleaching events are exacerbated by high levels of solar irradiance, especially during low-wind conditions (doldrums), when the water column remains stagnant and unable to cool through mixing.

The Reef Restoration and Adaptation Program (RRAP) Cooling and Shading Sub-program are investigating scalable and deployable technologies to mitigate the effects of excessive solar irradiance on the Great Barrier Reef (GBR). One of the promising technologies developed in this program is seawater fogging, which aims to reduce downwelling solar irradiance through the generation of seawater droplets. These droplets, dispersed in lower atmosphere, scatter sunlight and reduce the amount of solar energy reaching the reef surface. This report presents the key technical achievements, experimental findings, and potential applications of seawater fogging against the original research objectives set out in the project milestones. Fundamentally the research program sought to address two primary questions: 1) How much shading is needed during thermal bleaching events to impart a coral health or mortality benefit? 2) How much shading can be achieved and over how large an area using seawater fogging?

To gain insight into question one, a series of laboratory experiments were conducted to determine the impact of shading on bleaching onset, recovery, and coral mortality. Coral species commonly found on the GBR, such as *Acropora kenti* and *Acropora divaricata,* were subjected to heat stress in both shaded and unshaded conditions. Key physiological metrics, including photosynthetic efficiency, symbiont density, and bleaching severity, were measured to assess the potential biological response to shading.

Shaded corals maintained higher photosynthetic efficiency during thermal stress, suggesting that the reduction in light exposure helped alleviate photochemical damage to the symbiotic zooxanthellae. Furthermore, shaded corals exhibited higher levels of zooxanthellae retention compared to unshaded corals. Zooxanthellae density was measured using a hemocytometer, and shaded corals retained approximately 25% more symbionts than the control corals under heat stress conditions. Assessments of bleaching severity indicated that shading delayed the onset of bleaching by up to three-degree heating weeks. Shaded corals also exhibited less tissue damage and faster recovery once the thermal stress subsided.

To address the potential for creating an artificial sea fog the RRAP Cooling and Shading team have conducted two land tests of fogging equipment and five at-sea experiments. Using seawater atomisation technology to examine the ability of artificial seawater fog to create shade, the team conducted five years of laboratory testing of nozzle testing, modelling, and biological studies of coral response to shading. At-sea field trials were conducted at multiple locations along the GBR, including One Tree Island, Wallaby Reef and Fantome Island, to assess the ability to create artificially a low hanging seawater fog that provides shade. These trials were undertaken during real-world conditions, often during marine heatwaves, over multiple iterations of the seawater fogging technology. Initially the focus was on understanding what aerosol sizes would be produced by atomisation of seawater using ‘misting’ type impact pin nozzles and how prevailing atmospheric conditions influenced the dispersal of the humidified aerosol. Following basic proof-of-concept, field trials aimed to examine the shading characteristics of a single point source fogging plume to inform implementation modelling.

Field trials demonstrated that seawater fogging can be used to create shade over regions of reef downwind, with considerable variance in reductions in irradiance across the plume, which is to be expected when the fog is generated from a single point source. The system performed best under low-wind conditions (<3 m/s), where the fog plume remained concentrated over the target area. Higher wind speeds caused greater dispersion of the fog, reducing the concentration of droplets and the shading effect. Environmental factors such as relative humidity (RH) and temperature also influenced the performance of the system. In high-humidity conditions (>80%), evaporation of water from the droplets is minimised, promoting larger particle formation that provides more efficient shading.

The engineering development of seawater fogging technology progressed iteratively over the course of the project. Early systems were designed to provide basic proof-of-concept that impact pin seawater atomisation could produce dry sea salt aerosols targeted at a size of ~ 200 nm. This target was selected based on a typical boundary layer relative humidity of ~80% during summer. At this RH theory suggests that the equilibrium hydroscopic growth factor is ~ 2x the dry aerosol size, resulting in brine droplets of around 400 nm diameter, which is close to the optimal Mie light scattering per unit volume for this refractive index. Laboratory testing confirmed that MeeFog™ impact pin type water atomisation nozzles consistently produced dry sea salt particles across a spread of droplet sizes centred on the target. At 160 bar pressure, the nozzles achieve a particle size distribution with a median diameter of 200 nanometres (nm).

Over the course of the Project the fogging apparatus progressed through three major iterations. The initial concept fogging system was designed to test the basic principles of seawater fogging. This system was small scale using 100 MeeFog™ impaction pin nozzles but proved the ability to make suitably sized droplets through initial land and sea tests. A reduction in irradiance of up to 16% was measured on the plume centreline, but the low output system was not designed to achieve shading over usefully sized areas and was limited in coverage (less than one hectare).

The second generation of fogging apparatus was designed with sufficient output to explore the amount of shading which could result from a single fogging point source. This version featured 1,080 MeeFog™ nozzles arranged in six two-dimensional manifold arrays. The system was shown to be capable of generating shading levels of up to ~30% under low-wind doldrum type conditions. The third and most resent fogging system was designed as a self-contained portable unit, being the first prototype of a ‘deployable’ seawater fogging system. In contrast to previous research systems which required three phase power to operate, the high-pressure seawater pumps are directly driven by an onboard diesel engine. This configuration allows the units to be deployed on small manoeuvrable barges, providing flexibility in deployment and operation. The modular design allows for rapid deployment and repositioning of the system, with the goal of enabling targeted areas to be shaded during critical periods of high thermal stress.

The scattering efficiency of the fog can be quantified using the single scattering albedo (SSA) and the optical depth of the fog plume. The SSA measures the fraction of light that is scattered rather than absorbed by the droplets, with values close to one indicating efficient scattering. In field trials, the SSA of the fog plume was measured at approximately 0.9, indicating that most of the incident sunlight was scattered rather than absorbed by the fog plume. The optical depth of the fog plume, which represents the attenuation of light as it passes through the fog, was calculated using radiative transfer models. The models showed that an optical depth of 0.6 was sufficient to reduce irradiance by 30%. This was consistent with field measurements, where radiometers recorded reductions in irradiance ranging up to ~40%, depending on wind speed and humidity.

Seawater fogging technology has demonstrated potential as a short-term intervention to reduce solar irradiance on the Great Barrier Reef. However, further research and development are needed to optimise the system for broader deployment and long-term sustainability.

While our fogging system has successfully shaded areas of up to 13 hectares, future iterations of the system will need to be scaled up to protect larger sections of the GBR. This will require improvements in particle generation capacity, energy efficiency, and system deployment logistics. Increasing the number of modules and optimising the system’s performance and spraying strategy under different environmental conditions will be essential for scaling the technology to cover hundreds of hectares of reef.

In conclusion, the advancements made in fogging technology within the RRAP Cooling and Shading Sub-program highlight its potential as an intervention to mitigate coral bleaching caused by excessive solar irradiance. Field trials and modelling efforts have demonstrated that seawater fogging can effectively reduce light levels over coral reefs, particularly under low-wind conditions. At the same time, laboratory experiments have shown that even moderate shading can significantly delay bleaching and reduce coral mortality. However, species-specific responses and environmental variability emphasise the need for a cautious and adaptive approach to deployment. As the technology progresses, continued research and refinement of the engineering parameters and monitoring of the biological responses will be essential to ensure fogging strategies are optimised for real-world conditions and contribute meaningfully to coral reef resilience in the face of climate change.

Figure 1: Aerial view of marine fogging in the Great Barrier Reef 2023.

2 Background and Justification for the Research

Coral reefs are often described as the “rainforests of the sea,” due to their high biodiversity (Reaka-Kudla 1997). Despite covering less than 1% of the ocean floor (Spalding and Grenfell 1997), coral reefs are home to nearly a quarter of all marine species (Plaisance et al. 2011). They provide essential ecosystem services, including supporting fisheries (Newton et al. 2007), protecting coastlines from storm surges (Burke and Spalding 2022), and sustain tourism industries (Kenchington 1991). The Great Barrier Reef (GBR) contributes approximately $6 billion annually to the Australian economy (Deloitte Access Economics 2017).

Coral reefs are exceptionally sensitive to environmental stressors associated with climate change (Schoepf et al. 2023). Rising ocean temperatures, driven by anthropogenic climate change, have caused widespread coral bleaching across the globe. During marine heatwaves, elevated temperatures disrupt the delicate symbiotic relationship between corals and the photosynthetic algae (zooxanthellae) that live within their tissues. The algae provide energy to the corals through photosynthesis, and in return, the corals offer a protected environment. Under stress, corals expel their zooxanthellae, turning white, a phenomenon known as coral bleaching. Without their primary energy source, bleached corals can starve, become more susceptible to disease, and ultimately die if the stress persists.

While rising sea temperatures are the primary cause of bleaching, excessive solar irradiance also plays a significant role in exacerbating coral stress. During doldrum conditions, periods characterised by low wind and calm seas, solar radiation penetrates the water column without the cooling effect of water mixing, subjecting corals to further photochemical stress. This combination of high temperatures and intense light often accelerates the bleaching process. Therefore, reducing light exposure during periods of thermal stress could help mitigate coral bleaching and extend coral survival.

The idea of seawater fogging is based on the fundamental principle of light scattering (Harrison 2024). When radiative energy from the sun encounters a particle suspended in air, such as water droplets, the light interacts with the particles and is scattered in multiple directions. A plume of fine seawater droplets could scatter incoming solar radiation, thereby reducing the intensity of sunlight reaching the coral reefs. The objective is to reduce downwelling irradiance during periods of high thermal stress. This is particularly important during doldrums when wind-driven cooling is minimal, there is a rapid heat buildup in seawater temperatures, and maximum radiative (light) energy is reaching the corals (Richards et al. 2024). By forcing water through high-pressure nozzles, atomising it into droplets small enough to remain suspended in the air for extended periods, a seawater haze is produced. The amount of scattering depends on the size, composition, and concentration of the particles, as well as the wavelength of the light. Smaller particles scatter shorter wavelengths (blue light) more efficiently, while larger particles scatter longer wavelengths (red light).

The scattering of light by particles, specifically seawater droplets, is described by Mie theory, a set of equations that calculates how spherical particles interact with electromagnetic radiation. Mie theory is essential for understanding how the size and concentration of droplets affect the amount of sunlight scattered. In the context of seawater fogging, the effectiveness of the fogging system hinges on generating droplets at the correct size. Droplets need to be large enough to scatter light efficiently across the visible spectrum but not so large that they fall out of the air prematurely, reducing the shading effect. The salt content prevents droplets from fully evaporating, allowing them to stabilise at a humidity-dependent size for extended periods of time. It is also important to consider that the amount of water, and therefore power, required to generate sufficient droplet number concentrations rapidly increases with droplet diameter. For this reason, a dry diameter of approximately 200 nm was selected as an initial target size, aiming for a humidified droplet in equilibrium of around 400 nm diameter at an assumed typical relative humidity of 80%.

The primary goal of seawater fogging is to reduce the amount of solar irradiance reaching coral reefs, thereby alleviating photochemical stress during periods of thermal stress (Harrison 2024). The reduction in irradiance lowers the production of reactive oxygen species (ROS) within the coral's zooxanthellae, which in turn reduces the likelihood of bleaching.

Different coral species exhibit varying responses to light and temperature stressors, making it challenging to identify a universal shading level that protects corals uniformly during bleaching events (Ellis et al. 2024). Nonetheless, reducing irradiance during high-temperature episodes can be critical to alleviating coral stress. Laboratory experiments have shown that a 30% reduction in irradiance can delay the onset of bleaching by up to three degree heating weeks, depending on the coral species and local conditions (Butcherine et al. 2023). This delay provides a critical window for corals to survive through heatwaves, improving their chances of recovery once conditions stabilise. Corals subjected to shading exhibited higher levels of zooxanthellae retention, improved photosynthetic efficiency, and reduced tissue damage compared to unshaded controls (Butcherine et al. 2023).

Numerous studies have described the beneficial effect of managing excessive light on coral bleaching responses (Tagliafico et al. 2021). Although shading could benefit corals during periods of elevated bleaching risk, more information on the shading level and duration required to elicit responses is required. Many of the previous light impact studies were conducted at shading levels greater than 50%, which is expected to be technically difficult to achieve on the scales that the RRAP Cooling and Shading Sub-program is exploring. In addition to the shading level, considerations about how seawater fogging could be deployed need to account for variations in the distribution and frequency of favourable atmospheric conditions for fogging, such as intermittent, low-wind doldrum-like conditions.

This report summarises the iterative engineering efforts that advanced fogging technology from initial concept to prototypes suitable for on-reef experiments. It examines the effectiveness of these systems in shading reef environments, particularly during doldrum-like conditions when the risk of coral bleaching peaks. Details on the engineering development of fogging prototypes are presented, along with insights into system deployment and operation. Fieldwork results from various prototype systems are also presented, demonstrating the significant progress made in fogging engineering. The methodology, results, and analysis of laboratory tests conducted on different fogging nozzles are presented, focusing on determining the droplet concentration required to effectively shade corals in the Great Barrier Reef. A series of manipulative coral tank experiments were conducted to test the hypothesis that short periods of shading during peak bleaching risk (i.e. doldrum events) would be sufficient to reduce coral stress and mortality.

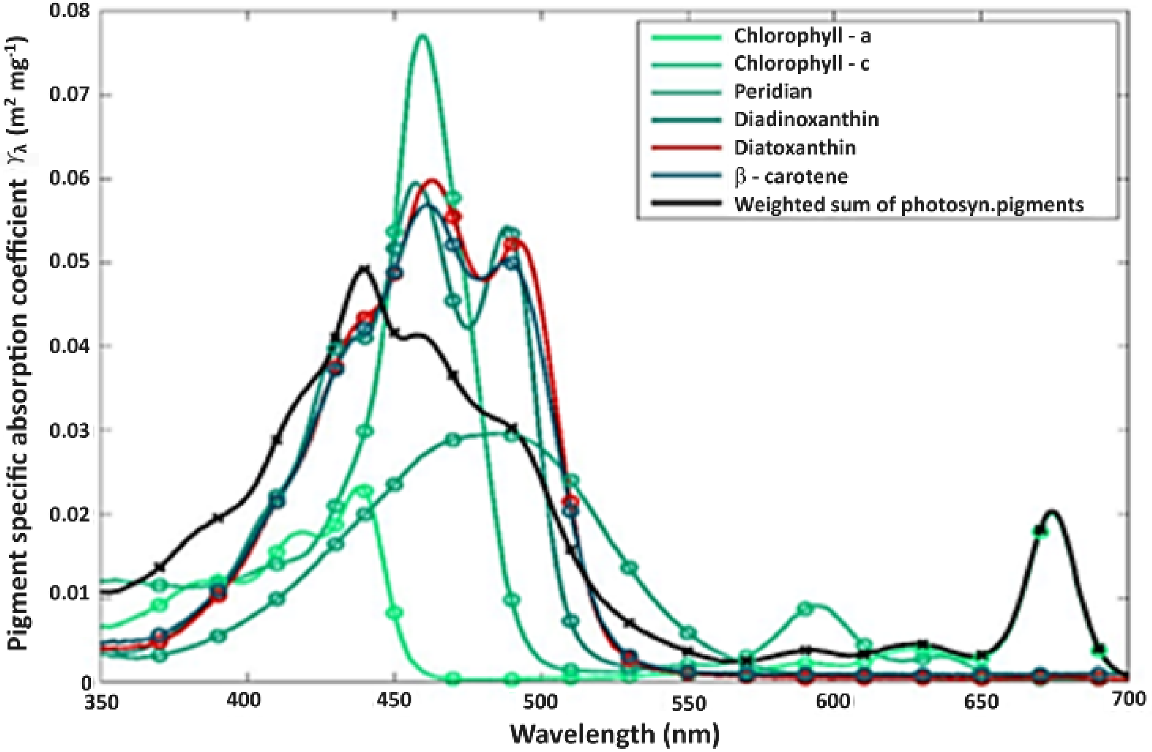
The physiological, biochemical, and physical responses of thermally stressed corals to varying light intensities and shading durations were assessed using a combination of established and novel methods. The results from these experiments have informed the engineering parameters of the Cooling and Shading fogging intervention and helped refine the CSIRO *e*Reefs coral sub-model.

