OPTIMIZING TORI LINE PERFORMANCE THROUGH TERMINAL TOWING CONFIGURATIONS IN TUNA LONGLINE FISHERIES

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Purpose, expectation and action intended (select one or more and include corresponding text)

Discussions (for information and open discussion):

The paper informs members of at-sea trial results on tori-line terminal towing configurations, as set out in Section 2-3.

Abstract

Tori lines are commonly used to mitigate seabird bycatch in distant-water tuna longline fisheries. Their effective application is important for reducing the impacts of distant-water fishing activities on marine biodiversity, and aerial extent directly determines the effective range of the aerial deterrent zone formed astern of a vessel. At present, several regional fisheries management organizations use an aerial extent of 100 m as an important reference benchmark. However, tori line performance under actual fishing conditions can be influenced by multiple factors, and whether aerial extent can consistently attain this target has not yet been systematically evaluated. To examine the effects of different tail-section towing configurations on tori line aerial-extent performance, an at-sea comparative trial was conducted aboard the tuna longline vessel Rongheng 513. Three tori line configurations were evaluated at representative operational vessel speeds of 4.5, 6.0, and 8.2 kt. These included the baseline streamer configuration as the reference, the plastic-cone configuration, and the drogue configuration. A sensitivity analysis was also conducted using low-, moderate-, and high-drag scenarios, and the drag force generated by each configuration was estimated using an engineering approach. The results showed that tail-section towing configuration clearly affected the aerial deployment of the tori line, and the ranking of estimated drag force was generally consistent with that of measured aerial extent. The drogue configuration achieved the best aerial-extent performance at all tested vessel speeds, with measured values ranging from 103.8 to 116.2 m, and met or exceeded the 100 m benchmark under all test conditions. The baseline streamer configuration ranked second, with aerial extent ranging from 98.9 to 109.7 m. The plastic-cone configuration consistently produced the shortest aerial extent, ranging from 70.8 to 82.5 m. These findings indicate that both the magnitude and stability of the drag generated by the tail-section towing configuration are important factors influencing tori line aerial-extent performance. A configuration that produces insufficient drag or exhibits poor dynamic stability may fail to improve aerial extent and may even reduce it. Accordingly, future revisions of relevant conservation and management measures or technical guidance should encourage fleets to conduct configuration assessments suited to their own vessel characteristics and operational conditions. Rather than prescribing a specific type of towing configuration, such measures or guidance should further clarify that tail-section towing configurations need to generate sufficient and stable hydrodynamic drag. These findings highlight the importance of performance-based evaluation of bycatch mitigation devices in distant-water fisheries.

Keywords: tuna longline fisheries; seabird bycatch mitigation; tori line; aerial extent; towing configuration; marine biodiversity conservation

Introduction

Fisheries bycatch is one of the major threats to pelagic seabird populations worldwide and remains an important concern in marine biodiversity conservation and fisheries ecosystem management[1,2]. Globally, different types of fisheries cause the deaths of hundreds of thousands of seabirds each year, with longline, gillnet, and trawl fisheries affecting seabird populations to varying degrees[3-7]. Among these fisheries, pelagic longline fisheries targeting tuna and swordfish are widely recognized as an important source of bycatch for albatrosses, petrels, and other seabirds. During line setting, seabirds may come into contact with sinking baited hooks while foraging, thereby creating a risk of bycatch[3,7].

Among the existing mitigation measures, tori lines are widely used in tuna longline operations because they are relatively simple to operate and readily adaptable. Their basic principle is to create a continuous zone of visual disturbance and physical deterrence above the line-setting area astern of the vessel, thereby reducing opportunities for seabirds to approach and attack sinking bait[8–11]. Best-practice advice issued by the Agreement on the Conservation of Albatrosses and Petrels (ACAP) clearly states that properly designed and deployed tori lines can effectively reduce seabird attacks on sinking bait and the associated risk of mortality[12,13]. However, their practical effectiveness is not determined solely by whether they are deployed, but is also influenced by configuration specifications, deployment quality, and operational conditions[8,10,11].

For a tori line, its protective capacity depends largely on whether it can maintain a sufficiently long and relatively stable aerial coverage over the critical area astern of the vessel. The principal quantitative metric used to measure this coverage is aerial extent, defined as the horizontal distance covered by the tori line between its attachment point and the point at which the line contacts the sea surface[8,12]. Melvin et al. noted that the aerial extent of a tori line should cover as much as possible of the distance astern travelled by the bait before it sinks beyond depths accessible to seabirds[8]. Otherwise, even when a tori line is deployed, it may fail to provide effective protection over the near-stern area where seabird attacks are most likely to occur. ACAP has provided specific recommendations for the minimum aerial extent of tori lines on vessels of different sizes, together with technical requirements for key parameters such as attachment height, streamer length, and streamer spacing[12,13]. It is therefore evident that aerial extent is not only a geometric measure of the physical deployment of a tori line, but also a key technical indicator for evaluating its potential protective capacity and configuration suitability.

