

At-sea comparative testing of the effects of different towed objects on the aerial performance of tori lines in tuna longline fisheries

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Abstract: Seabird bycatch in pelagic longline fisheries remains a major conservation concern, and tori lines are widely used as a practical mitigation measure. The aerial extent of tori line directly determines the effective range of the aerial deterrent zone astern of the vessel, where seabirds may encounter sinking baited hooks. This study conducted at-sea comparative tests aboard the tuna longline vessel Rongheng 513 under three routine operating speeds: 4.5, 6.0, and 8.2 kt to evaluate the effects of different towed objects on the aerial performance of tori lines in tuna longline fisheries. Three configurations were tested: the baseline streamer configuration as the control, the plastic-cone configuration, and the drogue configuration. The results showed that different towed objects can markedly affect the aerial deployment state of the tori line. The drogue configuration achieved the best performance at all tested vessel speeds, with an aerial extent of 103.8-116.2 m, consistently exceeding the widely recognized 100 m aerial extent reference. The baseline streamer configuration ranked second, with an aerial extent of 98.9-109.7 m, whereas the configuration fitted with a series of plastic cones consistently performed worst, with an aerial extent of 70.8-82.5 m. These findings indicate that the hydrodynamic drag characteristics of the towed object are critical in determining the aerial performance of a tori line, and that devices with insufficient drag may produce the opposite of the intended effect. Therefore, it is

recommended that the technical requirement for towed objects to provide sufficient and stable drag be further clarified, to improve the practical compliance effectiveness of seabird mitigation measures. In addition, fishing fleets are encouraged to evaluate the performance of mitigation measures based on their own operational conditions, thereby providing a basis for future revisions of seabird resolution.

Keywords: tuna longline fishery; seabird bycatch mitigation; tori line; aerial extent; towed object

1 Introduction

Fisheries bycatch is one of the major threats to global seabird populations and remains an important issue in marine biodiversity conservation and fisheries ecosystem management (Phillips et al., 2016; Dias et al., 2019). Globally, different types of fisheries cause the deaths of hundreds of thousands of seabirds each year, with fishing methods such as gillnet, trawl, longline, and purse-seine fisheries exerting varying degrees of impact on seabird populations (Anderson et al., 2011; Carle et al., 2019; Zydalis et al., 2013; Da Rocha et al., 2021; Votier et al., 2023). Among them, pelagic longline fisheries targeting tuna and swordfish are widely recognized as an important source of bycatch for seabirds such as albatrosses and petrels. During the line-setting phase, seabirds may come into contact with sinking baited hooks while feeding, thereby creating a risk of bycatch (Anderson et al., 2011; Votier et al., 2023). In the eastern Pacific Ocean, the Inter-American Tropical Tuna Commission (IATTC) has adopted Resolution C-11-02 specifically addressing seabird bycatch, and has continued to incorporate seabird mitigation measures into its relevant ecosystem and bycatch management frameworks (IATTC, 2011).

Among existing mitigation measures, tori lines are widely used in tuna longline operations because they are relatively simple to deploy and highly adaptable. Their basic function is to create a continuous zone of visual disturbance and physical deterrence above the gear-setting area astern of the vessel, thereby reducing opportunities for seabirds to approach and attack sinking baited hooks (Melvin et al., 2014; Sato et al., 2013; Jiménez et al., 2020; Gilman et al., 2021). The best-practice advice of the Agreement on the Conservation of Albatrosses and Petrels (ACAP) clearly states that properly designed and deployed tori lines can substantially reduce seabird attacks on sinking bait and the associated mortality risk (ACAP, 2019; 2023). However, their actual effectiveness is influenced by structural parameters, such as attachment height, backbone length, and streamer configuration, as well as deployment quality and operating conditions (Melvin et al., 2014; Gilman et al., 2021; Jiménez et al., 2020).

For a tori line, its protective capacity depends primarily on whether it can form a

sufficiently long and relatively stable aerial coverage zone above the critical area astern of the vessel. The core quantitative indicator used to measure this zone is the aerial extent, which refers to the horizontally extended aerial coverage distance from the point where the tori line leaves the attachment system to the point where the line contacts the sea surface (ACAP, 2019; Melvin et al., 2014). Melvin et al. (2014) noted that the aerial coverage provided by a tori line should, as far as possible, cover the astern distance over which bait sinks to depths accessible to seabirds. Otherwise, even when a tori line is deployed, it may fail to effectively protect the near-stern waters where seabird attacks are most likely to occur. ACAP has provided clear recommendations on the minimum aerial extent required for tori lines under different vessel-size categories, and has specified technical requirements for key parameters such as attachment height, streamer length, and streamer spacing (ACAP, 2019; 2023). Thus, aerial extent is not only a geometric indicator describing the physical deployment state of a tori line, but also a key technical indicator for evaluating its potential protective capacity and operational suitability.