3 Research Objectives and Key Findings

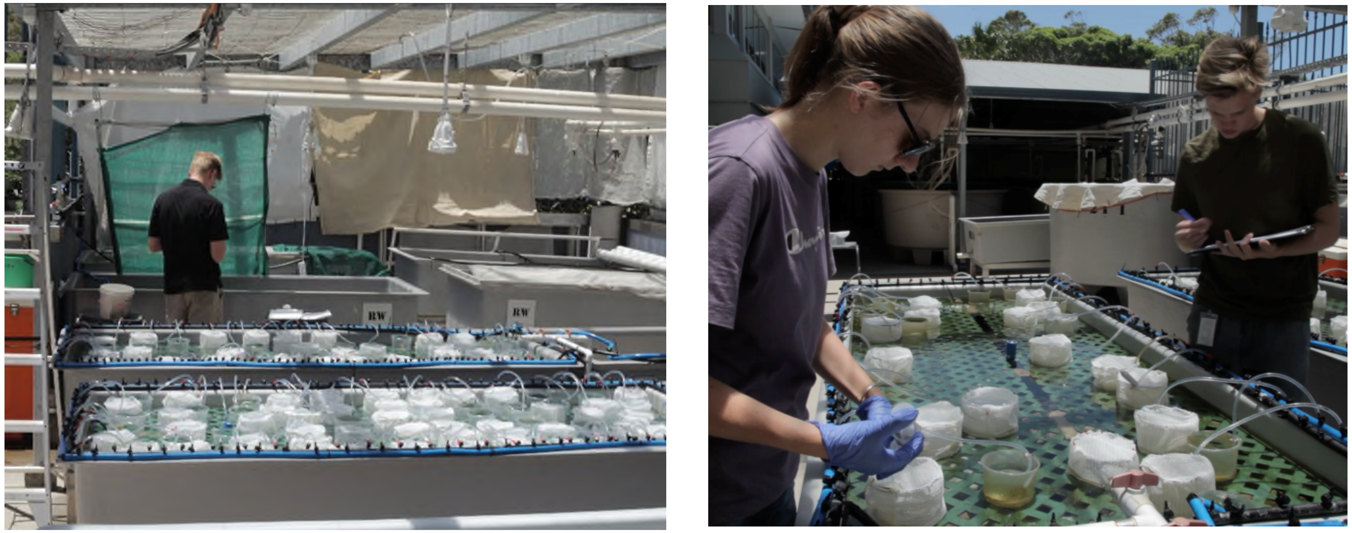
A current list of project outputs are listed on the RRAP website: gbrrestoration.org. Key research objectives and findings are detailed below.

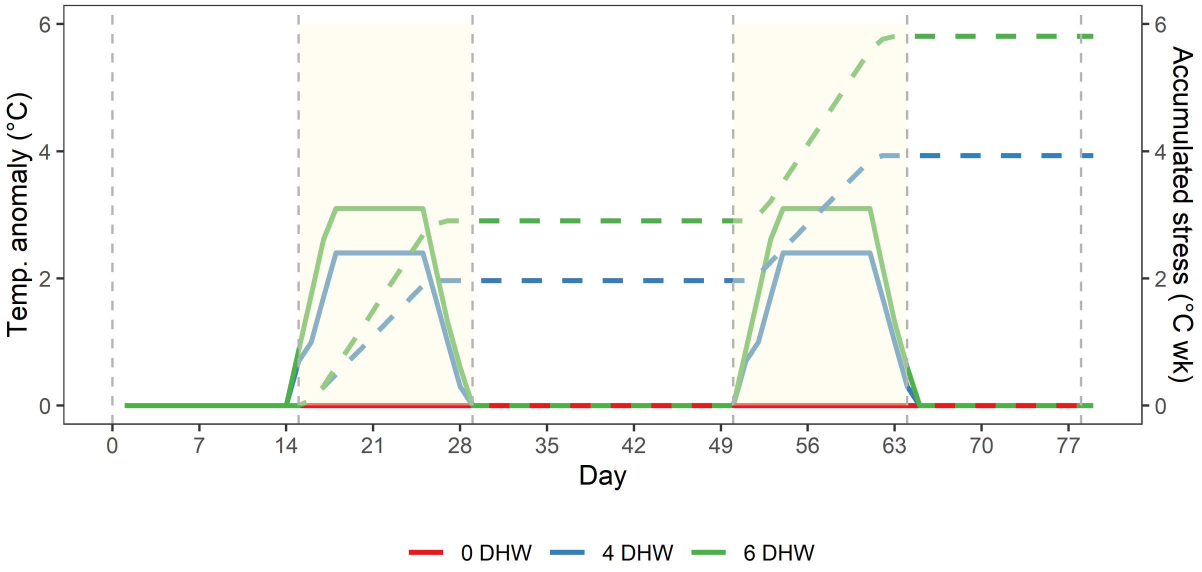
Table 1: Key findings of the Project aligned to the overarching and specific research questions for each sub-project.

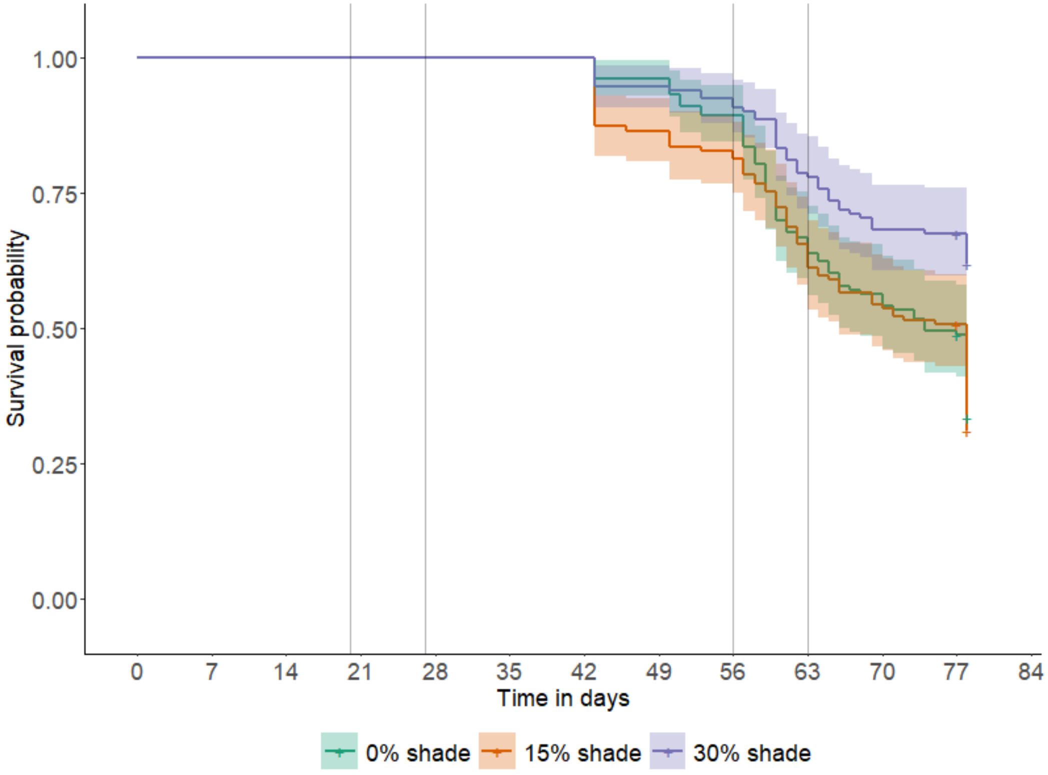
Objective		Key Findings and/or Outcomes
1. Conduct a feasibility study into the potential of using seawater fogging to shade and cool localised Reef environments.		
1 (a)	Identify the target wavelength of solar radiation to be reflected.	Different wavelength bands have distinct impacts on coral physiology. The visible light spectrum (400 - 700 nm) is essential for photosynthesis, but excessive exposure, can exceed the photosystem thresholds (Bouwmeester et al. 2023), causing the release of harmful reactive oxygen species (ROS) which can cause photosystem damage (Barber and Andersson 1992). High light irradiance coincident with exposure to elevated temperatures is believed to cause damage to both zooxanthellae and coral host tissues associated with enhanced ROS production under these combined stressors (Lesser and Farrell 2004). As well as being implicated in the above described processes, ultraviolet radiation (UVR) (280 - 400 nm) is known to cause direct deoxyribonucleic acid (DNA) damage and oxidative stress, which can also contribute to the severity of bleaching (Downie et al. 2024). Light in the UVR range can also cause bleaching under normal ocean temperatures, especially when the water clarity is high for extended periods, such as can occur with doldrum type conditions (Gleason and Wellington 1993). The impacts of UVR on corals have been reviewed by (Banaszak and Lesser 2009). Near-infrared (NIR) radiation (>700 nm) contributes to heating the water but is not believed to significantly affect coral photobiology. Based on the review of the literature (published in Tagliafico et al. 2022) we conclude that, generally under thermal stress conditions the primary target for light reduction should be to reduce the intensity of photosynthetically active radiation (PAR), i.e. sunlight with wavelengths between 400 - 700 nm. Light outside this range has lower intensity at sea level and undergoes greater attenuation in the water column. Nonetheless, attenuating light beyond the PAR range may still provide meaningful benefits. Ultraviolet radiation (UV, <400 nm) causes DNA damage in marine organisms, while infrared radiation (IR, >700 nm) contributes significantly to ocean heating. Therefore, although the target droplets should prioritise efficient scattering of PAR wavelengths, additional attenuation of UV and IR light should be considered. Therefore, broadband shading, covering the UV, visible light and near-infrared spectrum, specifically wavelengths from approximately 280 - 400 (UVR), through 400 - 700 nm (visible light) and up to 1,200 nm in the near-infrared is appropriate. Bespoke targeting of specific wavelengths may offer advantages for certain conditions of geography and environmental stress, such as enhanced shading in the UVR range for shallow reef environments under extended doldrum type conditions with high water clarity. The extent to which local shading at the physical scales achievable may be effective at reducing heat buildup and cooling shallow reef waters is unclear but warrants further investigation given the potential for reducing synergistic stressors.

Objective		Key Findings and/or Outcomes
1 (b)	Review and summarise the literature pertaining to the ability for shading to improve bleaching mortality outcomes, with consideration of multiple wavelength bands (e.g. visible, ultraviolet).	The potential of shading during thermal stress events to improve coral health outcomes was reviewed during this project and has been published in Tagliafico et al. (2022). The key wavelength bands to attenuate are UV-B (280 - 315 nm), UV-A (315 - 395 nm), the blue (450 - 485 nm) and cyan (485 - 500 nm) spectral bands since they are the wavelengths where the pigment specific absorption coefficients are the highest (Figure 1). These light bands can cause the most damage to thermally stressed coral via several mechanisms which are not yet fully described. Blue-green light saturates the photosynthetic systems (PSII) causing the creation of reactive oxidation species, while UV-B and UV-A causes DNA and protein damage and creates radicals. This can result in bleaching when coincident with anomalously high-water temperature" (Baker et al. *in-prep*).  *Figure 2: Key coral pigment absorption by wavelength.*

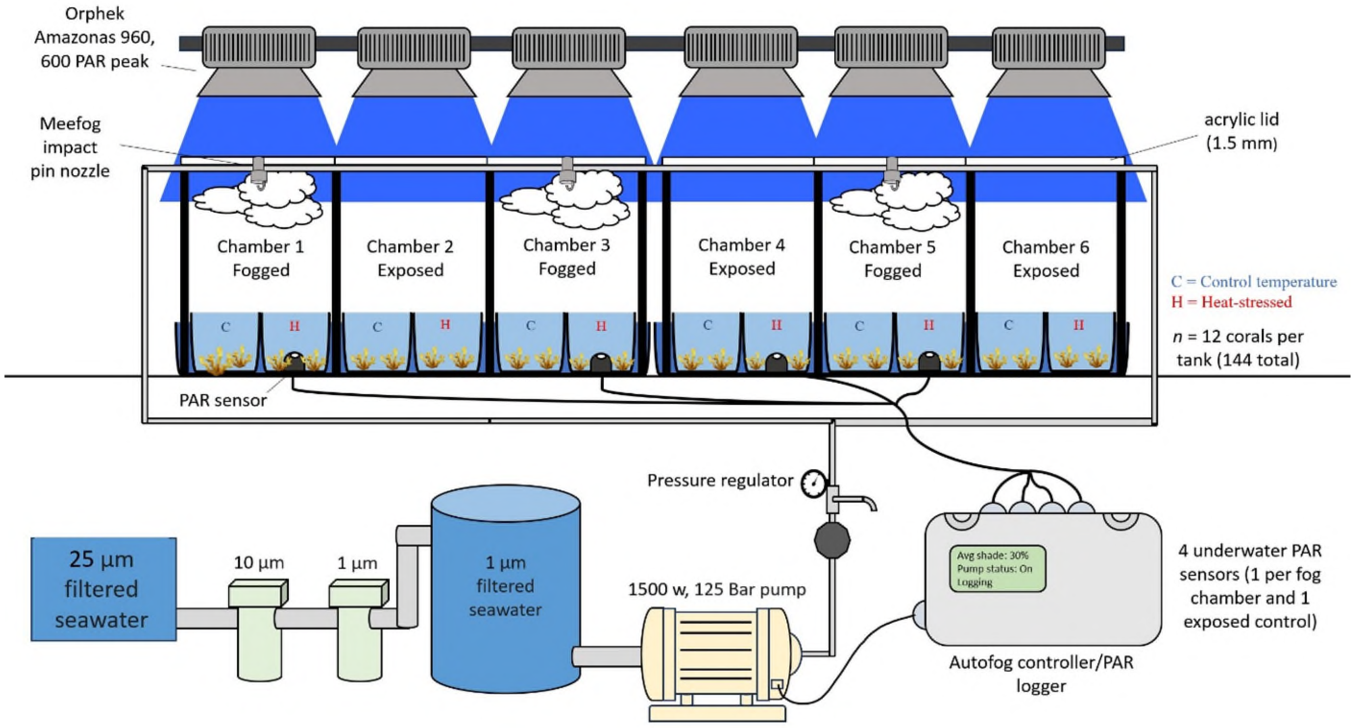
Objective		Key Findings and/or Outcomes
		Research on shading as a strategy to mitigate coral bleaching suggests that reducing solar radiation exposure can improve coral survival during thermal stress events. Shading interventions, including artificial structures, floating films, and cloud brightening, have been explored to lower light intensity and heat stress. Studies indicate that excessive solar radiation exacerbates bleaching by increasing the energy burden on symbiotic algae (zooxanthellae), leading to their expulsion from coral tissues. Shading can help maintain a more stable light environment, reducing oxidative stress and improving post-bleaching recovery rates. However, the effectiveness of shading varies based on factors such as coral species, local water movement, and shading duration.
1 (c)	Design and implement tank shading experiments to evaluate the capacity to improve mortality outcomes using plausible fogging scenarios. The tank shading experiments will extend previous in-situ and laboratory coral shading studies by considering the co-factors of intensity of light reduction and duration. Further experiments will be further extended by including treatments where the shading is provided by actual nozzle fogging systems selected for use in the fogging prototype systems.	A series of acute and chronic manipulative experiments were designed to test the response of corals to shading during periods of water temperatures that promote coral bleaching. A total of 7 experiments were carried out at the aquaria facilities at the National Marine Science Centre, Southern Cross University (Figure 2), and SeaSim at the Australian Institute of Marine Science. **Investigating shading duration** Initial investigations tested the shading duration required to affect the coral bleaching response. The study found that elevated water temperatures were the primary cause of coral bleaching (Butcherine et al. 2023; Ellis et al. 2024). However, shading for as little as four hours significantly reduced bleaching, and the effects were better as shading duration increased. Shading resulted in more colour retention, maintained higher chlorophyll-a levels, and showed delayed declines in photosynthetic efficiency (Butcherine et al. 2023). These benefits were most evident at lower temperatures and diminished under prolonged heat stress. The findings suggest that four hours of shading or more can help mitigate heat stress in some coral species. Shading reduced coral stress and helped preserve photosynthetic function, indicating that fogging or other shading techniques could be a viable short-term strategy to support coral survival during marine heatwaves.