From the perspective of fishing-gear physical characteristics, the aerial performance of a tori line depends not only on the deployed length of its backbone, but is jointly determined by several factors, including vessel speed, attachment height, backbone and streamer materials, and the drag generated by the terminal towing configuration. In its best-practice guidance on mitigating seabird bycatch in pelagic longline fisheries, ACAP explicitly states that the aerial coverage of a tori line depends on vessel speed, attachment height, towing drag, and the weight of the backbone material[12,13]. In particular, towed objects can directly affect the aerial deployment of a tori line by altering in-water drag and line tension, and therefore represent an important structural factor influencing aerial extent.

Previous 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. compared the effectiveness of single and paired tori lines and showed that deployment method can influence their deterrent performance[9]. Domingo et al. demonstrated on tuna longline vessels that the proper use of tori lines can significantly reduce seabird bycatch[14]. Melvin et al.[8], Jiménez et al.[10], and Gilman et al.[11] further showed that tori lines can perform consistently across different operational scales when deployed according to appropriate specifications and used in combination with other mitigation measures.

By comparison, research on the structural design of the tail-section drag components of tori lines and their performance under different hydrodynamic scenarios remains relatively limited. Goad divided tori lines explicitly into aerial and drag sections and, through at-sea trials of different drag-section configurations and towed-object designs, showed that drag-section design, the magnitude of towing drag, and its matching with operational speed can directly affect aerial extent and the operational stability of the configuration[15]. The latest ACAP review likewise identifies the generation of sufficient towing drag to maximize aerial extent as a key requirement for tori line design and deployment[16]. However, most existing studies have focused on the overall mitigation effectiveness of tori lines, comparisons among deployment methods, and their combined use with other measures. At-sea studies comparing the aerial performance of different tail-section towing configurations on a common experimental platform and at representative operating speeds remain scarce. This evidence gap is particularly relevant to the management of distant-water fisheries in Areas Beyond National Jurisdiction (ABNJ), where further field-based scientific evidence is still needed to improve the practical effectiveness of bycatch mitigation measures while maintaining the operational feasibility of fishing activities.

Accordingly, this study used a tuna longline fishing vessel as the experimental platform and conducted at-sea comparative trials at representative operational speeds. A baseline streamer configuration, which was used in actual fishing operations and had no additional terminal attachment, was selected as the control, while plastic-cone and drogue configurations fitted with terminal attachments were used as the experimental configurations. The objectives were to: (1) measure and compare the aerial extent of the three tori line configurations at different vessel speeds; (2) evaluate the gains or losses in aerial extent produced by the different towing configurations relative to the baseline streamer configuration; and (3) conduct engineering estimates of towing drag for different configurations under different drag scenarios. The results provide field-based evidence for optimizing tori line structure, selecting terminal towing configurations, and improving relevant technical guidelines, while also providing scientific support for bycatch management in distant-water fisheries and marine biodiversity conservation.

1 Data and methods

1.1 Experimental vessel and study area

At-sea trials were conducted in November 2025 in waters near Zhoushan, Zhejiang Province, China. The tuna longline fishing vessel Rongheng 513 was used as the experimental platform. The vessel had an overall length of 44.19 m, a moulded breadth of 7.6 m, a gross tonnage of 471, and a main-engine power of 960 kW (Figure 1a). All experimental measurements were completed consecutively in nearshore waters within 30°05′–30°07′ N and 122°25′–122°28′ E (Figure 1c) to minimize the influence of spatial differences in environmental conditions on measurements obtained for the different tori line configurations.

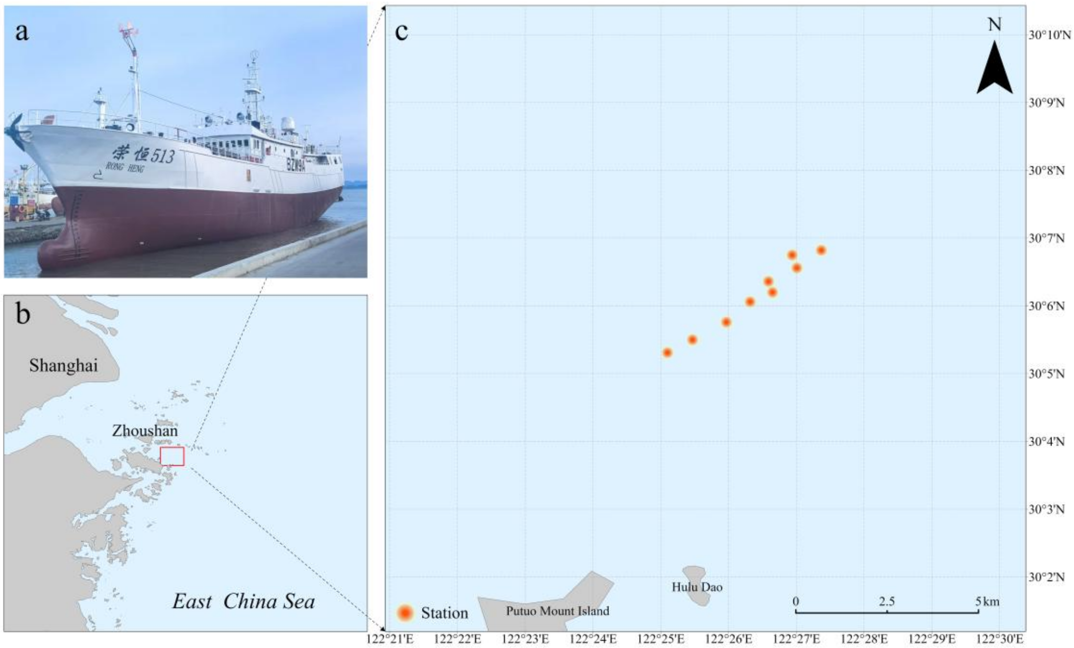

Figure 1 Schematic diagram of the test vessel, study area, and test stations (a: The test vessel Rongheng 513; b: location of the study area, with the red box indicating the enlarged area shown in panel c; c: starting stations of each test)