From the perspective of fishing-gear mechanics, the aerial performance of a tori line does not depend solely on the physical deployed length of the backbone. Instead, it is jointly determined by multiple factors, including vessel speed, attachment height, the materials of the line and streamers, and the drag generated by the terminal towed object. In its best-practice guidance on seabird bycatch mitigation in pelagic longline fisheries, ACAP clearly states that the aerial coverage provided by a tori line depends on factors such as vessel speed, attachment height, drag, and the weight of the line material (ACAP, 2019; 2023). Among these factors, the towed object may directly affect the aerial deployment state of the tori line by altering in-water resistance and line tension, making it an important structural factor influencing aerial extent.

Existing studies have also shown, from different perspectives, that the mitigation effectiveness of tori lines is closely related to their deployment method and technical specifications. Sato et al. (2013) compared the effectiveness of single and paired tori lines, demonstrating that deployment mode can influence their bird-deterrent

performance. Domingo et al. (2017) confirmed on tuna longline vessels that proper use of tori lines can significantly reduce seabird bycatch. Melvin et al. (2014), Jiménez et al. (2020), and Gilman et al. (2021) further showed that tori lines, when used in combination with other mitigation measures and deployed according to appropriate specifications, can provide consistent mitigation benefits across different operational scales. At the same time, some design and experimental studies on small longline vessels have begun to examine the influence of the tail-section drag component of tori lines on aerial performance. Goad (2017) explicitly divided the tori line into an aerial section and a drag section, and showed, through at-sea trials of different drag-section configurations and towed-object options, that the form of the drag section, the magnitude of drag, and its match with operating speed can directly affect aerial extent and the operational stability of the device. The latest ACAP review also identifies the generation of sufficient drag to maximize aerial extent as a key requirement for tori line design and deployment (Goad, 2017; ACAP, 2024). Current relevant work has mostly focused on the overall mitigation effectiveness of tori lines, comparisons of deployment modes, and their combined use with other mitigation measures. By contrast, quantitative at-sea comparisons of how different types of towed objects affect aerial extent under a unified test platform and representative operating speeds remain relatively limited.

Based on this context, the present study used a tuna longline vessel as the test platform to conduct at-sea comparative trials under different representative operating speeds. The baseline streamer configuration, which was actually used by fishers and was not fitted with an additional terminal attachment, was selected as the control configuration. Two terminal-attachment configurations, namely the plastic-cone configuration and the drogue configuration, were then tested as experimental configurations. By systematically measuring the aerial extent of the three tori line configurations under different vessel-speed conditions, this study compared their differences in aerial performance and analyzed the effects of changes in terminal configuration on the aerial deployment state of the tori line. From the perspectives of

fishing-gear mechanics and practical improvement, this study aims to provide field-based empirical evidence for optimizing tori line structure, selecting suitable terminal devices, and refining future technical specifications.

2 Materials and Method

2.1 Test vessel and study area

This study conducted at-sea trials on 3 November 2025 in waters near Zhoushan, Zhejiang Province, China. The test platform was the tuna longline vessel Rongheng 513, which has an overall length of 44.19 m, a moulded breadth of 7.6 m, a gross tonnage of 471 t, and a main engine power of 960 kW (Figure 1). All measurements were conducted consecutively in nearshore waters within 30°05'N-30°07'N and 122°25'E-122°28'E (Figure 1), in order to minimize the influence of spatial variation in sea-area conditions on the measurements obtained for different tori line configurations.