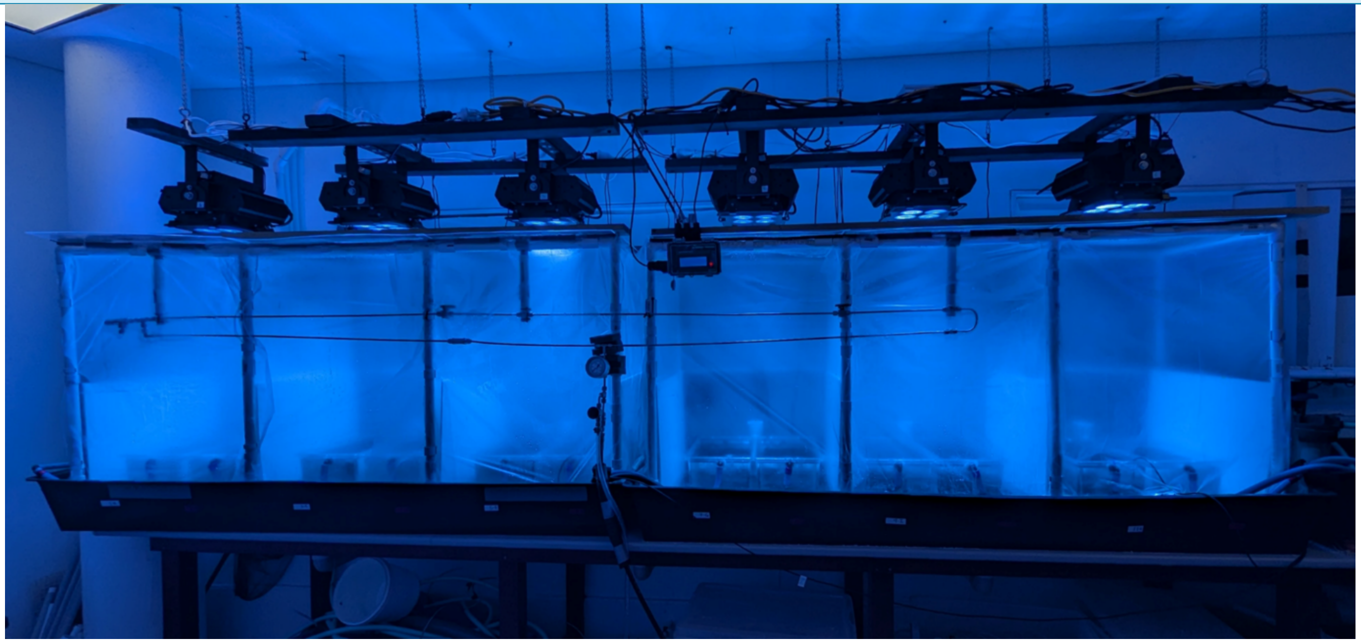
Objective		Key Findings and/or Outcomes
		 *Figure 3: (Left) Outdoor experimental tanks at the National Marine Science Centre. (Right) Researchers monitor and feed corals during outdoor experimentation, where removable shade covers are used to control lighting for the corals.* High variation was detected in bleaching responses among and within species. While variation is inherent in any biological system, the positive and negative response of *Acropora kenti* to light and shade suggests a complex relationship between the coral and zooxanthellae. Zooxanthellae composition significantly affects photochemical and physiological responses (Coles and Brown 2003), and the variation detected here could reflect those differences. Shuffling and switching zooxanthellae in response to environmental stressors can reduce bleaching stress (Brown and Dunne 2015). The final bleaching response is the result of each mitigation strategy, the environmental stressors during the event and the physiological state of the coral. **Doldrum shading experiment** The primary limitation of effective fogging on the Great Barrier Reef is the occurrence of low-wind doldrums conditions. To better understand coral responses under these conditions, an 11-week chronic stress laboratory experiment was conducted emulating a typical bleaching summer. Using *Acropora kenti*, we tested the combined effects of heat and light stress at the National Sea Simulator at the Australian Institute of Marine Science. The experiment included three levels of shading (0, 15, and 30%), and three temperature scenarios (representing 0, 4, and 6 degree heating weeks) (Figure 4). Light and temperature were

Objective	Key Findings and/or Outcomes
	adjusted to mimic real-world doldrum-like events based on field data, allowing us to assess coral resilience under these stressors.  *Figure 4: Water temperature anomaly (°C) and accumulated bleaching stress (degree heating week, DHW) for each doldrum event over the simulated bleaching summer. Dashed vertical lines designate the sampling events at the start and end of doldrum conditions (shaded).* This study found that both shading and temperature significantly influenced the health of *Acropora kenti*. Among these, temperature had the strongest impact on coral bleaching. As temperature stress increased, the coral antioxidant enzyme activity increased (Ellis et al. 2025). However, these responses were unable to mitigate lipid oxidation in the coral. Interestingly, providing shade helped reduce this stress. Corals under more shade had lower levels of enzyme activity and less membrane damage, suggesting they were less affected by harmful reactive oxygen species.

Objective	**Key Findings and/or Outcomes**
	Marked physiological changes between the moderate and high stress treatments suggest a shift in their internal processes. Suggesting that corals may have switched from relying on sunlight for energy (autotrophy) to feeding on external sources (heterotrophy), possibly due to a loss of their symbiotic algae. Importantly, under high stress conditions, increased shading lowered mortality risk in corals that were already bleached, showing that shading may also help coral recovery from thermal bleaching events (Butcherine et al. *in prep*).  *Figure 5: Survival probability (Cox Proportional Hazard Model) curves with 95% C.I. for Acropora kenti held at 0, 15, or 30% shade during two doldrum periods after accruing 6 DHW. Vertical lines mark doldrum periods.*

Objective		Key Findings and/or Outcomes
		Modelling coral responses to shade and temperature The eReefs coral sub-model could differentiate bleaching outcomes according to multiple stressors. Using inputs of light intensity, water temperature, and nutrient concentration, the model's explanatory power was tested using data obtained from *Acropora divaricata* subjected to either 30% shade or unshaded conditions. The coral bleaching model effectively predicted when bleaching and photochemical stress would begin under elevated water temperatures (Ellis et al. 2024). These predictions closely matched experimental observations, particularly in scenarios with higher temperatures and no shading. While the model accurately forecasted the severity of bleaching, some photochemical indicators, such as maximum quantum yield, may require refinement to improve predictive reliability. Overall, the model's alignment with observed outcomes supports its potential as a tool for anticipating coral stress under climate change conditions. **Small-scale fogging experiments** The initial experiments were performed using either shade cloth or manipulating lighting. We designed and manufactured a small-scale fogging system, the FOG-CUBE Mini (Fogging Output Generator – Compact unit for Bleaching Events), to emulate the shading potential of the proof-of-concept fogging system. The FOG-CUBE Mini supports up to eight nozzles, which are mounted individually in enclosed chambers. This system is a fully autonomous fog generator that is programmed to control shading levels and water temperature. The FOG-CUBE Mini system was installed at the National Marine Science Centre, Southern Cross University (Figure 6).

Objective	Key Findings and/or Outcomes
	 *Figure 6: Schematic of the FOG-CUBE Mini system using the same nozzle technology as the proof-of-concept fogging system. Filtered seawater is sourced from an onsite flow-through seawater system.* Using the FOG-CUBE Mini, coral bleaching and recovery responses of *Pocillopora meandrina, Pocillopora damicornis,* and *Acropora hyacinthus* were tested using a 25% shading level under bleaching conditions. These experiments have only just concluded, and the final results are not yet available; however, preliminary results suggest that fogging improved symbiont retention and reduced bleaching stress markers (Hendrickson et al. *in-prep*).

Objective	Key Findings and/or Outcomes
	 *Figure 7: Coral light stress experiment using the FOG-CUBE Mini at the National Marine Science Centre, Southern Cross University.* **Project Contribution** The coral tank experiments have delivered shading intensity and duration targets for the fogging intervention. • Fogging deployments should aim to decrease downwelling irradiance at the water surface by at least 15%. General reductions in physiological and photochemical stress markers result in less colour loss. Increased shading can further reduce bleaching stress and mortality risk, where the shading level is increased to 30%. At this same shading level, coral mortality risk is significantly reduced even after bleaching. • Fogging deployment should attempt to shade for at least four hours per day when the correct conditions exist. Intermittent shading can alter the physiological state and delay the onset of bleaching in some thermally stressed corals.

Objective		Key Findings and/or Outcomes
		Temperature was generally the most significant factor affecting colour loss, photochemical decline, and mortality. Shading benefited thermally stressed corals by reducing bleaching symptoms as thermal stress increases for some species (Butcherine et al. 2023; Ellis et al. 2024). Intermittent shading of corals for four hours around solar noon was found to delay bleaching responses in thermally stressed corals (Butcherine et al. 2023). While shading may delay the onset of bleaching and reduce bleaching and mortality during moderate-stress events, its efficacy diminishes under higher levels of thermal stress. Shading corals during doldrum-like events under emulated bleaching conditions delayed pigmentation loss. Importantly, under high thermal stress, increased shading can lower mortality risk in already bleached corals. High variation was detected in bleaching responses among and within species. While the varied responses can reflect the zooxanthellae composition of the specific coral, the shading response in the doldrum experiment suggests that additional factors, such as nutritional state, contribute to bleaching responses. The coral tank experiments have delivered shading intensity and duration targets for the fogging intervention. • Fogging deployments should aim to decrease downwelling irradiance at the water surface by at least 15%. General reductions in physiological and photochemical stress markers result in less colour loss. Increased shading can further reduce bleaching stress and mortality risk, where the shading level is increased to 30%. At this same shading level, coral mortality risk is significantly reduced even after bleaching. • Fogging deployment should attempt to shade for at least four hours per day centred on solar noon when the correct conditions exist. Intermittent shading can alter the physiological state and delay the onset of bleaching in some thermally stressed corals.
1 (d)	Identify the target equilibrium droplet diameter to maximise the aerosol-radiation interactions at the targeted wavelength/s. The nozzle should be designed to emit larger wet droplets that will shrink through evaporation to quickly reach equilibrium with the surrounding high relative humidity GBR atmosphere.	Investigation of practically viable nozzle technologies indicates that equilibrium droplet diameters between 0.15 to 2.7 micromeres (µm) can be achieved, influenced by the nozzle design, sprayer operating conditions, and the ambient humidity. Mie extinction calculations were performed for a selection of droplet diameters within this range, examining their capacity to scatter light for wavelengths between 200 – 1000 nm. Here, the relative intensity of each wavelength has been considered, as it reaches the ocean surface, weighting PAR wavelengths more heavily than IR or UV.

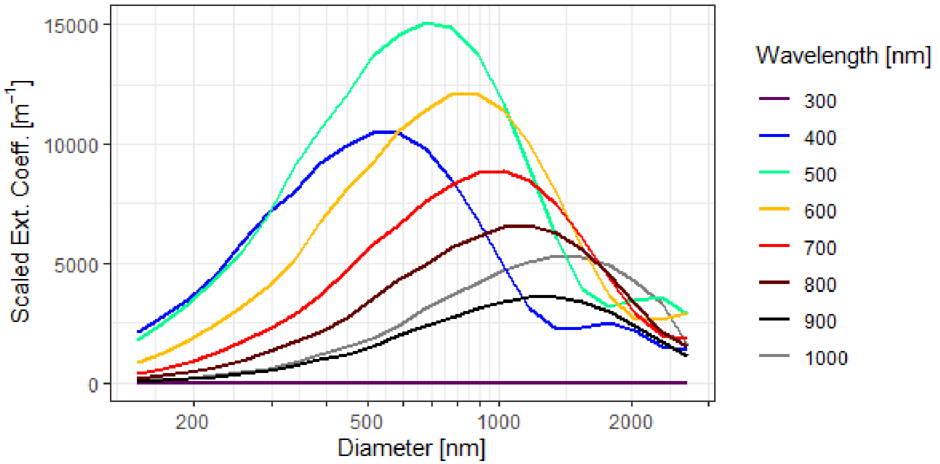
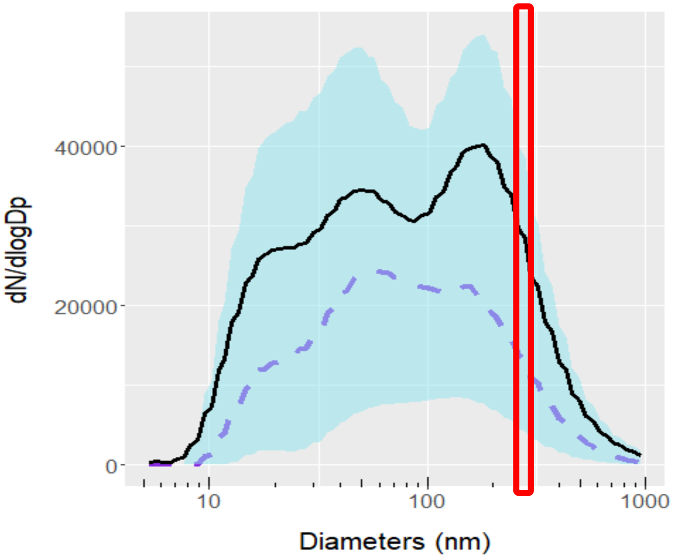


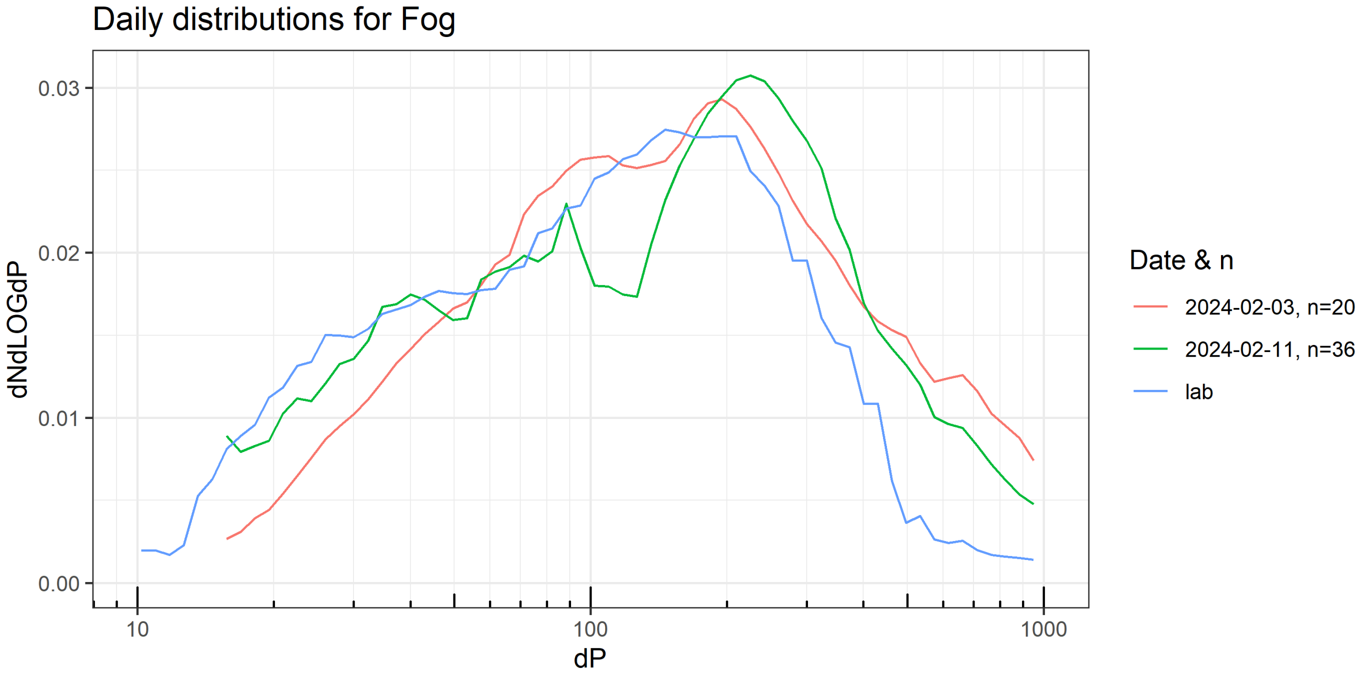
Figure 8: Size-dependent light scattering efficiency of sea water droplets scaled by the relative intensity of the solar spectrum at each wavelength.