1.2 Tori line configurations and experimental design

The different terminal configurations were designed to alter the force characteristics of the tail section and thereby influence the aerial deployment of the tori line over the critical area astern of the vessel, allowing their effects on aerial extent to be evaluated.

Three tori line configurations were compared: the baseline streamer configuration, the plastic-cone configuration, and the drogue configuration. The baseline streamer configuration served as the control and represented the conventional deployment condition without an additional terminal attachment. The plastic-cone and drogue configurations served as the experimental configurations and were fitted with different types of terminal attachments to modify the in-water towing drag and force distribution of the tori line tail section. The field deployment and in-water trial configurations are shown in Figure 2, and the main structural parameters are provided in Table 1.

All three configurations were tested by towing at sea from the same experimental platform, Rongheng 513, to compare their aerial extent under actual operating conditions. It should be noted that the trial was designed to evaluate the practical application potential of the different tori line designs. Accordingly, within a realistic at-sea operational setting, the baseline streamer configuration and the two experimental configurations fitted with different terminal attachments were treated as three independent practical configuration options for a comparative assessment of their overall physical performance. This design provides a more objective representation of the actual effects of different terminal modifications in commercial fishing operations.

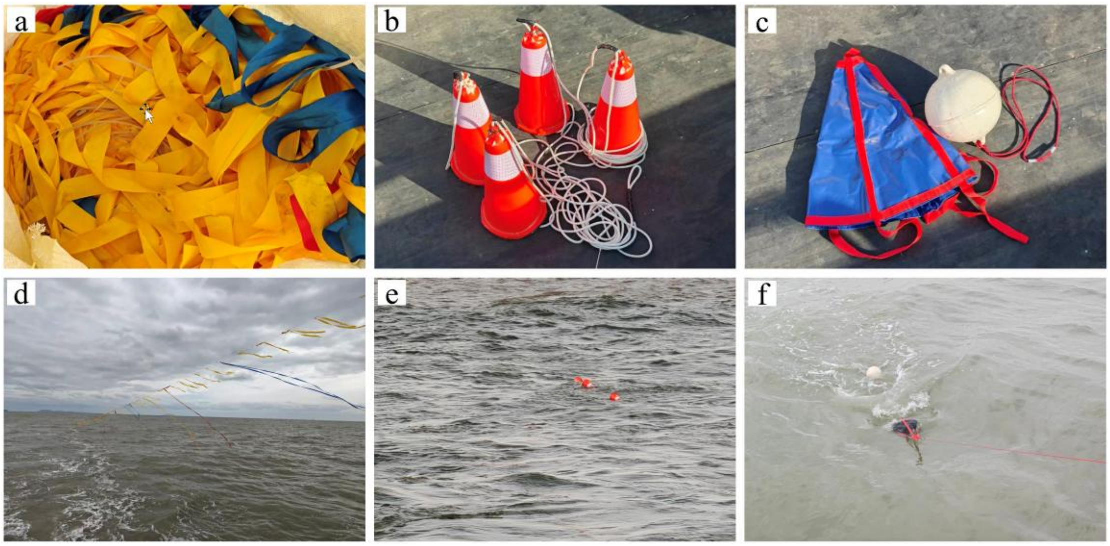

Figure 2 Physical photographs and at-sea operating conditions of the three tori line configurations (a-c: physical photographs of the baseline streamer configuration, plastic-cone configuration, and drogue

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	Drag-section and terminal towed-object structure
Baseline streamer configuration (control)	210 m	120 m backbone made of ultra-high-molecular-weight polyethylene (UHMWPE), 4.8 mm in diameter	Drag section approximately 90 m long; one Ø200 mm float attached at the terminal end; no additional towed object
Plastic-cone configuration (experimental)	140 m	120 m; identical in structure to the backbone of the baseline streamer configuration	Drag section approximately 20 m long; four plastic cones, each 45 cm high, installed at intervals of 2 m; approximately 5 m from the rearmost cone to the terminal end
Drogue configuration (experimental)	140 m	120 m; identical in structure to the backbone of the baseline streamer configuration	Drag section approximately 20 m long; one Ø50 cm drogue attached at the terminal end, followed by approximately 10 m of resin rope (Ø7.2 mm) and one Ø200 mm float

Note: Ø denotes diameter.

1.3 Definition and measurement of aerial extent

Aerial extent was used as the primary evaluation metric in this study to characterize the ability of a tori line to provide aerial deterrent coverage over the critical area astern of the vessel. Aerial extent was defined as the aerial coverage distance between the attachment point of the tori line and the point at which the line contacts the sea surface, namely, the horizontal distance over which the tori line remains suspended above the sea surface[15], as illustrated in Figure 3. To ensure comparability among configurations, the attachment height and experimental procedures were kept consistent for all three tori line configurations.