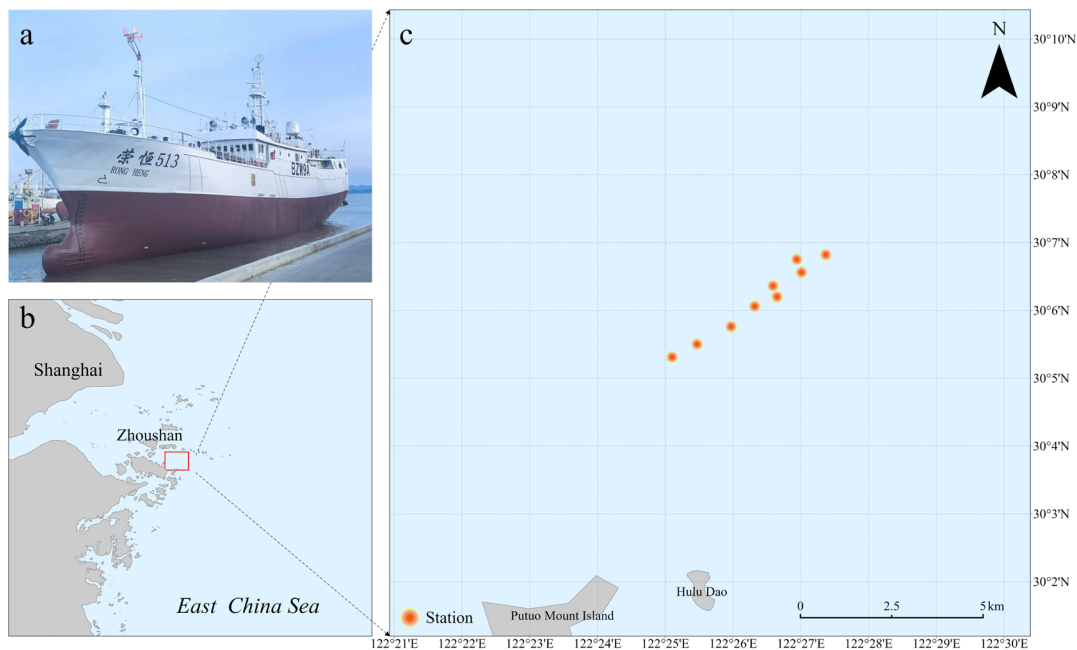


Figure 1 Schematic diagram of the test vessel, study area, and test stations (a: The test vessel Rongheng 513; b: location of the study area, with the red box indicating the enlarged area shown in panel c; c: starting stations of each test)

2.2 Tori line configurations and experimental setup

The design rationale for the different terminal configurations was to modify the

force characteristics at the tail end of the tori line, thereby affecting its aerial deployment state above the critical area astern of the vessel and assessing the resulting effects on aerial extent. This study compared three tori line configurations: the baseline streamer configuration, the plastic-cone configuration, and the drogue configuration. The baseline streamer configuration served as the control configuration, representing the conventional deployment condition without an additional terminal attachment. The plastic-cone configuration and drogue configuration served as experimental configurations, in which different types of terminal attachments were added to alter the in-water drag and force distribution of the tail section of the tori line. The structural schematics of each configuration are shown in Figure 1A, the field deployment and in-water testing conditions are shown in Figure 2, and the main structural parameters are detailed in Table 1.

All three configurations were tested through at-sea towing trials on the same test platform, Rongheng 513, to compare their differences in aerial extent performance under actual operating conditions. It should be noted that this trial was designed to evaluate the practical application potential of different tori line designs. Therefore, based on real at-sea operating scenarios, this study treated the baseline streamer configuration and the two experimental configurations fitted with different towed objects as three independent practical configuration options, and compared their overall physical performance. This design can more objectively reflect the real-world effects of different terminal modification measures in actual fishing operations.

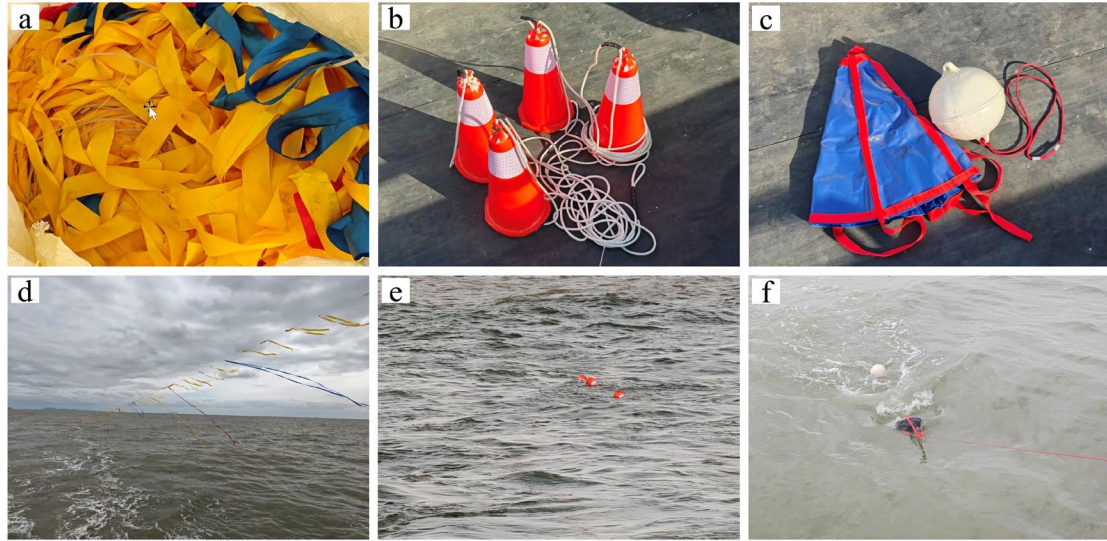


Figure 2 Physical photographs and at-sea operating conditions of the three tori line configurations (a-c: physical photographs of the baseline streamer configuration, plastic-cone configuration, and drogue configuration, respectively; d-f: at-sea operating conditions of the baseline streamer configuration, plastic-cone configuration, and drogue configuration, respectively)

Table 1 Main structural parameters of the three tori line configurations

Configuration type	Total length	Main-section configuration	Tail-section and terminal towed-object structure	Other parameters
Baseline streamer configuration (control configuration)	210 m	Main section: 120 m; made of ultra-high-molecular-weight polyethylene (UHMWPE) with a diameter of 4.8 mm	Tail section: approximately 90 m; terminal end connected to one ϕ 200 mm float; no additional towed object was fitted	See Appendix 1
Plastic-cone configuration (experimental configuration)	140 m	120 m; consistent with the main-section structure of the baseline streamer configuration	Tail section: approximately 20 m; fitted with four 45 cm-high plastic cones at 2 m intervals; the distance from the last plastic cone to the terminal end was approximately 5 m	See Appendix 1
Drogue configuration (experimental)	140 m	120 m; consistent with the main-section structure of the	Tail section: approximately 20 m; terminal end connected to one ϕ 50 cm drogue,	See Appendix 1

configuration)	baseline configuration	streamer	followed by approximately 10 m of resin rope (ϕ 7.2 mm) connected to one ϕ 200 mm float
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Note: ϕ denotes diameter.