At 80% relative humidity (RH), PAR wavelengths are most efficiently scattered by droplets with equilibrium diameters between 0.5 and 1 µm. This size range is also moderately effective for attenuating IR wavelengths up to 1 µm. Conversely, UV light is more sensitive to droplet diameter, with droplets <400 nm providing improved UV extinction but at the cost of lower efficiency across the rest of the spectrum. Changes in relative humidity do not significantly affect these findings, within the range typically observed over the Great Barrier Reef.

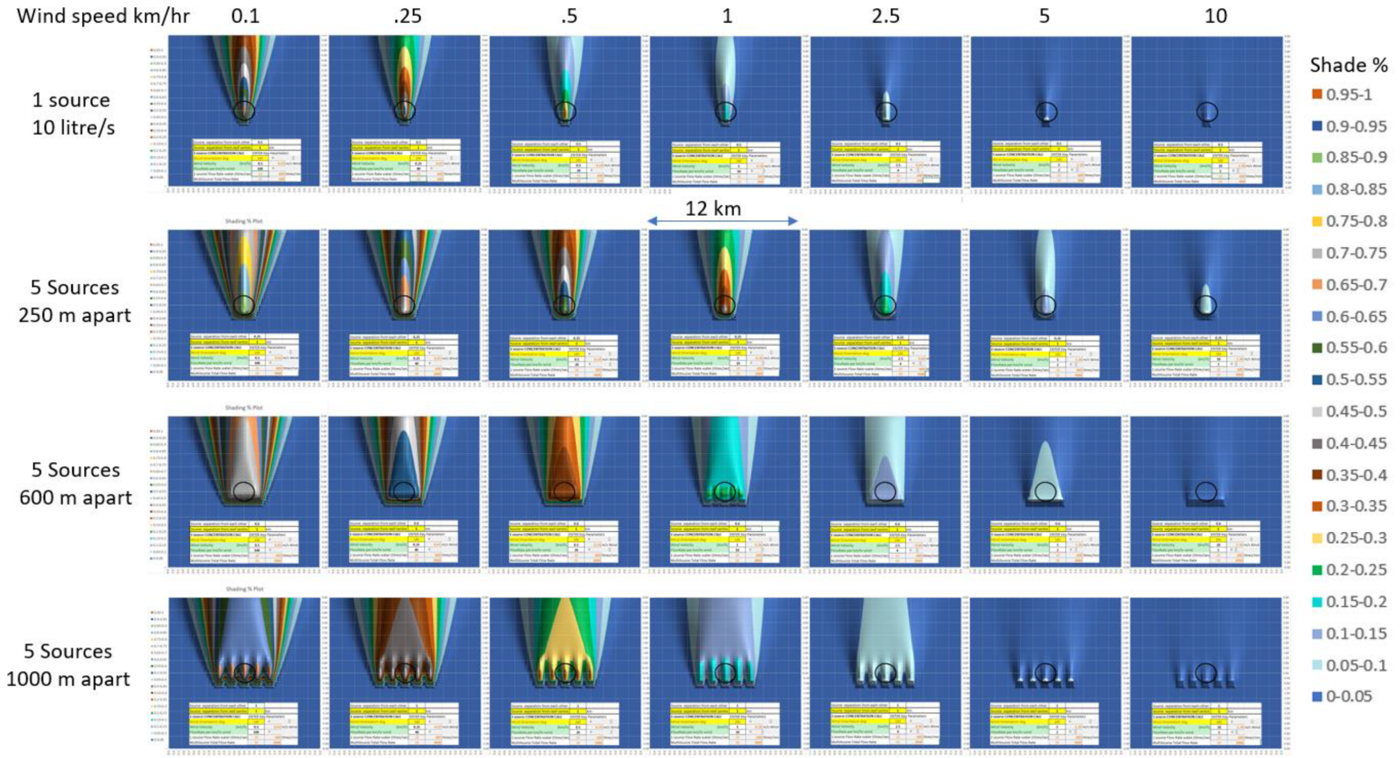
In addition to the scattering efficiency, the atmospheric lifetime of the droplets must also be considered. It is practically impossible to constrain all droplets to a single, uniform size; the actual size distribution depends on the spray generation method and interactions between the sprayed droplets and the environment as well as with each other. Larger droplets lead to several drawbacks: they provide less surface area per unit of liquid volume, suffer greater losses from gravitational settling and can scavenge other droplets through collision and coalescence. These effects reduce the overall shading efficiency of the plume and the energy efficiency of the spraying system.

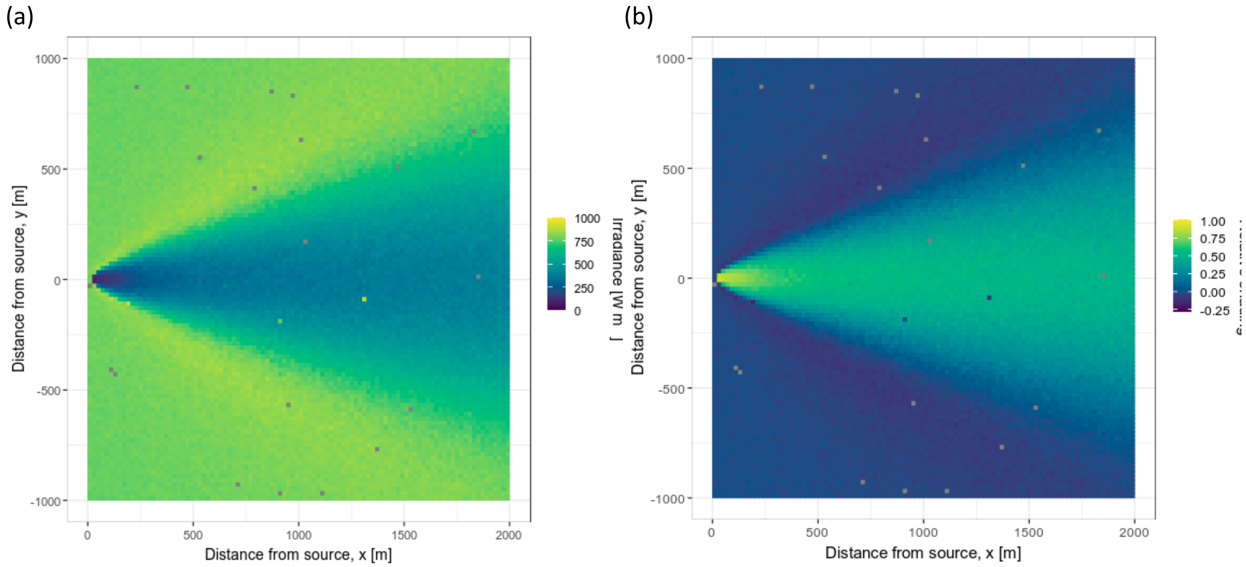
To minimise these losses and optimise performance, it is recommended to target smaller sizes. As sprayed seawater droplet size increases the scattering per unit volume approaches a maximum and then rapidly decreases. This is despite the total light scattering from the droplet continuing to increase. Given that the energy required for water atomisation is a function of pressure and volume of water atomised this indicates that there is an ideal droplet size to achieve maximum shading for a given

Objective	Key Findings and/or Outcomes
	amount of energy. The equilibrium size of a droplet in air containing sea salt is set by the ambient humidity. Accordingly, the target droplet size of 400-500 nm diameter results in an equivalent dry aerosol size target of approximately 200 nm. The dry diameter of 200 nm was determined assuming a relative humidity of ~80% being a typical summertime value over the GBR. According to Kolher theory, at 80% RH, in equilibrium the droplet would have a diameter of ~400 nm. This implies a sprayed droplet size of ~800 nm exiting the nozzle. This droplet size is large enough to scatter visible light efficiently, particularly in the blue and green portions of the spectrum, while also being small enough to remain suspended in the air for a considerable time under typical environmental conditions. Our field trials of these prototypes have explored fogging technology concepts aimed at shading single reefs on the Great Barrier Reef in Australia. Preliminary results from these trials indicate that prototypes employing impaction pin nozzle technology can generate a sufficient number of sub-micron seawater droplets to form a fog plume with the desired light scattering properties. The sprayed droplets, once dried, produce a modal dry aerosol size of ~200 nm, which is potentially suitable for shading coral reef sites, particularly under low wind conditions. Considering logistical constraints, fogging is ideally suited for rapid response, short-term applications, over regions similar in size to individual coral reefs. In such context, it can complement localised restoration activities from other RRAP themes or target high priority sites to reduce coral mortality.  *Figure 9: Measured size distribution of an early non-optimised prototype fogging plume. Showing the target size in red.*

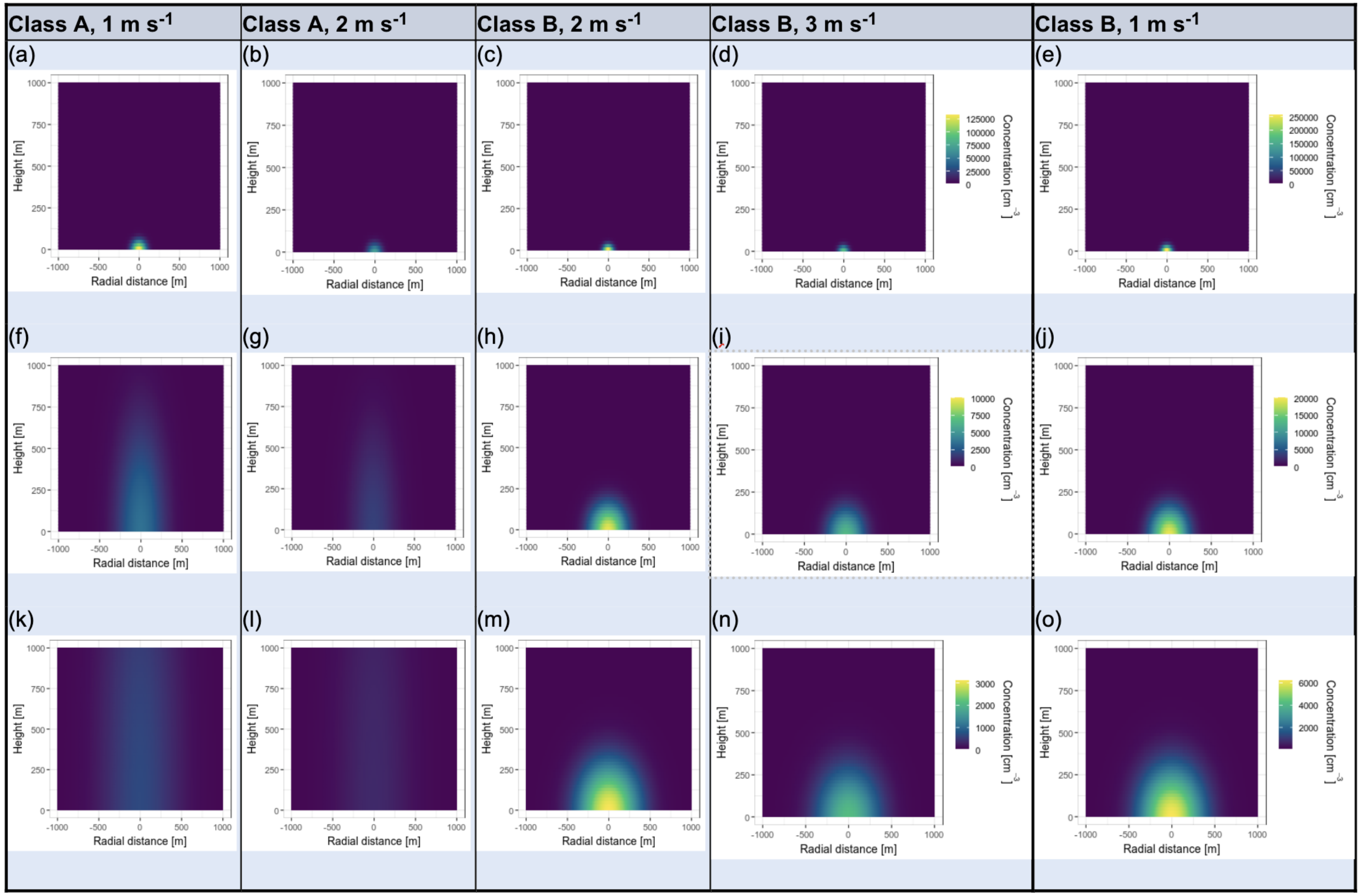
Objective		Key Findings and/or Outcomes
		 *Figure 10: Fogging size distributions measured from later iterations of the Cooling and Shading seawater fogging plant once nozzles and operating conditions were adjusted to target the 200 nm dry aerosol diameter target.*
1 (e)	Develop preliminary scenarios of logistics for achieving fogging at a target reef (e.g. using multiple mobile vessels, fixed stations, or a combination while factoring in the wind climate, likely plume characteristics, and priority reef site dimensions). Estimate the required droplet emission rate under these different fogging scenarios	Achieving seawater fogging at a target reef requires strategic deployment of fogging systems based on local environmental conditions, including prevailing winds, target area dimensions, and dispersion dynamics. Three preliminary logistical scenarios have been considered: 1. **Mobile Vessel-Based Fogging**: Multiple vessels equipped with high-pressure seawater atomisers could be deployed to generate a localised fogging effect over priority reef areas. This approach provides flexibility to target different sites as needed and adjust position to remain upwind of the target area. 2. **Fixed Station Fogging**: Permanent or semi-permanent fogging stations, such as floating platforms or barges, could continuously release seawater fog in strategic locations. These stations could be positioned to optimise fogging dispersion with prevailing winds. This approach is less flexible than mobile stations but may be lower cost.