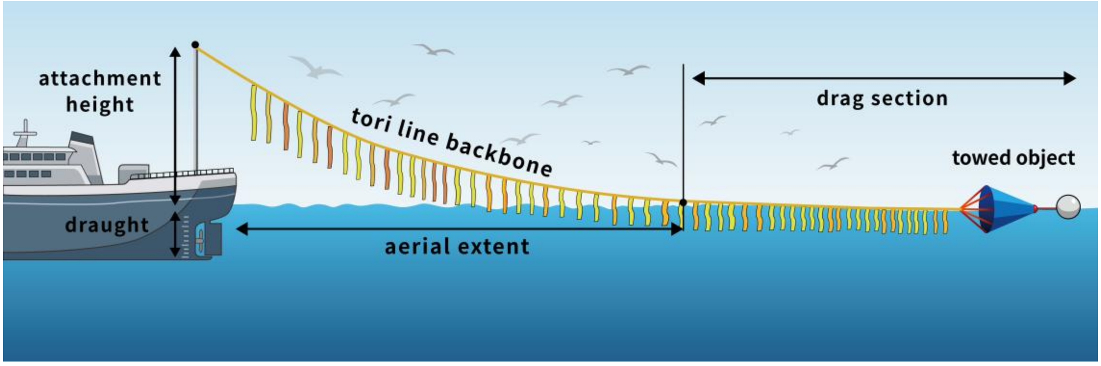

Figure 3 Schematic diagram of the tori line structure with a tail-section towed object and the definition of aerial extent (The definition shown in this schematic was adapted from Goad[15])

Field measurements of aerial extent were made using an INKERSI KE500 visual laser rangefinder (Figure A1), with a nominal measurement range of 3–500 m and a nominal ranging accuracy of ±(1 + D × 0.3%) m, where D denotes the measured distance. The supporting pole on the experimental vessel was 6 m long, the height from the top of the pole to the sea surface was 8.3 m, and the vessel draft was 4.2 m. During the field trials, each configuration was towed for 5 min after the vessel speed had stabilized. Once the tori line had reached a generally stable deployment state, its aerial extent was measured using the horizontal-distance mode of the instrument, and one representative measured value was recorded. Environmental parameters corresponding to each trial, including vessel speed, heading, current speed, and current direction, were also obtained from the vessel's instruments and recorded as background information for interpreting the results.

1.4 Experimental design and data analysis

The at-sea trial used a full-factorial design comprising three configurations and three vessel speeds. Based on routine line-setting practices in longline operations, three vessel-speed levels were selected: 4.5, 6.0, and 8.2 kt. At each vessel speed, towing trials were conducted separately for the baseline streamer configuration, plastic-cone configuration, and drogue configuration. During the trials, corresponding environmental information, including trial time, latitude and longitude, vessel heading, wind speed, current speed, and current direction, was recorded simultaneously as background information for subsequent interpretation of the results.

Aerial extent was measured for each combination of vessel speed and configuration, and the analytical approach comprised two dimensions. First, the 100 m aerial-extent requirement specified in seabird conservation measures was used as a reference benchmark to compare the absolute differences in aerial extent among the different tori line configurations at the same vessel speed and to determine whether each configuration met the benchmark. Second, the response of aerial extent to changes in vessel speed was examined separately for each configuration, and the relative percentage change in aerial extent was calculated to quantify the gains or losses in aerial performance associated with the different terminal attachments.

1.5 Engineering estimation of towing drag for different towing configurations under different drag scenarios

In addition to the comparison of measured aerial extent, the in-water towing drag of the three configurations was estimated using an engineering approach based on the measured geometric parameters. These estimates were used as a supplementary analysis to interpret differences in aerial performance among the configurations. Towing drag was estimated using the classical fluid-drag equation:

$$F_d = \frac{1}{2}\rho C_d A_{eff} V^2$$

where F_d is the estimated drag force, in N; ρ is the seawater density, set at 1025 kg m^{-3}; C_d is the drag coefficient; A_{eff} is the effective frontal area, in m^2; and V is the velocity of the towing configuration relative to the surrounding water. In this study, V was estimated by converting the experimental vessel speeds.

Because the orientations, degrees of submergence, and opening states of the plastic cones and drogue could vary during actual towing, their drag coefficients and effective frontal areas could not be determined in the field. Therefore, $C_d A_{eff}$ was combined and interpreted as the effective drag area, and three scenarios representing low, moderate, and high drag were established for sensitivity analysis (Table 2). The low-drag scenario represented parameter combinations in which the in-water line had a relatively low effective exposure to the flow and the additional attachment was only partially submerged or insufficiently opened. The moderate-drag scenario used representative intermediate parameter combinations as the nominal scenario for comparisons among configurations. The high-drag scenario represented parameter combinations in which the in-water line had a relatively high effective exposure to the flow and the additional attachment was more fully submerged or opened. These scenario parameters were used primarily to test the robustness of the relative ranking of estimated drag among configurations under different assumptions. The drag coefficients and drag-estimation method were based on classical fluid-mechanics references[17,18].