2.3 Definition and measurement method of aerial extent

This study used the aerial extent of the tori line as the core evaluation indicator to characterize its ability to provide aerial deterrent coverage above the critical area astern of the vessel. In this study, aerial extent refers to the aerial coverage distance from the point where the tori line leaves the attachment system to the point where the line contacts the sea surface; in other words, it is the horizontal extension distance over which the tori line remains suspended above the sea surface (Goad, 2017). The definition is illustrated in Figure 3. To ensure comparability among configurations, the three tori line configurations were tested under the same deployment height and experimental operating procedures.

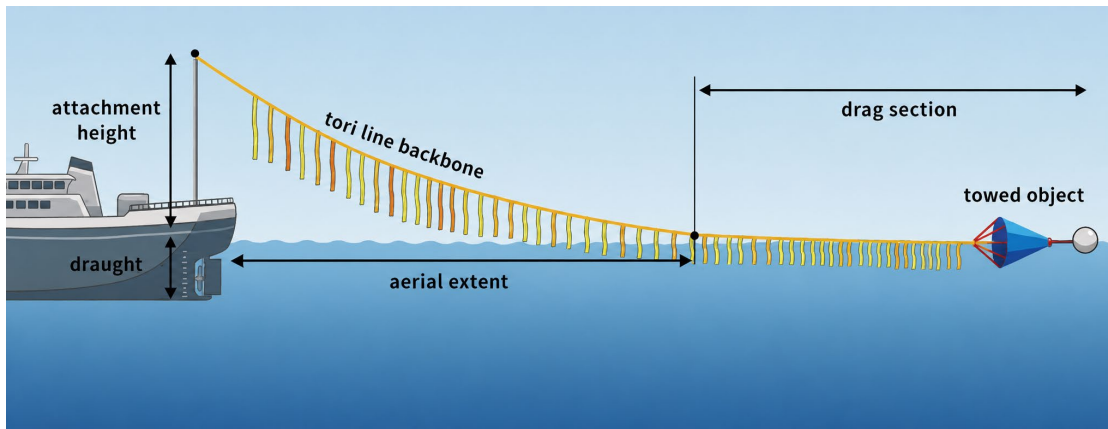


Figure 3 Schematic diagram of the tori line structure with a tail-section towed object and the definition of aerial extent (The definition shown in this schematic was adapted from Goad (2017))

The field measurement of aerial extent was conducted using a visual laser rangefinder (INKERSI KE500; Figure 4), with a nominal measurement range of 3-500 m and a nominal distance-measurement accuracy of $\pm(1 + D \times 0.3\%)$ m, where D denotes the measured distance. The support pole on the test platform was 6 m long, the height from the pole tip to the sea surface was 8.3 m, and the vessel draught was 4.2 m. During the at-sea trials, each configuration was measured after the vessel speed had

stabilized and towing had continued for 5 min. Once the posture of the tori line was generally stable, its aerial extent was measured using the instrument's horizontal-distance measurement mode, and one representative measured value was recorded. Meanwhile, environmental and operational parameters, including vessel speed, heading, current speed, and current direction, were recorded from the vessel instruments and used as background information for interpreting the results.



Figure 4 Schematic diagram of the aerial extent measurement equipment and field measurement procedure for the tori line (a: the INKERSI KE500 visual laser rangefinder; b: researchers measuring the aerial extent in the field)

2.4 Experimental design and data analysis

This at-sea trial adopted a **two-factor full factorial design**, with three vessel-speed levels: 4.5, 6.0, and 8.2 kt. Under each vessel-speed condition, towing tests were conducted for the three tori line configurations, namely the baseline streamer configuration, plastic-cone configuration, and drogue configuration. During the trial, environmental and operational information, including test time, latitude and longitude, vessel heading, wind speed, current speed, and current direction, was recorded simultaneously and used as background information for interpreting the subsequent results.

Given that only one representative stable aerial extent value was obtained for each cross-combination of vessel speed and configuration, and that within-group repeated observations were not available, the data were analyzed using a descriptive comparative approach. The analysis was conducted along two dimensions. First, the minimum aerial extent of 100 m required under seabird conservation measures was introduced as the compliance threshold, and the absolute differences in aerial extent and compliance status among different tori line configurations were compared horizontally under the same vessel-speed condition. Second, the dynamic response of aerial performance to changes in vessel speed was analyzed vertically within each configuration, and the relative percentage change in aerial extent was calculated for each configuration to quantify the positive or negative effects of different terminal towed objects on aerial performance.