Objective	Key Findings and/or Outcomes
	3. **Hybrid Approach (Mobile and Fixed Systems)**: A combination of fixed stations for baseline fogging and mobile vessels for adaptive deployment could offer both stability and flexibility. The fixed stations would maintain continuous shading, while mobile units could respond dynamically to changing conditions. Based on the experiences gained during the proof-of-concept field research undertaken during this project it is apparent that in all but unique situations, seawater fogging is best achieved by mobile fogging stations that can respond to fluctuations in wind direction and plume behaviour. Mobile platforms have several other advantages including: 1. Flexibility in deployment. Mobile systems can be directed to reefs or target areas experiencing thermal stress or where thermal stress is predicted. 2. Lower environmental footprint. Mobile systems do not require permanent seabed anchoring, pilings, or structures, which can damage benthic habitats and may need frequent re-location. 3. Lower capital and operating expenses. The portable fogging systems developed by the RRAP Cooling and Shading Sub-program can be deployed on existing maritime infrastructure (research / tourism / private vessels, or barges). Production of a sufficient optical thickness of fog to reflect and scatter incoming solar radiation depends on achieving a required droplet emission rate with respect to atmospheric conditions, droplet size spectra produced, and desired level of shading. To gain an estimate of the required droplet production rate a simple two-dimensional Gaussian Plume Model was used to understand how some of the key parameters will influence the feasibility of fogging at adequate shade levels: aerosol size, volume of water to be pumped, and wind speed. The results of this modelling indicated that a flow rate of at least 7.5 litres per second was required to produce 30% shading at distances of around one kilometre downwind of the sprayer. These levels of shading were achieved across a range of droplet sizes equivalent to dry salt aerosols of 02 – 0.4 µm, consistent with theoretical projections of a droplet size that gives optimum efficiency for a given atmospheric relative humidity condition. The midpoint of this range corresponds to production rate of approximately 8 x 1015 droplets per second assuming monomodal droplets. It should be noted that this modelling approach gives the time-integrated values for plume dispersion and shading, whereas at any given time the instantaneous plume dispersion is much less and the instantaneous shading higher. These results can be thought of as the time averaged production rate required to create a time-averaged area consistently above 30% shade. To increase the area subjected to time-averaged values of shade above 30% multiple spraying sources can be positioned so that their plumes superimpose. The results of such an experiment using the 2D Gaussian Plume Model are presented in Figure 11. In these modelling scenarios a seawater flow rate of 10 $l\ s^{-1}$ is assumed which is significantly higher than the current fogging prototypes, equating to a droplet number production rate of $\sim 10^{16}$ droplets per second. Lower production rates will have similar dispersion but produce lower values of time-averaged shade.

Objective		Key Findings and/or Outcomes
		 *Figure 11: Seawater fogging plume shading predictions by the simple 2D Gaussian model. Results are shown for multiple sources, crosswind spacing, and wind speeds. A flow rate of 10 l s^{-1} is assumed in all cases.*
1 (f)	Identify initial constraints for the implementation of fogging interventions by: modelling shortwave solar radiation scattering over reef sections to estimate the required droplet concentration and fog plume profile to achieve the desired shading; and plume	To identify initial constraints for implementing seawater fogging interventions, the Gaussian dispersion model described above was implemented to estimate the horizontal and vertical spread of the fog plume and to map resulting droplet concentrations under doldrums-like weather patterns. Simulations considered both calm, sunny days with very low wind speeds between 1 – 2 m s^{-1} and strong atmospheric convection, as well as more atmospherically stable conditions with reduced convection associated with wind speeds of up to 3 m/s. The Gaussian model provides an estimate of the longer-term average plume extent and droplet concentrations, while neglecting short-term spatial and temporal variations in wind direction or wind speed. Droplet emission rates ranging from 5×10^{13} s^{-1} (representing the proposed output of the initial proof of concept fog generator) up to 10^{16} s^{-1} (representing ambitious future technology improvement) were assessed.

Objective	Key Findings and/or Outcomes
dispersion modelling to establish the required emission rate to achieve the target droplet concentration over the reef.	**3D Radiative Transfer Modelling** The *htrdr* radiative transfer model was used to simulate light scattering by fog droplets, based on Mie theory. This model accounts for full three-dimensional interactions with fog, air, and the ocean surface. Outputs from the dispersion model, including spatial distributions of droplet number concentrations and corresponding meteorological conditions, were used as inputs. Simulations covered relative humidities between 60 – 90% RH, corresponding to mean droplet sizes between 500 – 670 nm, consistent with earlier recommendations from the Mie scattering model. All simulations assumed clear-sky conditions with the sun positioned at its zenith, avoiding any dependence on plume orientation or solar angle.  *Figure 12 Examples of (a) the simulated light intensity flux at sea level during plume production and (b) the corresponding shading produced by the plume, for wavelengths between 200 and 1000 nm and droplet production rates of 1015 s-1, at 70%RH, PGT Class A and wind speeds of 1 ms-1. Grey pixels represent outliers produced through the Monte Carlo simulation.* **Key Findings** The combined modelling results showed that under favourable conditions (1 m/s wind, 70% RH, Figure 11), a mid-range droplet production rate of 10^{15} s^{-1} could produce at least 15% shading across 2.7 km², or 30% shading across 1.9 km², within 3 km downwind from the generator. Higher humidity improved both the shading intensity and wider area of effective shading.

Objective		Key Findings and/or Outcomes
		Conversely, increased wind speeds and greater atmospheric stability reduced shading effectiveness, due to increased plume dilution, and reduced the lateral width of the shaded area. Importantly, the modelling indicates that a minimum production rate of at least 10^{14} droplets per second is required to achieve meaningful time averaged shading levels of up to 15%. Higher production rates are recommended to achieve 30% shading and to counteract potential reductions in performance caused by sustained shifts in wind direction requiring repositioning of the fogging vessels which are not accounted for in the model. Lower than typical relative humidity, or suboptimal alignment between the plume and solar angle can also decrease the time-averaged level of shade achieved.

Objective	Key Findings and/or Outcomes
	 *Figure 13: Modelling of the fogging plume profile showing cross-sectional plume concentrations at axial distances of (a-e) 250, (f-j) 1000 and (k-o) 1750 m from the source, for each of the simulated PGT stability classes and wind speeds. Note the change in scales for each of the Class B 1 m* s^{-1} *profiles. A droplet production rate of* 10^{15} s^{-1} *was used in all cases.*

<table>
<tr><th colspan="2">Objective</th><th>Key Findings and/or Outcomes</th></tr>
<tr><td>1 (g)</td><td>Determine if fogging could alleviate bleaching stress, and reduce coral mortality, and build a preliminary fogging intervention deployment strategy.</td><td>Feasibility of seawater fogging for coral bleaching mitigation
Shading coral reefs to reduce light stress has been identified as a technique to reduce coral bleaching. However, cost-effectively deploying shading materials over entire individual reefs or even larger areas is very challenging technically and economically. This constraint provided the impetus to investigate artificial seawater fog as a scalable technology that can quickly, and cost effectively deliver shading over areas of larger scale that can significantly reduce solar radiation stress on corals. The RRAP Cooling and Shading Sub-program field trials successfully produced a seawater fog over an area of tens of hectares. Fogging during doldrum conditions to mitigate coral bleaching and mortality appears technically feasible as an intervention.

<i>Figure 14: The electric proof-of-concept saltwater fogger operating from the research vessel in 2023 near Heron Island.</i></td></tr>
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Objective		Key Findings and/or Outcomes
		Other sections of this report present the literature review and work to determine the best approach in terms of target wavelengths, droplet diameter, and light attenuation. Also considered is potential light attenuation impact on corals, wind climatology, plume modelling/emission targets, fogging implementation scenarios and the potential for thermal impacts to the water column. Research in this program has highlighted the link between doldrum conditions when winds speeds drop below 3 ms^{-1} and clear skies cause the water to warm, thermally stratify, and become clearer allowing light to penetrate deeply into the water column and mass bleaching events on the GBR (Richards et al. 2024). These doldrum conditions are the exact conditions where engineering research has determined that shading by fogging will be most effective. Coral bleaching literature strongly suggests (Tagliafico et al. 2022), and results from the numerous coral tank experiments conducted during this project indicate, that shading up to 30% for four to twelve hours a day is beneficial to corals and delays the onset of bleaching up to 3.1 Degree Heating Weeks or more (Butcherine et al. 2023), but the bleaching response can vary by coral species (Ellis et al. 2024). The team has made considerable inroads improving and validating coral physiological models to adequately represent the dual stressors of light and excessive temperature on corals and thus to better consider the potential benefits of shading (Ellis et al. 2025). After determining that both UV and visible light should be shaded to reduce damage to corals, optical modelling indicated that seawater aerosol particles around 300nm dry diameter are the optimum for scattering the desired wavelengths. Both simple 2D Gaussian modelling and more sophisticated 3D modelling indicate that seawater fog systems spraying ~10 litre s^{-l} or 10^{15} – 10^{16} droplets per second of the right size distribution around 300nm dry size can provide up to 30+ % shading over two to three square kilometres in the doldrum low wind conditions. Further model refinement and validation will improve these estimates.

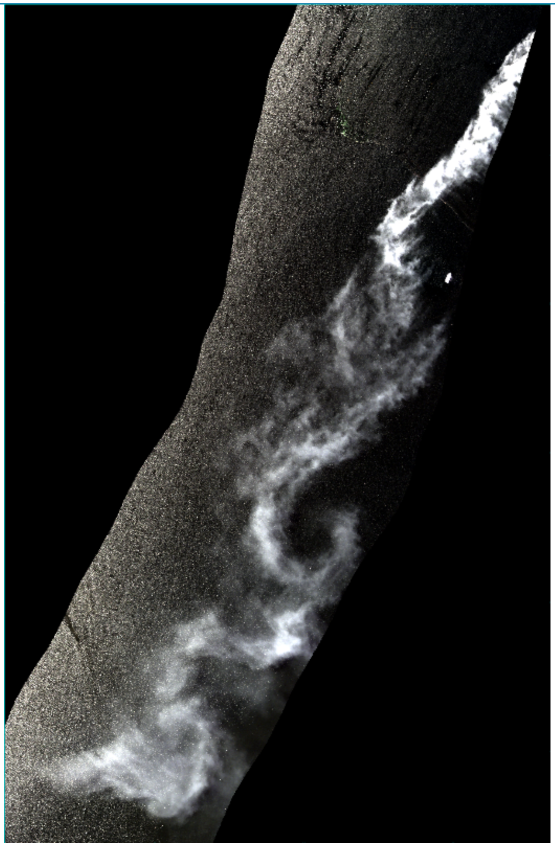


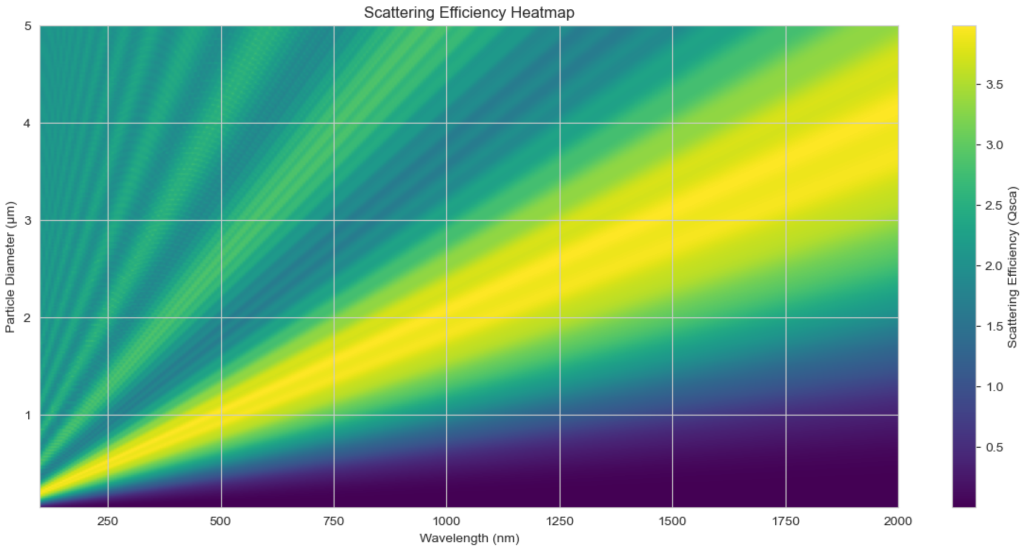
Figure 15: Example plot of albedo of a fogging plume captured by the airborne hyperspectral imager on the SCU aircraft. The total fog coverage in this capture was 22 hectares.

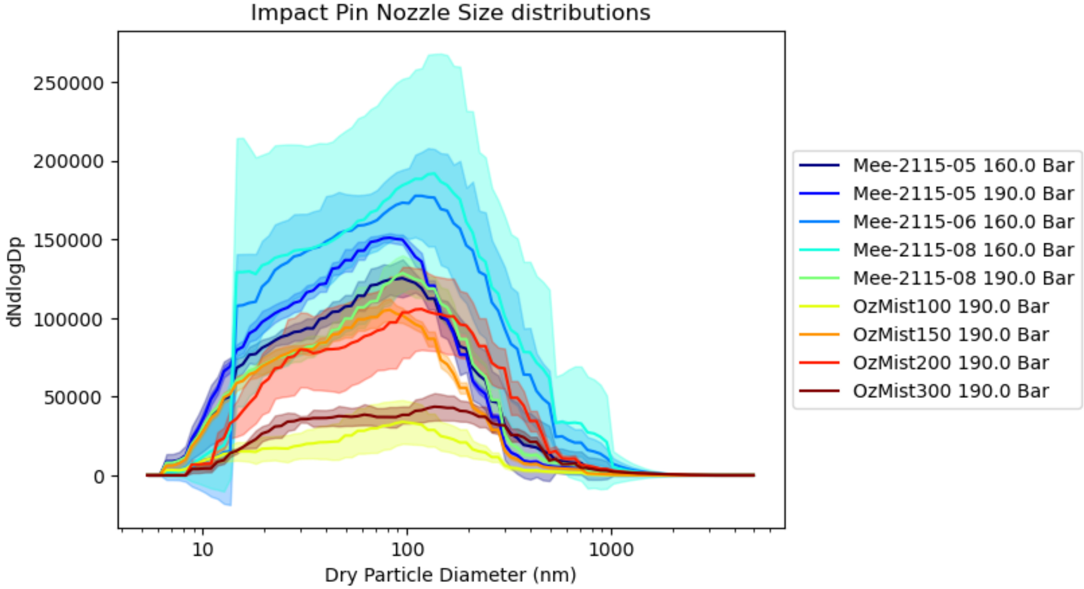
The OZmist^{TM} Fog Cannon fitted with 100 fogging nozzles used in the initial fogging tests has shown that saltwater fogging is technically feasible. Land trials showed that this device produced 5x10^{13} droplets per second with a peak diameter of ~120 nm dry diameter. Although smaller than the optimal size and with a smaller emission of droplets than the modelling recommends, field evaluation over the reefs in February 2022 showed that with a similar emission of droplets up to 16% of shading was achieved albeit over a smaller area (~0.5 km).