Table 2 Parameter values and scenario settings used for engineering estimation of drag force in the three tori line configurations

Configuration type	Hydrodynamic drag components	Engineering estimation scenarios for towing drag		
		Low-drag scenario	Moderate-drag scenario	High-drag scenario
Baseline streamer configuration	Distributed drag from the submerged line in the drag section	β = 0.05	β = 0.10	β = 0.15
Plastic-cone configuration	Drag from the submerged line in the drag section and additional drag from the plastic cones	C_d = 0.4 η_c = 0.10	C_d = 0.6 η_c = 0.20	C_d = 0.8 η_c = 0.40
Drogue configuration	Drag from the submerged line in the drag section and concentrated drag from the drogue	C_d = 0.8 η_d = 0.60	C_d = 1.0 η_d = 0.80	C_d = 1.2 η_d = 1.00

Note: β is the effective flow-exposure reduction coefficient for the submerged line; C_d is the drag coefficient of the additional towing device; η_c is the effective flow-exposure coefficient of the plastic cones; and η_d is the drogue-opening correction coefficient. These correction coefficients are engineering assumptions adopted in this study for the parameter sensitivity analysis.

2 Results

2.1 Overview of experimental environmental conditions

The at-sea trials for all configuration combinations were completed consecutively on the same day and within the same sea area, and the meteorological and current conditions remained relatively stable throughout the overall testing period. No substantial changes in surface-current conditions occurred during the trials; current speed remained between 1.4 and 1.6 km h^{-1}, and current direction remained stable at 65°. Sea-surface wind speed exhibited some natural variation, with measured values ranging from approximately 12.7 to 28.6 km h^{-1}. Specifically, wind speeds during testing of the baseline streamer configuration at the different vessel-speed levels were relatively low, ranging from 12.7 to 15.8 km h^{-1}. Wind speeds during testing of the plastic-cone configuration and drogue configuration were relatively higher, ranging from 26.3 to 28.6 km h^{-1} and from 22.7 to 26.2 km h^{-1}, respectively (Figure 4).

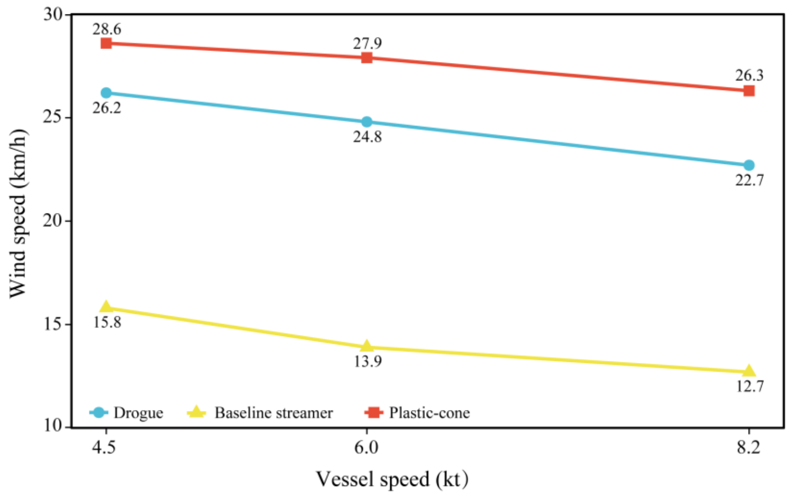

Figure 4 Wind speed under different vessel speeds and tori line configurations

2.2 Overall aerial extent performance and comparison with the 100 m benchmark

In the at-sea comparative trials, the three tori line configurations showed clear differences in aerial extent at the three operating speeds of 4.5, 6.0, and 8.2 kt. Under all tested conditions, the drogue configuration consistently achieved the best aerial performance, with aerial extent ranging from 103.8 to 116.2 m, followed by the baseline streamer configuration, with values ranging from 98.9 to 109.7 m. The plastic-cone configuration produced the shortest aerial extent, ranging from 70.8 to 82.5 m (Figure 5a).

Using a minimum aerial extent of 100 m as the reference benchmark, the drogue configuration exceeded this benchmark at all three vessel-speed levels and provided a sufficient safety margin of +3.8 to +16.2 m. This indicates that, even under fluctuations in vessel speed or sudden decreases in wind speed during operations, this configuration would still have a relatively high probability of maintaining compliance. The baseline streamer configuration exceeded the reference benchmark at the moderate and high vessel speeds of 6.0 and 8.2 kt, although its safety margin was relatively limited, ranging from +4.2 to +9.7 m. At the low vessel speed of 4.5 kt, its aerial extent was 98.9 m, slightly below the benchmark. By contrast, the plastic-cone configuration remained below the 100 m reference benchmark at all tested vessel speeds, reaching a maximum aerial extent of only 82.5 m and failing to form an ideal aerial deterrent zone (Figure 5 b-d).