3 Results

3.1 Overview of test environmental conditions

The at-sea tests of all configuration combinations were conducted consecutively on the same day and in the same sea area, with relatively stable meteorological and current conditions during the overall test window. During the trial, the surface current conditions did not change markedly; current speed remained between 1.4 and 1.6 km/h, and current direction was stable at 65°. Sea-surface wind speed showed some natural variation, with measured values ranging from approximately 12.7 to 28.6 km/h. Specifically, the baseline streamer configuration was tested under relatively lower wind speeds across all vessel-speed levels, ranging from 12.7 to 15.8 km/h. By contrast, wind speeds during the tests of the plastic-cone configuration and drogue configuration were relatively higher, ranging from 26.3 to 28.6 km/h and from 22.7 to 26.2 km/h, respectively.

3.2 Overall performance of aerial extent and compliance buffer

In the at-sea comparative trials, the three tori line configurations showed clear between-configuration differences in aerial extent at the three operating vessel speeds

of 4.5, 6.0, and 8.2 kt (Table 2). Under all test conditions, the drogue configuration consistently achieved the best aerial performance, with an aerial extent of 103.8-116.2 m. The baseline streamer configuration ranked second, with an aerial extent of 98.9-109.7 m, whereas the plastic-cone configuration had the shortest aerial extent, ranging from 70.8 to 82.5 m.

Using the minimum aerial extent of 100 m as the reference benchmark, the drogue configuration exceeded this benchmark at all three vessel-speed levels and showed a sufficient compliance buffer (+3.8 to +16.2 m). This indicates that, even if vessel-speed fluctuations or a sudden drop in wind speed occur during fishing operations, this configuration is still likely to maintain compliance. The baseline streamer configuration exceeded the reference benchmark at medium and high vessel speeds, namely 6.0 and 8.2 kt, but its compliance buffer was relatively limited (+4.2 to +9.7 m); at the low vessel speed of 4.5 kt, however, it was slightly below the benchmark, with an aerial extent of 98.9 m. By contrast, the plastic-cone configuration remained below the 100 m reference benchmark at all tested vessel speeds, reaching a maximum of only 82.5 m, and therefore failed to form an ideal aerial deterrent zone (Figure 5).

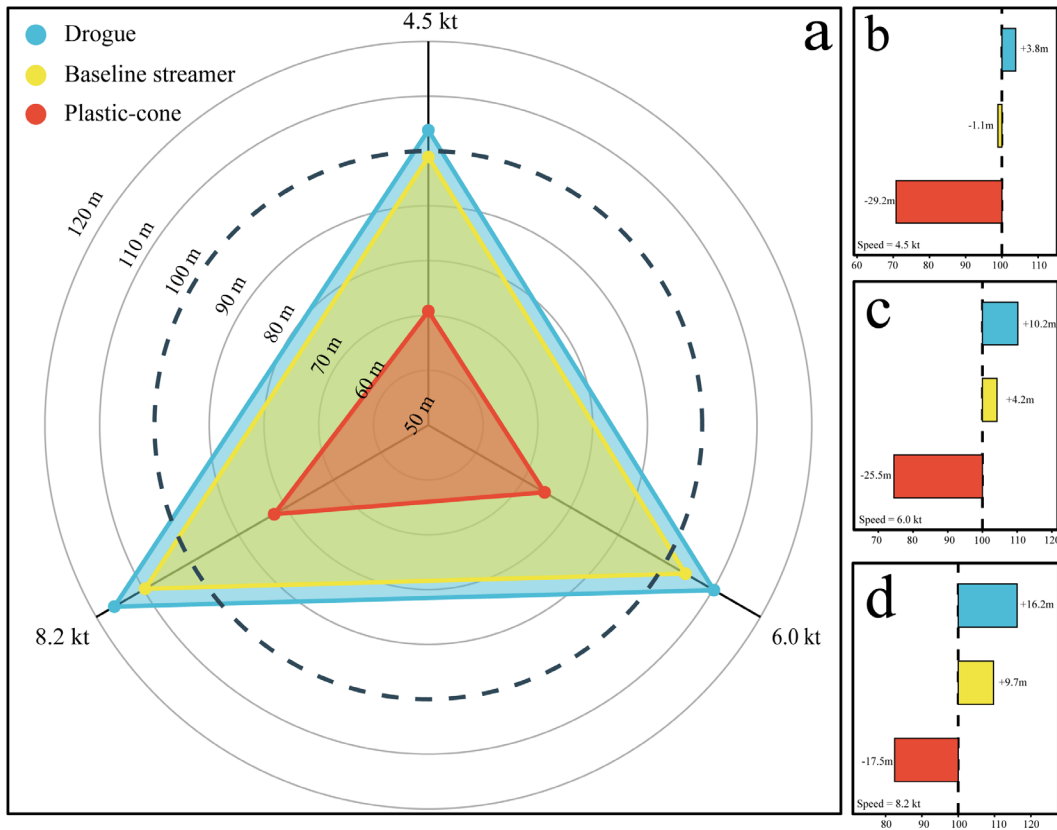


Figure 5 Comprehensive comparison of aerial extent performance among different tori line configurations at different vessel speeds (a: overall performance of the three configurations; b-d: compliance buffer at vessel speeds of 4.5, 6.0, and 8.2 kt, respectively)