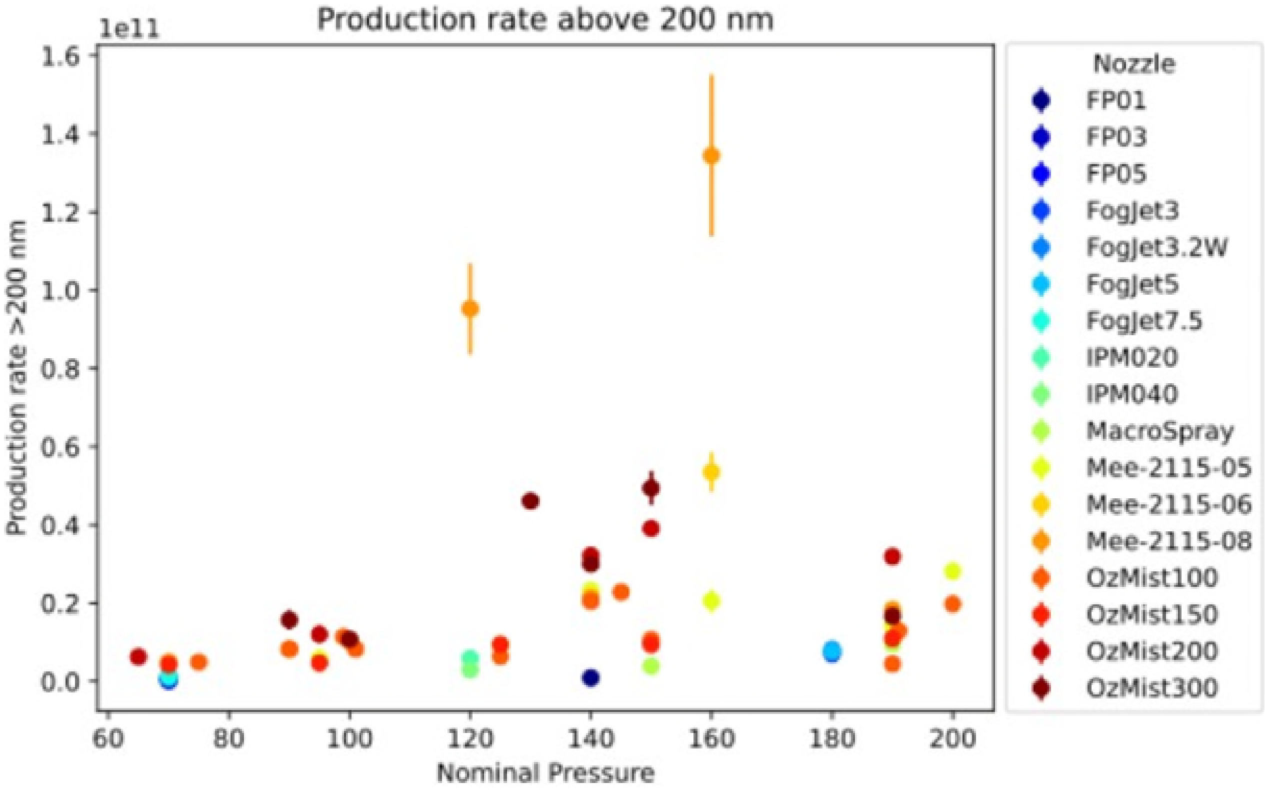
As the droplet diameters were smaller than desired, nozzle investigations are continuing to find more effective and efficient nozzle designs, droplet distributions and optimal operating conditions. A larger system was deployed during the proof-of-concept experiment in early 2025, consisting of two portable fogging systems and the larger system installed onboard the

Objective	Key Findings and/or Outcomes
	research vessel. In total this deployment included five arrays of 360 nozzles each for a total of 1800 nozzle and a total droplet production rate of ~ 5x10^{14} and achieved detectable fog coverage over an area of around 20 hectares, with ~7 hectares of coverage with albedo (approximately equal to shading) > 15%. The current proof-of-concept system struggles to achieve the target shading intensity of 30%. In the example cited above, only around 300 m^{2} exceeded 30% albedo. This outcome is consistent with the modelling predictions, which indicate that the current production rate is below the level required to achieve such levels of shading on a time integrated basis. The proof-of-concept experiment in 2025 was designed to assess the time-integrated shading performance of the current prototype system. The analysis of that data is ongoing and not available at the time of writing this report. Initial impressions suggest that, consistent with the modelling, the level of time integrated shading is likely to be closer to 10-50% over areas spanning hectares to tens of hectares. It should be noted however that the results collected do not represent sampling in very low wind (doldrums) conditions. Limited very low wind sampling opportunities occurred during the 2025 proof-of-concept field campaign. Unfortunately, during the one doldrum period which did occur the aircraft was grounded due to a mechanical issue so shading-area data is not yet available for these conditions. Ongoing nozzle technology development for the fogging systems will aim to increase the droplet production rate, energy efficiency and further intensify the level of shading by producing more optimal particle sizes that are more monodisperse with higher monodispersivity. Higher levels of time-integrated shading are also likely to be achievable for intervention deployments by operating a larger number of individual sources in concert to target a specific area, particularly under very low wind conditions. **Preliminary fogging intervention deployment strategy** A preliminary strategy has been developed for a fogging trial deployment, aiming to implement the intervention over a target coral region during one or more doldrums events occurring within a period of coral thermal stress (i.e. marine heatwave conditions). The expected deployment standby period will coincide with a marine heatwave event or a bleaching summer, with fogging operations conducted over multiple doldrum periods (if occurring, and logistically feasible). This approach is intended to test fogging conducted under the most suitable conditions of increased sea surface temperatures, increased irradiance, low wind speeds, and accumulating coral stress. Fogging activities may also extend beyond peak sea surface temperatures to facilitate coral recovery. If sufficient funding is available, the standby deployment would span the majority of summer. The mobilisation and demobilisation period will extend the timeline by two weeks before and after the deployment. Pre-deployment planning and preparation are estimated to require six months, with permit applications submitted prior to this phase. Post-deployment, an estimated 8–12 months will be needed to write up findings, disseminate results, and produce publication-standard research.

Objective		Key Findings and/or Outcomes
		Scale and potential location of activities Ideal conditions for fogging are during doldrums or low wind conditions. In the most recent field campaign, fogging operations were conducted in areas of the GBR that offered some protection from trade winds or when ideal conditions presented themselves, this previous proof-of-concept fieldwork was not conducted over a coral reef but rather sought to evaluate the ocean surface shading potential of fogging. For the planned fogging deployment, site selection will need to account for a variety of factors, including reef size, shape, depth, and prevailing wind conditions. The scale of the trial deployment site will be local – a single bay, small reef, portion of a larger reef, or plot of out planted coral. The scale should be of a few hectares, ideally at a scientifically well-monitored reef or perhaps a tourism snorkelling area which might lie adjacent to a pontoon-type operation. The current strategy is to focus on reef zones that are less than six metres deep, since that is where most coral mortality due to bleaching occurs, while deeper corals usually recover (Cantin et al. 2021). The final deployment location is subject to negotiation amongst involved research parties, funders, and subject to GBRMPA permitting.
2. A systematic review, and laboratory characterisation of the current state of technology for water based fogging systems and their application to seawater.		
2 (a)	Determine whether an existing system can achieve the desired droplet size, emission rates/concentration with practical energy consumption.	A comprehensive scan of the different water fog generating technologies and nozzles identified impact pin fog generators as the lowest energy devices that produce particles in the region of target droplet size range. A nozzle testing program was undertaken at the SCU nozzle testing facility to evaluate a large number of off-the-shelf impact pin nozzles of different orifice sizes, designs, and manufacturers to determine their suitability for use in seawater fogging apparatus.

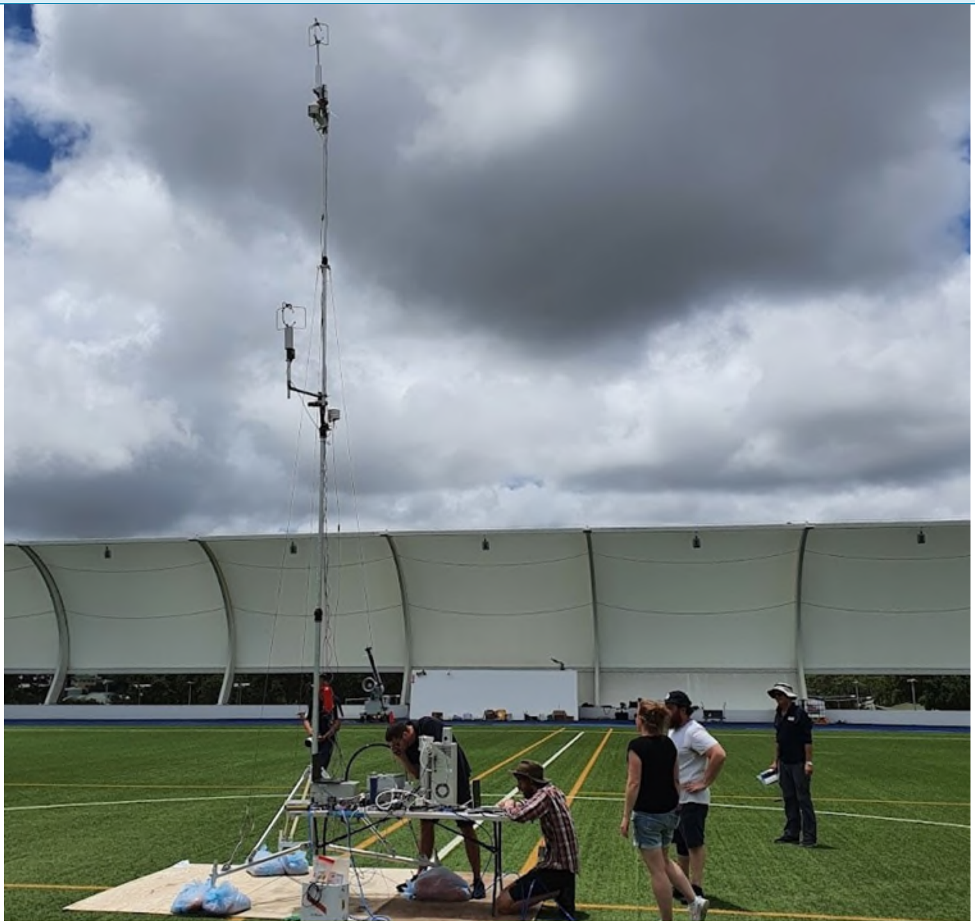
Objective	Key Findings and/or Outcomes
	Ideal droplet size can be informed by Mie scattering theory. Scattering efficiency varies with droplet size and wavelength with the greatest scattering efficiency occurring where droplet radius approximately equals the radiation wavelength. For this reason, a range of emitted droplet sizes is acceptable as smaller droplets can block shorter wavelengths, while the larger droplets can block longer wavelengths more effectively. In general, droplet diameters 500-1500 nm would produce the most efficient scattering of the visible spectrum (Figure 16). In aerosol science, instrumentation is most typically used to measure dry particle diameters. In the case of seawater fogging that is the size of the remaining sea salt crystal when the droplet is fully evaporated. These are approximately four-times smaller than the sprayed seawater droplets. The extent to which the droplets dry out while suspended in the lower atmosphere in real world environments depends upon the local humidity, wind and plume dynamics. Growth factors from 2-4 from the dry particle to wet droplet are the range expected for typical relative humidities over the GBR, although smaller is possible under conditions of low (<70% relative humidity. This results in a desirable dry particle diameter range of 125-750 nm. Impact pin nozzles produce particles within this range, although a significant number are produced with smaller diameters (Figure 17).  *Figure 16: Mie scattering efficiency for different sized droplets and wavelengths.* We set 200 nm as a dry particle diameter cut off, a comprise between the 2x and 4x growth factors which would create 500 nm droplets. Summing the total number of particles produced from each nozzle above this limit we obtain a ‘useful’ production rate of droplets per second that provide the majority amount of shade. Plotting this value against the power required to run each nozzle (a function of water flow rate and pressure), we can identify the most energy efficient of the nozzles tested (Figure 17). For single nozzle types we see diminishing returns in efficiency as we apply more power (i.e. pressure). Of the tested nozzles we consistently see that the MeeFog$^{\text{TM}}$ and OzMist$^{\text{TM}}$ nozzles are most efficient. While similar in performance (by this

Objective	Key Findings and/or Outcomes
	metric) the MeeFog-08 nozzle (203 µm orifice) appears in our testing to give more consistent results than the OzMist300 (300 µm) and was therefore chosen for field trials.  *Figure 17: Dry particle diameters measured for a range of impact pin nozzles tested at the Southern Cross University nozzle characterisation facility. The airborne suspended wet droplet is generally 2-4 times larger in diameter.*

Objective		Key Findings and/or Outcomes
		 *Figure 18: Impact pin nozzles characterised for production rate per unit energy. Each plotted point shows multiple tests of a nozzle at a given flow/pressure operating condition.*
2 (b)	Implement a technology review, testing, and development cycle to identify the most prospective nozzle candidate/s for incorporation into a prototype testing apparatus which can be deployed to the field for real-world dispersion, droplet size	A survey of water misting / fogging technologies that can produce seawater droplets around one to two microns was undertaken. After partial evaporation, such drops should scatter visible light well, and when concentrated in a cohesive plume create shade. The most promising fogging technologies were identified as impact pin nozzles and acoustic nozzles. Impact pin nozzles use mechanical force to break a water stream into droplets while acoustic nozzles use ultrasonic resonance to shatter drops at relatively low pressures and flow rates compared to other air/water nozzles. Commercially proven nozzles have a wide cost

Objective		Key Findings and/or Outcomes
	characterisation, light shading and heat interactions and plume behaviour testing during summer atmospheric conditions.	range from ~$10 to ~$1000 each, and widely differing energy requirements for pumping and heating water, and / or compressing air. Nozzles made from materials that are suitable for extended use in the marine environment such as marine grade 316 stainless steel are considerably more expensive than options suitable for use on land using a freshwater medium. Subsequent testing of a range of impact pin and acoustic nozzles revealed that the impact pin nozzles produce orders of magnitude larger numbers of droplets and so technology development proceeded concentrating on this nozzle type. **Fog Cannon** The Initial Proof of Concept device (Fogger V1) specifications are for an Australian Company called OZMIST to custom build a version of their S45AU Fog Cannon comprising: • High pressure 316 SS pump suitable for 43 l/min of seawater up to 170 bar (2,500 psi) • Variable Frequency Drive Pump control to adjust pump pressure / flow rates controlled by panel mounted potentiometer • Three S.S. nozzle rings containing a total of 100 nozzle mounts. • 100 Impact Pin nozzles (MeeFog$^{\text{TM}}$ 200 micron throat internal diameter) • Cannon fan sufficient for initial 50 m projection of spray • Turret • Remote control • Actuator • Oscillation • Filters 50 micron and 10 microns • Transfer pump with suction line and fittings included • All rings, pipes and fittings specifications to handle 170 bar • System requires 32 kVA 3-phase power source (hired generator, or boat power)

Objective	Key Findings and/or Outcomes
	 *Figure 19: Initial POC Fog Cannon (Fogger V1) - left view showing control pane (Left). POC Fog Cannon Spray during the land trials at the Queensland University of Technology (QUT) soccer stadium, Brisbane (Right).* **Proof of Concept Land Trial** Trials were conducted at Queensland University of Technology's (QUT) Kelvin Grove sports field in Brisbane. The stadium provided flat, uniform grounds and relatively sheltered conditions to simulate a calm ocean surface. The fog cannon produced an estimated 1.89x10^{13} droplets per second with a peak diameter of 145 nm dry salt crystals. A mast was installed mid-field where aerosol number concentration, three-dimensional wind velocity, air temperature and humidity were measured at heights of four and eight metres, allowing investigation of the vertical depth and uniformity of the plume and its impact on local meteorology. Light intensity and aerosol sizing measurements were taken at the base of the mast, to verify the expected distribution of aerosol sizes produced by fog cannon, and to evaluate the amount of shading generated by the plume. For comparison, the ambient light intensity and meteorological conditions outside the plume were measured at a secondary sampling station located in the corner of the sports field, 40 metres to the side of the fog cannon. Drones filmed the fog plume development inside the semi-enclosed stadium with both high definition (HD) and infrared cameras, allowing researchers to study the shape and coverage of the evolving seawater fog, and the localised atmospheric cooling within the plume. Further trials were conducted during the 2021-2022 field season on the Great Barrier Reef when doldrum weather conditions were suitable.