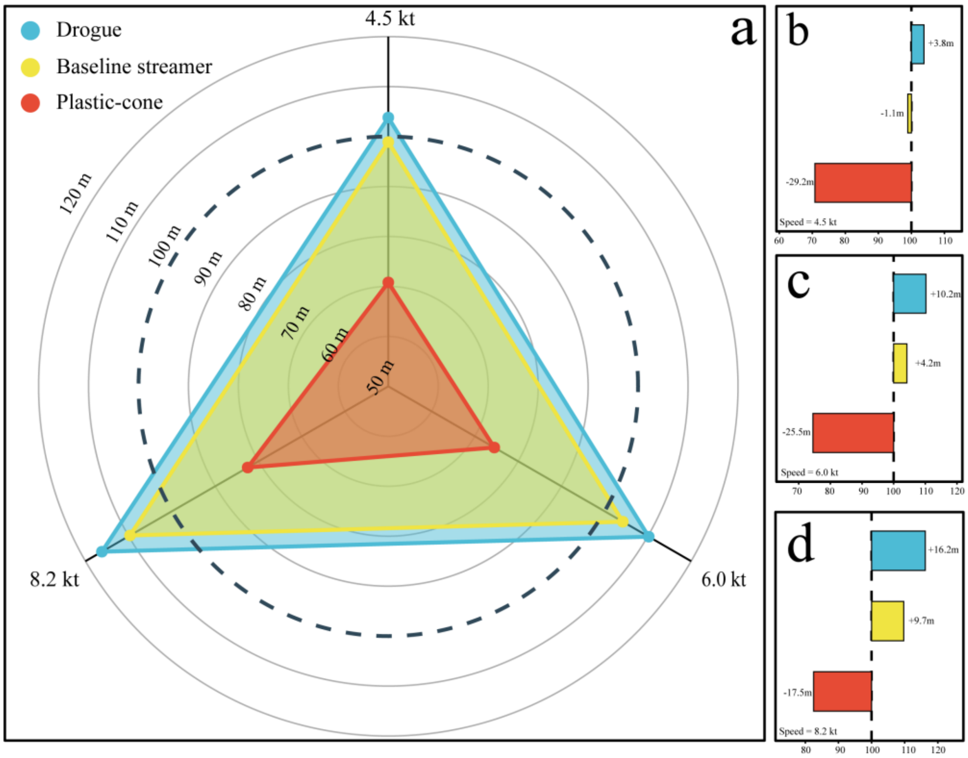

Figure 5 Comprehensive comparison of aerial extent performance among different tori line configurations at different vessel speeds (a: overall performance of the three configurations; b-d: differences from the 100 m benchmark at vessel speeds of 4.5, 6.0, and 8.2 kt, respectively)

2.3 Response of aerial performance to changes in vessel speed

The aerial extent of all three configurations increased with increasing vessel speed, indicating that the greater hydrodynamic drag associated with higher vessel speeds increased the aerial tension of all tori line configurations. However, the different attachments varied in their degree of response to changes in vessel speed (Figure 6). Specifically, when vessel speed increased from 4.5 kt to the highest routine operating speed of 8.2 kt, the drogue configuration showed the greatest absolute increase in aerial extent, rising from 103.8 to 116.2 m, an increase of 12.4 m (+11.9%). The plastic-cone configuration increased from 70.8 to 82.5 m, an increase of 11.7 m (+16.5%), while the baseline streamer configuration increased from 98.9 to 109.7 m, an increase of 10.8 m (+10.9%). Based on the average rate of change across the low- to high-speed range, the increases in aerial extent per unit increase in vessel speed were 3.35 m/kt for the drogue configuration, 3.16 m/kt for the plastic-cone configuration, and 2.92 m/kt for the baseline streamer configuration.

Using the baseline streamer configuration as the reference, the effects of the different additional tail-section attachments on aerial performance were clearly evident. The drogue configuration showed positive differences relative to the baseline streamer configuration, with aerial extent increasing by 5.0%, 5.8%, and 5.9% at vessel speeds of 4.5, 6.0, and 8.2 kt, respectively. By contrast, the plastic cones arranged in series showed negative differences relative to the baseline streamer configuration, with aerial extent decreasing by 28.4%, 28.5%, and 24.8% at the three vessel speeds, respectively.