Table 2 Comparison of aerial extent among different tori line configurations under different vessel-speed conditions

Tori line configuration	Vessel speed (kt)	Towing duration after vessel-speed stabilization (min)	Aerial extent (m)	Rank
Drogue	4.5	5	103.8	1
Baseline streamer	4.5	5	98.9	2
Plastic-cone	4.5	5	70.8	3
Drogue	6.0	5	110.2	1
Baseline streamer	6.0	5	104.2	2
Plastic-cone	6.0	5	74.5	3

Drogue	8.2	5	116.2	1
Baseline streamer	8.2	5	109.7	2
Plastic-cone	8.2	5	82.5	3

3.3 Response of aerial performance to changes in vessel speed

The aerial extent of all three configurations showed a positive trend with increasing vessel speed, indicating that the increased hydrodynamic towing force associated with higher vessel speed enhanced the aerial tension of all tori line configurations. However, the magnitude of the response to vessel-speed changes differed among configurations (Figure 5). Specifically, when vessel speed increased from 4.5 kt to the highest routine operating speed of 8.2 kt, the drogue configuration showed the largest absolute increase in aerial extent, rising from 103.8 m to 116.2 m, an increase of 12.4 m (+11.9%). The plastic-cone configuration increased from 70.8 m to 82.5 m, an increase of 11.7 m (+16.5%), while the baseline streamer configuration increased from 98.9 m to 109.7 m, an increase of 10.8 m (+10.9%). Based on the average rate of change from the low-speed to high-speed condition, the increases in aerial extent per unit vessel speed were 3.35 m/kt, 3.16 m/kt, and 2.92 m/kt for the drogue configuration, plastic-cone configuration, and baseline streamer configuration, respectively.

Using the baseline streamer configuration as the control benchmark, different tail-section towed objects showed pronounced positive or negative effects on system-level aerial performance. The drogue configuration produced a stable positive gain: at vessel speeds of 4.5, 6.0, and 8.2 kt, its aerial extent increased by 5.0%, 5.8%, and 5.9%, respectively, compared with the baseline streamer configuration. By contrast, the series of plastic cones produced a substantial negative effect, with aerial extent decreasing by 28.4%, 28.5%, and 24.8%, respectively, relative to the baseline streamer configuration at the three vessel speeds.

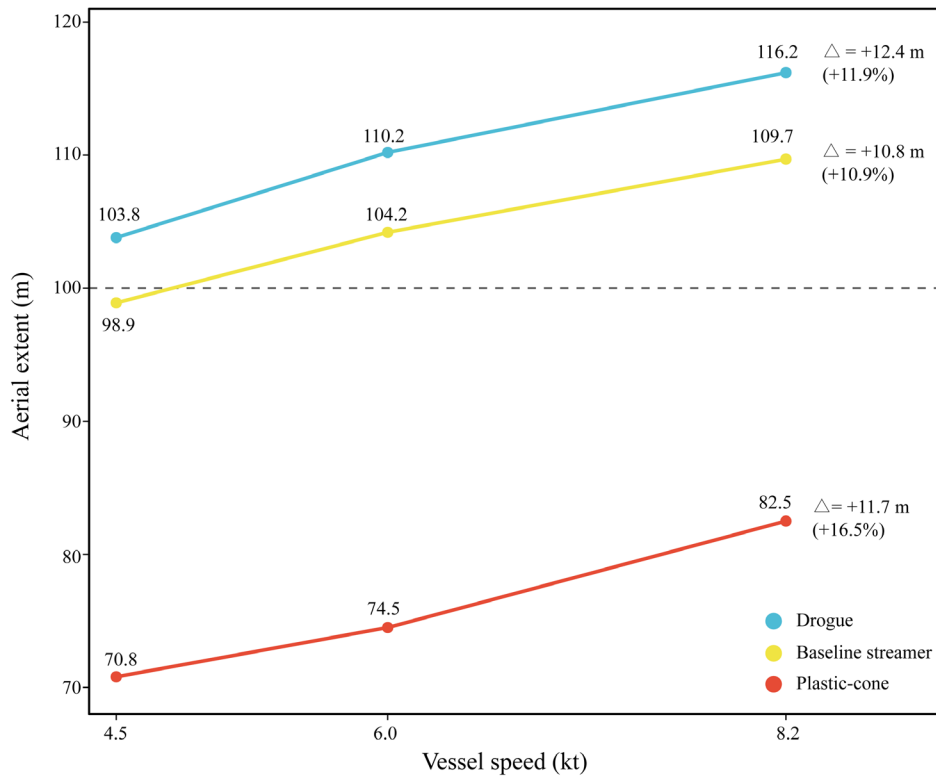


Figure 6 Changes in aerial performance of the three tori line configurations at different vessel speeds