Objective	Key Findings and/or Outcomes
	 *Figure 20: Monitoring station with eight metre instrument stand.*

Objective	Key Findings and/or Outcomes
	 *Figure 21: Fog plume moving toward instrument stand with some shading visible under plume.* **Proof of concept system** Following the technology review and initial land and sea testing of the Prototype System MeeFog^{TM} impact pin nozzle technology was confirmed as producing suitable atomisation of seawater. MeeFog^{TM} have also developed scalable fogging systems using their arrays (Figure 22), and also produce large pumping skids as supply plant (Figure 23). However, the research and development in this project found that optimum operating parameters were beyond what off-the-shelf water fogging systems are designed to deliver. Thus, further development of the system will focus on combining MeeFog^{TM} nozzle and array technologies with custom designed and manufactured fogging plant, based on Meefog^{TM} systems to achieve the desired operating parameters and function reliably in a harsh marine environment using seawater as a feed source. Over 10,000 MeeFog^{TM} systems are used worldwide, and are mature systems produced with automated welding equipment. A nozzle manifold usually costs about US$50 per nozzle, including the cost of nozzles, nozzle adapters, fittings, support frame, etc. Any array size can be built and/or use multiple modules for scale out and ease of trucking, shipping transport, barge sizes. Due to the manifold size, a movable cannon mount and fan will not be used.

Objective	Key Findings and/or Outcomes
	 *Figure 22: Spray test of ~400 nozzles from a MeeFog*^{TM} *nozzle manifold with 1600 nozzles.*

Objective		Key Findings and/or Outcomes
		 *Figure 23: MeeFog^{TM} 138 Bar pump skid with 4 pumps up to 500 litre/min.*
3. Engineering design, construction and characterisation of seawater fogging system for field testing.		
3 (a)	Construct the seawater fogging system including designing and constructing proof-of-concept nozzles, prototype and final full scale seawater fogging system.	**Overview of the Fogging System Design and Development Process** The iterative development of the seawater fogging system involved several key engineering challenges, ranging from droplet generation and scalability to energy efficiency and operational robustness. The project evolved over multiple phases, with each prototype addressing specific limitations identified in earlier versions and increasing in scale and output. The central goal of the system was to generate seawater droplets in the size range optimal for scattering solar radiation and to disperse these droplets over large reef areas on the GBR. Achieving these goals required careful optimisation of nozzle design, high-pressure pump systems, filtration to prevent clogging, and overall system control.

Objective	Key Findings and/or Outcomes
	Fogger V1: Initial proof of concept testing system The first iteration, Fogger V1, was a small-scale proof-of-concept model designed to evaluate the feasibility of generating seawater fog to scatter sunlight. The system used 100 MeeFog™ impaction pin nozzles (2115- 08), which are well utilised in industry and recognised for their high atomisation efficiency. The nozzles were operated at pressures of 160 bar, which was necessary to achieve the required droplet size for light scattering. The primary objectives of Fogger V1 were to: • Verify Droplet Size Distribution: due to droplet coalescence, deposition, and scavenging processes the size distribution of droplets in an outdoor plume generated by multiple closely spaced nozzles may not match the aerosol and droplet size distributions measured from a single nozzle in the SCU nozzle facility. • Assess Fog Stability: testing needed to confirm whether the fog plume could remain stable and concentrated over the target area, especially under low-wind conditions typical of doldrum conditions. **Technical Performance** Droplet Size: laboratory tests confirmed that MeeFog^{TM} nozzle 08 produced droplets with a corresponding dry median diameter of 180 nm, close to the design target. Furthermore, the nozzle provided a relatively wide distribution of sizes, including a substantial proportion that met or exceeded the optimum diameter. Irradiance Reduction: during controlled field tests in Brisbane and Coffs Harbour, this small test system achieved a maximum shading of ~16% reduction in solar irradiance with an average of about 6%. This was considered an extremely encouraging result given the small size of the system. Challenges: while Fogger V1 succeeded in generating close to the desired droplet size, its coverage area was very limited, and operational issues with nozzle clogging and plume dispersion emerged as significant challenges. However, the protype provided foundational knowledge for the design and development of the next generation of the RRAP Cooling and Shading fogging system. **Fogger V2: Scaling up for larger at sea proof of concept tests** Building on the results from Fogger V1, the engineering team developed Fogger V2 to scale up the system's capacity and address the coverage limitations of the initial prototype. Fogger V2 introduced several key innovations to improve both the operational scale and reliability of the fogging system. Key Enhancements in Fogger V2

Objective	Key Findings and/or Outcomes
	• Nozzle Arrays: Fogger V2 featured 1,080 MeeFog™ nozzles arranged in six arrays, significantly increasing the system's fog output. Each array was supported by a multi-pump high-pressure skid capable of delivering seawater at 160 Bar, ensuring consistent droplet generation across all nozzles. • Fog Coverage: field trials at One Tree Island demonstrated that Fogger V2 could achieve an instantaneous reduction in solar irradiance of up to 27% over 3 hectares or 23% over 23 hectares under low-wind conditions. This was a significant improvement over Fogger V1 and provided evidence of scalability. • Improved Filtration System: to address nozzle clogging, Fogger V2 introduced a multi-stage filtration system. This system included a 10-micron coarse filter for removing large particulates, followed by a 1-micron fine filter to eliminate smaller contaminants that could build up over time and obstruct the nozzle orifices. Despite these improvements, nozzle clogging remained a challenge during extended operation, particularly in areas with high sediment concentrations in seawater. A simple solution was to remove the fine scale nozzle filters and operate the system with only the input water filtration. Due to the high pressures and flow rates of the system build-up of finer particles was not observed to be an issue. Fogger V2 was designed to operate with a flow rate of 342 litres per minute (L/min) across its entire array. However, this higher flow rate came at the cost of increased energy consumption. The system's total energy requirement was measured at 139 kW, which, while manageable, posed concerns for long-term operation, especially in remote reef environments where sustainable energy sources are limited. The field trials of Fogger V2 provided valuable insights into the environmental factors affecting the system's performance. While the system performed well in low-wind conditions, higher wind speeds (>7 m/s) caused dispersion of the fog plume, reducing its effectiveness in maintaining consistent shading over the reef area. This was consistent with expectations and confirmed that fogging over open ocean waters for shade is only practical during low-wind doldrum type conditions. **Fogger V3: Optimising Performance, Scalability, and Sustainability** Fogger V3 was created by applying significant upgrades to Fogger V2 to solve a range of technical and engineering issues that were revealed during the first at-sea tests of the large fogging system. It was designed with a modular architecture, separating each pumping system and its associated nozzle array to operate independently. Each module consisted of: • A high-pressure pump unit capable of delivering seawater at 160 Bar. • A filtration system with three stages of particle removal: 10-micron, 1-micron, and 0.35-micron filters, providing superior protection against nozzle clogging. • 360 MeeFog™ nozzles per module, optimised for consistent droplet production at an average dry aerosol size close to the target of 200 nm diameter.

Objective	Key Findings and/or Outcomes
	The modular design allowed for flexible deployment configurations, making it now possible to scale the system for larger reef areas or to target specific coral populations experiencing heat stress. • Nozzle Clogging Prevention: the upgraded filtration system proved highly effective in preventing nozzle clogging, allowing Fogger V3 to operate continuously for eight hours during field trials without maintenance interruptions. This was a marked improvement over earlier prototypes, where nozzle clogging was an issue. • Energy Efficiency: Fogger V3 operated with an average energy consumption of 124.5 kW, representing a 10% reduction in energy use compared to Fogger V2, while still maintaining a high flow rate of 298 L/min per module. This improvement in energy efficiency was achieved through better pump optimisation and more efficient water distribution across the nozzle arrays. Notably, Fogger V3 can now be run as three independent fogging systems at ~40kW per system. One of the most significant advancements in Fogger V3 was the integration of an advanced programmable logic controller (PLC) system. This system continuously monitored key operational parameters, including: • Water pressure and flow rate through each module. • Nozzle performance and droplet size distribution. • Energy consumption and overall system efficiency. The PLC system allowed for real-time adjustments to optimise system performance in response to changing environmental conditions. It also provided detailed operational data that could be used for further refinements in future iterations of the fogging system. **Fogger V4: A community deployable system** Fogger V4 was designed to move the technology towards a community deployable intervention. The focus was to create a prototype field deployable unit that did not rely on a large research vessel to operate and could be flexibly deployed onboard small tourism sized vessels or barges. To enhance energy efficiency and create a self-contained unit Fogger V4 was designed around a diesel direct-drive pump rather than the previous versions with required three phase electricity. This system reduced overall energy consumption, while also improving the system reliability advanced filtration and self-contained low pressure feed pumps. The at-sea testing of two of these prototypes took place in early 2025. The system performed very well from an engineering perspective logging ~8 hours per day for each system over 13 days. Results on the performance in terms of generating fog and shade of these systems are not available in this reporting period but will form the basis of publications to be submitted for peer review in late 2025.

Objective	Key Findings and/or Outcomes
	Environmental Considerations and Engineering Challenges Developing a scalable fogging system for use in marine environments presented several engineering challenges, particularly related to energy consumption and operational robustness. These considerations were central to the design and operational strategies of each fogging prototype. Reducing energy consumption remained a challenge throughout the development of the fogging system. The high-pressure pumps required to atomise seawater into fine droplets are energy-intensive, particularly when operating at the flow rates necessary to cover sizeable reef areas. The use of large onboard diesel generators carried by the research vessel during field trials provided the necessary electrical power, but this solution is deemed to be impractically expensive for future practitioners, especially considering the need to have the infrastructure on standby across the summer ready for when doldrum events occur during heat stress periods. The most recent iteration of the fogging system was developed with direct drive pumps dramatically reducing the size and cost of infrastructure required to deploy them. These systems are capable of operating on biodiesel creating the possibility of using renewable energy, reducing the carbon footprint of the fogging operation and making it more sustainable in the longer term for larger scale deployment in remote reef environments. Given the harsh marine environment in which the fogging system operates, all system components, particularly the nozzles, pumps, and filtration units, needed to be constructed from materials resistant to corrosion. Stainless steel and corrosion-resistant alloys were used in the fabrication of the nozzles and pumps to ensure durability and reduce maintenance requirements. However, long-term field testing will be necessary to assess the lifespan of these components and identify any potential for material degradation. The need for corrosion resistant components throughout combined the demanding operational parameters (supplying high pressure high flow seawater) adds manufacturing cost to the system. **Summary of Engineering Achievements** The engineering development of the fogging system has resulted in several key innovations that position it as a viable tool for mitigating coral bleaching by reducing solar irradiance: • Scalability: the fogging system has evolved from a small-scale proof-of-concept to a modular, scalable system capable of covering significantly sized areas. • Energy Efficiency: through pump optimisation and filtration improvements, the system's energy consumption has been reduced, making it more feasible for long-term use. Combined with development of direct-drive portable units it will be possible to run the systems using renewable energy in the future. • Nozzle Technology: the selected MeeFog™ nozzles with refined operating parameters have been optimised for droplet size and consistency, ensuring effective light scattering across the visible spectrum.

	Objective	Key Findings and/or Outcomes
		• Automation: the integration of real-time monitoring systems allows for continuous optimisation of system performance, improving reliability and operational efficiency. As the project continues, future iterations will focus on further scaling the technology, reducing energy consumption through renewable sources, and refining system components to ensure long-term durability and ease of use.
3 (b)	Confirm that the lab tested fog nozzle technology can produce the desired droplet production rate within the target droplet diameter range and with reasonable energy consumption. Conduct staged tests for the seawater fogging system. Each of these will potentially have a land based (outside of bleaching season) field testing component and a summertime GBR in-situ testing component.	Four major field trials were conducted, including land-based proof-of-concept (PoC) assessments and ship-based deployments on the Great Barrier Reef (GBR). Each trial progressively enhanced the system's efficacy, from evaluating plume persistence and droplet production rates to refining fogging system design. **Land Trial 1 (November 2021):** This trial was conducted at a sheltered sports stadium at QUT, Brisbane, as an initial system validation prior to deploying it on the GBR. The key goals were to: • Develop an operating procedure for the new PoC fogging system. • Compare the laboratory-based single-nozzle measurements of the droplet size distribution against field-based observations from the PoC fogging system. • Evaluate sampling methodologies, including the use of drone-based aerial measurements, ground-based particle and light sensors, and background meteorology. The droplets were found to be 33% smaller than observed in the laboratory, prompting a change to the operating pressure for Fogger 1.1 to produce larger droplets. Valuable insight was also gained with respect to the effect of variable winds, the influence of nearby structures and clouds on wind and plume direction and on sunlight measurements. **Sea Trial 1 (December 2021 and February 2022):** Opportunistic trials were conducted on the GBR to assess the seaworthiness of the fogging system and confirm fog persistence under typical meteorological conditions for the GBR. These trials were crucial in demonstrating the feasibility of deploying the fogging system in a marine environment. The system was tested under various weather conditions. Under calm, doldrum-like conditions that are typical during heat stress events, a fog plume was successfully and repeatably produced. The results showed that the fog plume could be maintained over the target area, with promising shading observed during favourable conditions. Data from these trials were used to calibrate the radiative transfer model, particularly in terms of the scattering and absorption characteristics of the salt aerosols. **Land Trial 2 (December 2022):** Following upgrades to the Fogger 1.1, the system was deployed on a sports field near Coffs Harbour with a view to: • quantify the amount of shading produced, • trial fog production with minimal airflow from the integrated turbine

Objective	Key Findings and/or Outcomes
	Setting the turbine to its lowest speed reduced dilution of the plume, significantly increasing its density and persistence. Highly variable winds and lower humidity produced lower average shading than observed during the doldrums-like weather conditions of Sea Trial 1. However frequent peaks of 16 – 20% shading were observed when the plume passed over the sampling site, 50 metres from the fogger. **Sea Trial 2 (March 2023)** The full-scale 1080-nozzle prototype, Fogger 2, was deployed on a ship at One Tree Island and Wistari Reefs. The trial provided the most comprehensive data on fog-induced shading, in which multiple measurement platforms (including drones and boats) provided detailed data on the spatial extent and shading effectiveness of the plume. This trial represented a significant step forward in scaling up the fogging intervention with an average plume width of 500 m at a downwind distance of 600 m and fog clearly detected at distances of up to 1200 m from the source. The increased number of nozzles allowed for a larger plume, and the use of in-situ measurements of irradiance beneath the plume showed reductions of up to 27% in solar irradiance within an area of three hectares, and reductions of up to 23% over 13 hectares, confirming the potential of the fogging intervention to provide effective shading under optimal conditions. Furthermore, the in-plume droplet sizes were captured showing a median diameter of ~180 nm, confirming that the droplet distributions observed in the laboratory were being successfully reproduced over the reef. As this was the first deployment of Fogger V2, further improvements to production rates, plume extent and shading were expected to be required for subsequent trials.