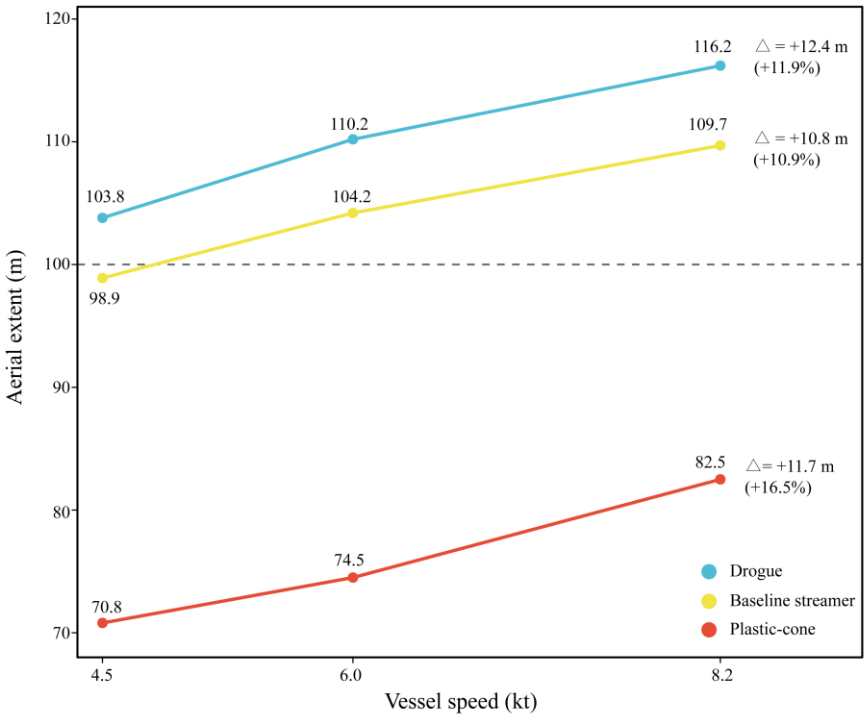

Figure 6 Changes in aerial performance of the three tori line configurations at different vessel speeds

2.4 Engineering estimates of towing drag for different configurations under different scenarios and their correspondence with aerial performance

Based on the characteristics of each configuration and the low-, moderate-, and high-drag scenarios, the effective drag area and towing drag of the three tori line configurations were estimated using an engineering approach at vessel speeds of 4.5, 6.0, and 8.2 kt (Figure 7). The results showed that the estimated drag force of all configurations increased markedly with increasing vessel speed, with clear differences among configurations. Across all three vessel speeds and drag scenarios, estimated towing drag was consistently highest for the drogue configuration, intermediate for the baseline streamer configuration, and lowest for the plastic-cone configuration. The different drag scenarios primarily affected the absolute values of the estimated drag but did not alter the relative ranking among the configurations.

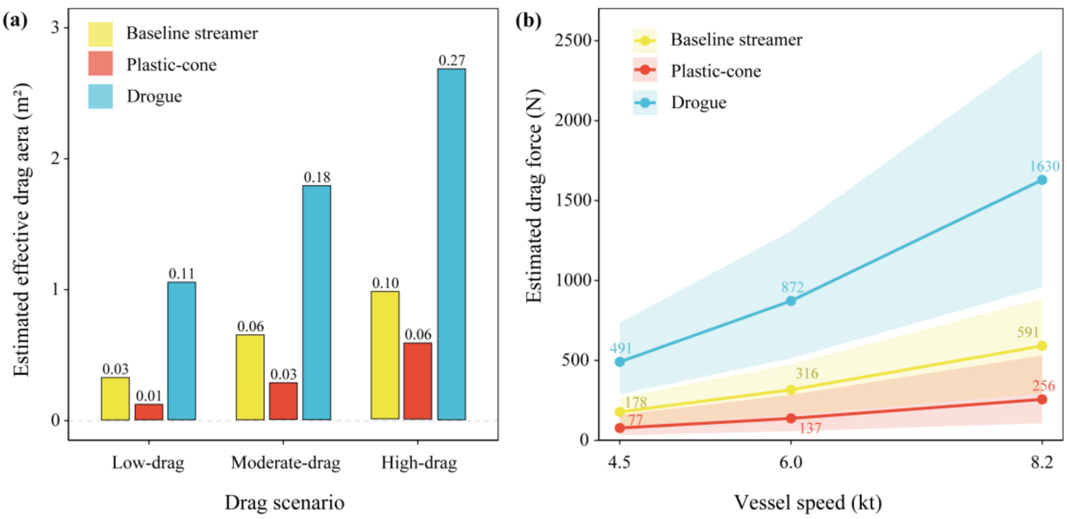

Figure 7 Scenario-based engineering estimates of drag section for the three tori line configurations (a: effective drag area under the low-, moderate-, and high-drag scenarios; b: estimated drag force at different vessel speeds, with solid lines representing the moderate-drag scenario and shaded bands representing the range from the low- to high-drag scenarios)

To further illustrate the correspondence between estimated towing drag and aerial performance, the engineering estimates obtained under the low-, moderate-, and high-drag scenarios were compared with the measured aerial extent at the corresponding vessel speeds (Figure 8). For the drogue configuration, all three observations were located above the 100 m reference line, whereas for the plastic-cone configuration, all three observations were located below it. For the baseline streamer configuration, the observation at 4.5 kt was slightly below 100 m, whereas those at 6.0 and 8.2 kt exceeded this reference value. Overall, the ranking of estimated towing drag among configurations was consistent with that of measured aerial extent. The blue shaded intervals in Figure 8 were defined by the two baseline streamer configuration observations at 4.5 and 6.0 kt and corresponded to estimated drag ranges of 89.0–158.2 N, 178.0–316.4 N, and 267.0–474.6 N under the low-, moderate-, and high-drag scenarios, respectively. These intervals represent descriptive brackets for this configuration relative to the 100 m reference value.