4 Discussion

This study showed that different tori line configurations exhibited clear differences in aerial extent under the same test platform and similar operating conditions. Among them, the drogue configuration achieved the longest aerial extent at all three vessel speeds, the baseline streamer configuration showed intermediate performance, and the plastic-cone configuration consistently recorded the shortest aerial extent. These results indicate that changes in tail-section configuration can markedly affect the deployment state of a tori line above the critical area astern of the vessel and its ability to maintain continuous aerial coverage. The primary function of a tori line is to form a continuous aerial deterrent zone astern of the vessel, thereby reducing opportunities for seabirds to approach and attack sinking baited hooks. Therefore, aerial extent has long been regarded as an important technical indicator for evaluating the physical performance of tori lines. Relevant studies and best-practice guidance have emphasized that the aerial coverage provided by a tori line should, as far as possible, cover the critical astern area

until baited hooks sink to depths accessible to seabirds, and that tori lines should be used in combination with other mitigation measures (Melvin et al., 2014; Sato et al., 2013).

Based on the results of the present trial, the drogue configuration achieved the longest aerial extent at all vessel speeds. We infer that this was mainly attributable to the large submerged projected area of the drogue, together with the anti-sinking float, which allowed the drogue to stably “hold” the water flow at its optimal operating depth and generate substantial hydrodynamic drag to support the aerial self-weight of the 200 m-class tori line backbone. By contrast, the most striking finding of this study was that the series of plastic cones, which was originally designed specifically to reduce the risk of entanglement between the terminal attachment and the longline gear, performed worse across all tested conditions than the baseline streamer configuration, which had no terminal attachment. This counterintuitive phenomenon reveals the dynamic force-balance mechanism of tori lines at the air-water interface. Although the baseline streamer configuration had no specific additional drag-generating component, several tens of metres of its terminal backbone were submerged, providing relatively stable and continuous towing tension through the skin friction drag generated by the line itself. In contrast, the series of plastic cones had a relatively low overall drag-generating capacity, and at medium to high vessel speeds of 4.5-8.2 kt, the lightweight cones were prone to surfing or porpoising on the wave surface. Once the cones skipped over wave crests, hydrodynamic drag could be lost instantaneously, causing sharp fluctuations in backbone tension and a rapid collapse of aerial extent. The engineering implication of this phenomenon is that the presence of a terminal attachment is not necessarily better than its absence. If the drag-generating component is poorly selected or has excessive dynamic instability while attempting to balance anti-entanglement safety, it may instead disrupt the original underwater configuration of the tori line backbone.

It should be noted that this study compared differences in aerial extent among different configurations. The differences between the drogue configuration and the plastic-cone configuration may have been influenced not only by their structural forms,

but also by the size and number of the attached components and the resulting differences in towing drag. Therefore, the present results are more appropriately interpreted as indicating that, under the configuration parameters used in this trial, the drogue configuration exhibited better aerial performance. They should not be directly attributed to an absolute inherent advantage of any particular structural form of terminal attachment. In addition, this study evaluated physical aerial extent, rather than actual bycatch rates. Seabird bycatch levels are influenced not only by tori line configuration, but also by multiple factors such as night setting, branchline weighting, seabird community composition, vessel type, sea state, and operational consistency (Dias et al., 2019; Jiménez et al., 2020; Good et al., 2020). Therefore, the present conclusions should not be taken as final verification of bycatch mitigation effectiveness.

At the same time, only one representative aerial extent value was obtained for each “configuration-vessel speed” combination in this trial, and wind conditions differed to some extent among tests. Owing to the constraints of the actual vessel operating schedule, certain environmental characteristics were objectively associated with specific configurations. This data structure involved a high degree of multicollinearity, making it difficult to effectively isolate the main effect of wind speed using a simple multivariate statistical model. However, from the perspective of fluid mechanics, seawater is approximately 800 times denser than air. Therefore, the high towing tension of the tori line was derived predominantly from the hydrodynamic drag generated by the underwater components, whereas the aerodynamic lifting effect of wind-field fluctuations on the backbone configuration was extremely limited. Cross-comparison of the data also strongly supports this interpretation: the plastic-cone configuration still showed the poorest aerial performance under the highest wind speed recorded during the trial, whereas the drogue configuration continued to show increasing aerial extent as vessel speed increased and wind speed decreased. This indicates that the fundamental driving force behind the significant differences in aerial extent was the difference in underwater hydrodynamic resistance, rather than aerodynamic disturbance. Overall, the experimental conditions of this study met the logical requirements for horizontal

comparison.

In view of these considerations, future studies should conduct repeated trials under a wider range of sea states, vessel types, and operating conditions. Under conditions where the drag level of the towed object and the basic tail-section structure are standardized as far as possible, further work should distinguish between structural effects and size-related effects among configurations. In addition, seabird behaviour observations or actual bycatch records should be incorporated to further verify the mitigation effectiveness of different configurations.