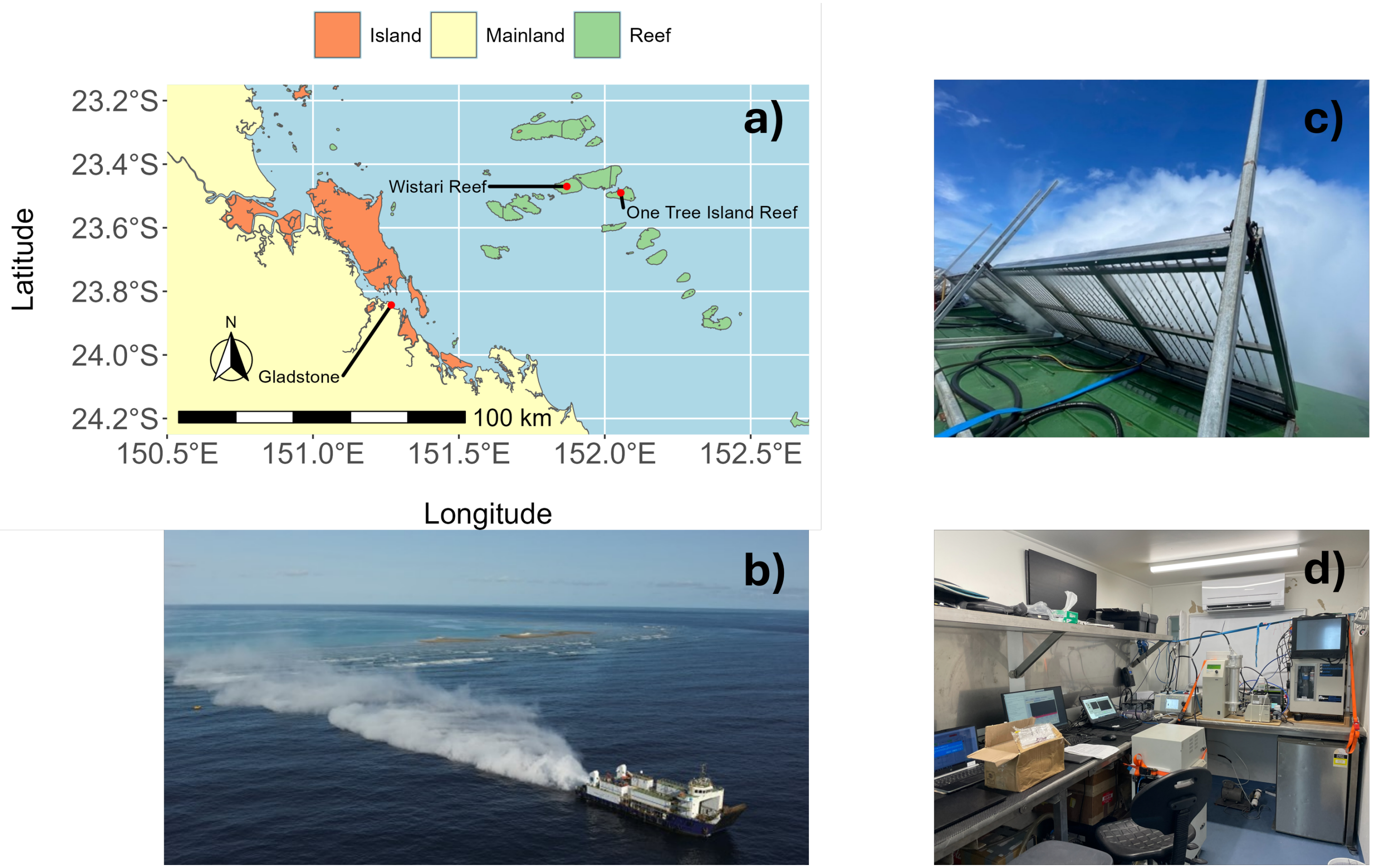
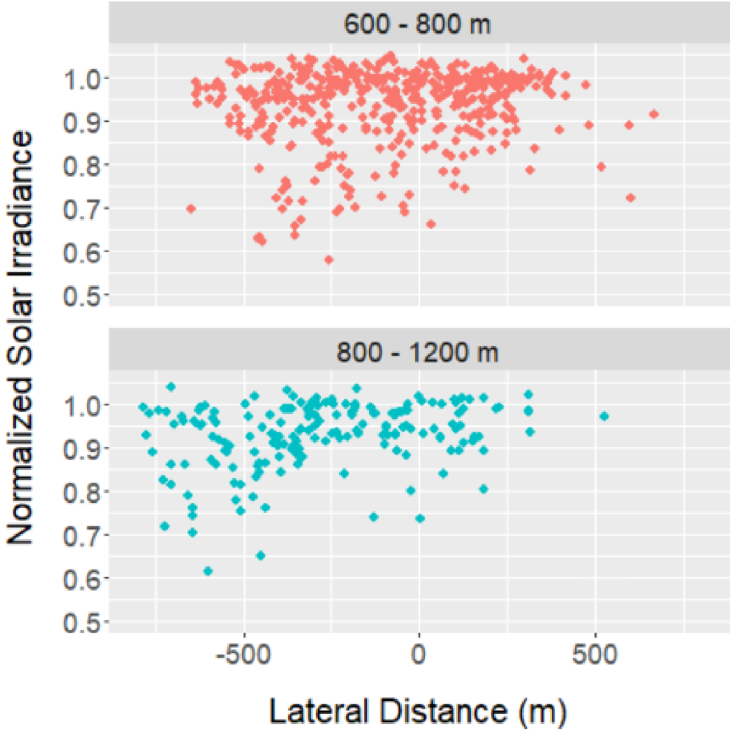
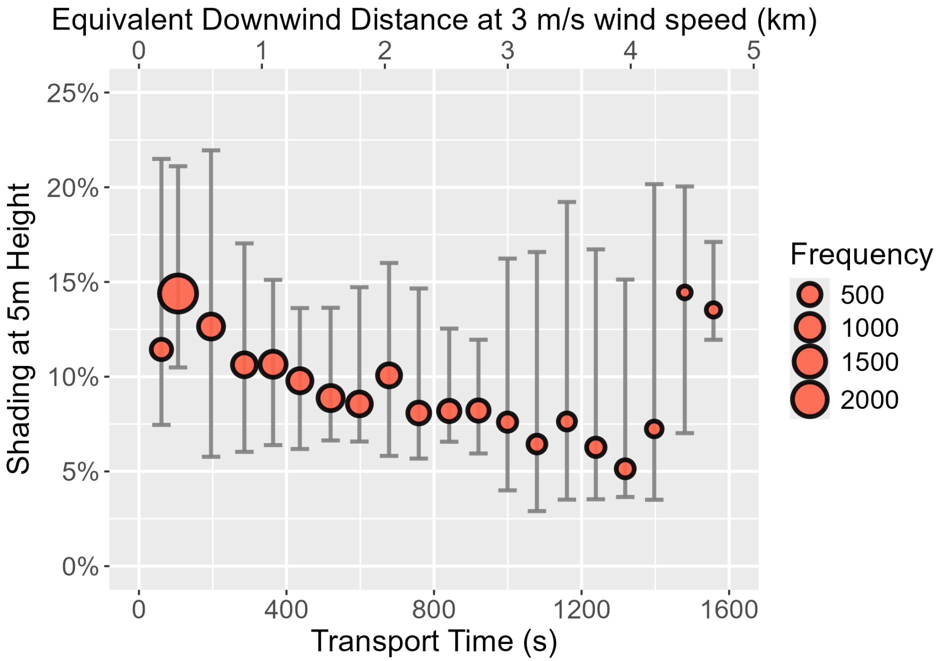


Figure 24: Location of the Shading Trial 2023 at the Great Barrier Reef (a), spraying vessel R/V Bandicoot (b), newly-developed fog generator (c), and instrumentations in the temperature-controlled sampling container on the sampling vessel R/V Magnetic (d).

Objective		Key Findings and/or Outcomes
		 *Figure 25: Normalised solar irradiance as a function of lateral distance from the centre of the plume at two distances from the spraying vessel, 600-800 m and 800-1200 m.*
3 (c)	Evaluate the modelling undertaken in the feasibility study with in-situ measurements of shading and cooling and plume related parameters. Quantify a suite of metrics including: droplet number concentrations; droplet size distribution; droplet composition	Shading Effectiveness: at wind speeds of 1 m/s, fogging with droplet production rates of 10^{15} s^{-1} achieved shading of 15% over an area of 2.7 km^2, or 30% over an area of 1.9 km^2. In higher humidity conditions (>70%), shading increased, extending the shaded area. The effectiveness of the shading was found to be closely linked to the droplet size and the stability of the plume, with larger droplets providing more consistent shading under high humidity conditions and less effective shading for the same output under low humidity conditions. Wind Sensitivity: low wind speeds enhanced plume persistence and shading capacity, while higher winds diluted the plume, reducing its impact. Stability conditions significantly influenced the vertical and lateral spread of the plume. Under stable atmospheric conditions, the plume remained more concentrated, providing higher shading intensity, while unstable conditions

Objective		Key Findings and/or Outcomes
	from filter samples; shortwave energy balance with and without artificial fog; three-dimensional characterisation of the plume concentrations over the target area.	promoted greater dispersion and a wider coverage area. The Gaussian plume model showed that wind speeds above 3 m/s led to significant plume dilution, reducing the effective shading area by up to 50% compared to low-wind conditions.  *Figure 26: Median shading observed at five metre height as a function of plume transport time (distance), with marker size proportional to the sample size. The top x-axis indicates the equivalent downwind distance from the fog generator at 3 m/s wind speed.* Fieldwork Insights: practical challenges such as plume buoyancy, turbulence, and varying atmospheric conditions were highlighted. Shading was found to decrease with increased plume transport distance due to dispersion. The field trials also revealed the importance of real-time monitoring and adaptive control of the fogging system to maintain optimal plume coverage. Issues such as nozzle clogging, variable wind directions, and changes in humidity required constant monitoring of the system to achieve the desired shading effect. The integration of environmental sensors, such as anemometers and humidity probes, provided valuable data that were used to inform plume characteristics.

Objective	Key Findings and/or Outcomes
	Environmental Considerations The environmental impact of fogging interventions must be carefully assessed to ensure that the benefits of coral shading outweigh any potential negative effects. One concern is the potential for fogging to affect marine life beyond coral reefs. The presence of a fog plume may alter local light conditions, potentially impacting photosynthetic organisms such as seagrasses and phytoplankton. The fogging system is designed to be deployed only during periods of extreme heat stress, minimising the duration of its impact on the ecosystem. However, careful monitoring of non-target species is recommended to ensure that the intervention does not inadvertently harm other components of the marine environment. **Limitations and Recommendations** Field trials revealed several limitations, including the need for better understanding of plume behaviour under varying environmental conditions, low mobility of sampling vessels, and practical difficulties in estimating plume height and coverage area and biases due to the presence of cloud coverage. Recommendations for future work include: • Smaller Sampling Vessels: using smaller, more manoeuvrable sampling vessels to improve spatial and temporal resolution. This would allow for more detailed mapping of the plume and better assessment of its coverage and persistence over time. The use of autonomous surface vehicles or mini fixed platforms equipped with aerosol and irradiance sensors could provide continuous measurements without the logistical constraints of manned vessels. • Wet Particle Measurements: implementing in-situ wet fog measurements to directly assess droplet numbers and sizes. Current methods rely on sampling dried aerosols, which may not accurately reflect the properties of the fog plume in its natural state. In-situ wet measurements would provide more accurate data on droplet size distribution and concentration, leading to improved model validation. Instruments such as the Fog & Aerosol Spectrometer (FAS) could be used to measure droplet size distributions in real-time. • Optimising Spraying Strategies: testing different fog spraying strategies using models to extrapolate plume distribution and shading effects. For example, varying the height and angle of the nozzles or using multiple spraying vessels in tandem could enhance coverage and improve shading efficiency. Simulations using the Gaussian plume model could help identify the most effective configurations before conducting field trials. Additionally, using variable nozzle pressures to adapt to changing environmental conditions could help maintain a consistent plume. • Low-cost Irradiance Sensors: deploying a network of low-cost irradiance sensors to improve shading data acquisition over larger areas. These sensors could be placed on floating buoys or small autonomous vehicles, providing continuous measurements of solar irradiance at the sea surface. This would help build a more comprehensive understanding of the shading effect over time and under different environmental conditions. • Field Trials in Periods of Minor Cloud Coverage: to address the bias in shading observations caused by clouds, we propose that instead of conducting the tests during the bleaching seasons, when cloud cover is significant, the experiments should be conducted during periods with less cloud coverage, such as in winter. In addition to the in-situ

Objective	Key Findings and/or Outcomes
	shading measurements taken on the research vessel, we suggest including airborne measurements using drones or aircraft to provide comprehensive data on the shading induced by the plume. **Conclusions** The RRAP Fogging Development (CS-0) Project's fogging intervention shows promise as a targeted cooling solution to protect coral reefs during extreme heat stress. By atomising seawater to generate low-lying fog, the intervention effectively reduces downwelling solar radiation, mitigating coral bleaching. Continued development is required to refine system design and deployment strategies, optimise shading potential, and enhance coverage area. Field trials have confirmed that the fogging system can provide persistent shading under ideal conditions, though challenges remain in operational deployment and consistent coverage in natural settings. The effectiveness of the fogging intervention depends on several key factors, including droplet size, wind speed, atmospheric stability, and ambient humidity. Understanding the relationship between these parameters is crucial to achieving consistent and effective shading. The use of computational models, combined with extensive field trials, has provided valuable insights into how to potentially deploy the fogging system to maximise its benefits. Future trials should focus on optimising fog deployment, sampling methodologies, and improving data collection consistency to make the fogging intervention a reliable, scalable solution for coral reef conservation. The integration of new technologies, such as autonomous sampling platforms and real-time control systems, could further enhance the effectiveness of the intervention. By continuing to refine and improve the fogging system, it may become an essential tool in the fight to protect coral reefs from the impacts of climate change. In addition to technical improvements, future research should explore the ecological implications of large-scale fogging interventions, including the potential impacts on marine biodiversity and local climate. By addressing these knowledge gaps, the fogging intervention can be developed into a robust and environmentally sustainable solution for coral reef protection.

Adjustments to key research objectives

Table 2: Variation in the Project over time.

Initial Research Question	Explain when, how and why the research question changed
Conduct a desktop and initial proof of concept feasibility assessment of seawater fogging as an intervention.	In 2022 following the promising performance of the initial proof-of-concept testing apparatus (Fogger V1) the project was extended beyond the initial scope to further develop the proof-of-concept to a system large enough to conduct at-sea testing of plume dispersion dynamics and light attenuation.

4 Future Research Recommendations

The seawater fogging intervention shows promise as a targeted cooling solution to protect coral reefs during extreme heat stress. By atomising seawater to generate low-lying fog, the intervention has been shown to reduce downwelling solar radiation, providing shading. Continued development is required to refine system design and deployment strategies, optimise shading potential, and enhance coverage area. Field trials have confirmed that the fogging system can provide persistent shading under ideal conditions, though challenges remain in operational deployment, cost, and achieving consistent coverage under variable winds.

The effectiveness of the fogging intervention depends on several key factors, including droplet size, wind speed, atmospheric stability, and ambient humidity. Understanding the relationship between these parameters is crucial to achieving consistent and effective shading. The use of computational models, combined with extensive field trials, has provided valuable insights into how to potentially deploy the fogging system to maximise its benefits.

The RRAP Cooling and Shading Sub-program have made significant progress in validating and demonstrating new techniques to enhance reef resilience during marine heatwaves. The 2025 campaign concluded a pivotal phase in the development of fogging technologies for coral reef protection. The outcomes of the campaign provide a strong foundation for the transition from experimental research to planning for a trial deployment. Successful pilot deployment would represent a significant step towards positioning seawater fogging as a deployable tool within Australia's climate resilience portfolio for coral reef protection. Future trials should focus on optimising fog deployment, sampling methodologies, and improving data collection consistency to make the fogging intervention a reliable, scalable solution for coral reef conservation. The integration of new technologies, such as autonomous sampling platforms and real-time control systems, could further enhance the effectiveness of the intervention.

A trial deployment would aim to reduce solar irradiance during a thermal stress event over a limited target region of shallow water coral and evaluate the health and mortality outcomes of coral in the treated area in comparison to control plots nearby. The expected outcomes include measurable reductions in light intensity at the ocean surface and depth of corals, leading to measurable alleviation of stress and potentially a reduction in mortality (depending on the severity of the event and success of the intervention). A potential co-benefit that could be assessed is whether the shortwave solar energy reduction created by fogging is sufficient to create a measurable localised reduction in sea surface temperatures. If verified this is expected to act synergistically with the reduction in light intensity to alleviate bleaching stress in the target corals.

Figure 27: Close up of fogging nozzles during operation on the Great Barrier Reef, 2023.

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