Based on the above field measurements and physical mechanisms, this study suggests that although the conservation and management measures (CMMs) of some RFMOs require a towed object to be attached when a tori line is shorter than a specified length, they have not yet clearly defined the physical characteristics required for such an object. The at-sea tests showed that if a device with insufficient drag is used, it may induce surfing and porpoising at the sea surface, preventing the tori line from achieving the required minimum aerial extent and thereby compromising the effectiveness of bycatch mitigation.

Accordingly, it is recommended that future revisions of relevant CMMs further refine the technical requirements for towed objects. Considering the differences in operating conditions among fleets, it is first recommended that CPCs be encouraged to undertake feasibility and performance studies of mitigation measures based on their specific operational conditions. Furthermore, without mandating any specific type of towed object, it is recommended that “the ability to provide sufficient and stable drag” be established as the technical benchmark requirement for towed objects, so as to ensure that the aerial extent can effectively cover the sinking area of baited hooks. This combined approach would provide fleets with more science-based guidance for equipment selection and help improve the practical compliance effectiveness of seabird bycatch mitigation measures.

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Appendix 1

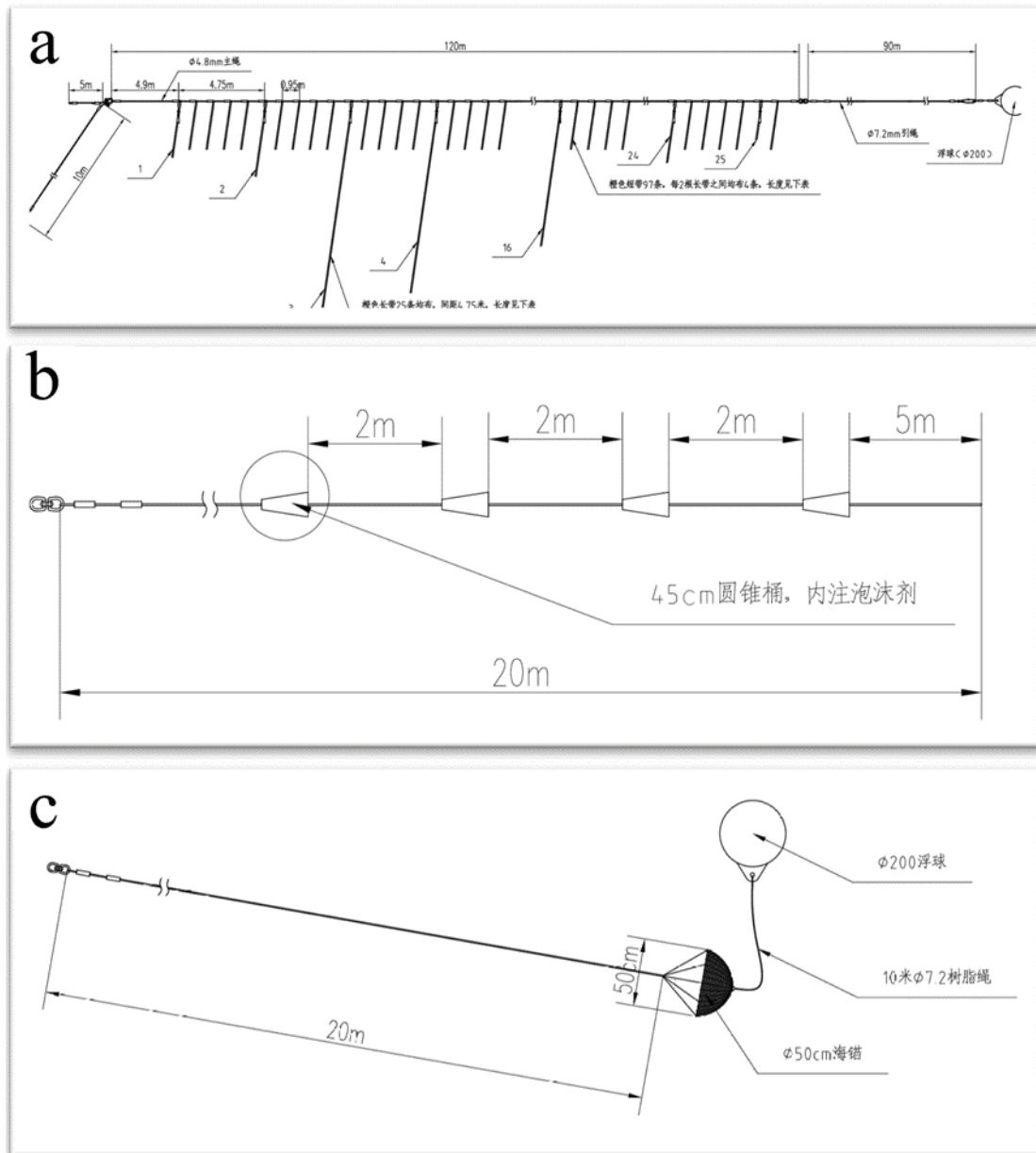


Figure 1A Schematic diagram of the tori line structure and the structures and main parameters of the two modified tail-section towed objects (a-c: the baseline streamer configuration, plastic-cone configuration, and drogue configuration, respectively)