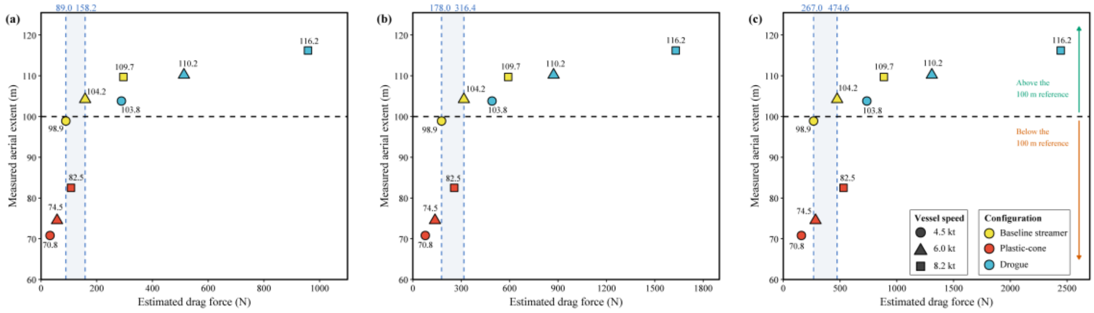

Figure 8 Correspondence between engineering estimates of drag force under the low-, moderate-, and high-drag scenarios and attainment of the 100 m aerial-extent reference benchmark (a: low-drag scenario; b: moderate-drag scenario; c: high-drag scenario. The blue dashed intervals were defined using the baseline-streamer observations and represent configuration-specific descriptive drag ranges relative to the 100 m reference value.)

3 Discussion

3.1 Differences in aerial performance among tail-section towing configurations

This study compared three tail-section towing configurations. The results showed that, using the same experimental vessel and broadly similar operating procedures, the drogue configuration achieved the greatest aerial extent at all three tested vessel speeds, followed by the baseline streamer configuration, whereas the plastic-cone configuration produced the shortest aerial extent. The engineering estimates of theoretical drag based on the parameters of each configuration and the different drag scenarios showed the same ranking, with the drogue configuration producing the highest estimated drag, the baseline streamer configuration ranking second, and the plastic-cone configuration producing the lowest estimated drag. This consistency in ranking indicates that the towing drag generated by the tail-section towing configuration and its stability may be among the important factors explaining the observed differences in aerial performance.

Aerial extent is generally regarded as an important indicator for evaluating the physical deployment and potential protective capacity of a tori line. Previous studies and technical guidance have emphasized that the aerial coverage of a tori line should extend as far as possible over the critical area astern of the vessel before baited hooks sink beyond depths accessible to seabirds[8,16]. From a structural perspective, Goad divided tori lines into aerial and drag sections and noted that drag-section design can affect aerial extent, configuration stability, and operational feasibility[15]. The results of the present study are broadly consistent with this view: the tail-section configuration is not merely an accessory structure at the end of the tori line, but may influence its ability to remain suspended above the area astern of the vessel by altering in-water drag, tail-section tension, and the position of the point at which the line contacts the sea surface.

The superior performance of the drogue configuration in this trial may be related to its larger effective frontal area and relatively stable operating orientation. Once opened underwater, the drogue can generate relatively concentrated towing drag, while the float attached behind it may help maintain its submerged operating state and reduce the likelihood of collapse or failure. Under all three drag-estimation scenarios, the drogue configuration produced the highest estimated drag at each of the three vessel speeds. Its measured aerial extent was also consistently the greatest and reached or exceeded the 100 m reference benchmark in every case. These findings indicate that, under the specific dimensions, connection arrangement, and operating-speed range used in this study, the drogue configuration was more likely to provide sufficient and relatively stable towing drag, thereby helping to maintain a greater aerial extent.

Although the baseline streamer configuration was not fitted with an additional towing device, its tail section was approximately 90 m long, and the portion of the line submerged during towing could generate sustained distributed drag through surface friction and its transverse projected area. Accordingly, the ability of the baseline streamer configuration to reach or approach an aerial extent of 100 m at moderate and high vessel speeds may be related to the continuous tension provided by its relatively long submerged tail section. The plastic-cone configuration produced the shortest aerial extent in this study, indicating that adding a towing device does not necessarily improve aerial performance. According to the engineering estimates, the effective drag of the plastic-cone configuration was lower than that of both the baseline streamer configuration and the drogue configuration. Two factors may explain this result. First, the geometric projected area of the plastic cones does not necessarily correspond to their effective frontal area during actual towing. Second, when towed near the sea surface, the plastic cones may become partially submerged, deflect from the flow, skim along the surface, or briefly emerge from the water, resulting in discontinuous drag generation.

In terms of relative changes, the drogue configuration showed a relatively large increase in theoretical drag compared with the baseline streamer configuration, but its aerial extent increased by only approximately 5.0–5.9%. By contrast, the plastic-cone configuration had lower theoretical drag than the baseline streamer configuration, and its aerial extent decreased by approximately 24.8–28.5%. These results suggest that the response of aerial extent to towing drag may not be proportional. When tail-section drag is insufficient or unstable, aerial extent may decrease markedly; once the drag is sufficient to maintain the basic deployment of the tori line, however, further increases in drag may produce only limited additional gains in aerial extent. Therefore, optimization of the tail-section configuration should not be understood simply as “the greater the drag, the better”. Instead, the configuration should provide sufficient and stable towing drag while ensuring safe retrieval, reducing entanglement risk, and remaining suitable for the vessel type.

3.2 Effects of operational conditions on tori line aerial performance

In addition to the towing configuration, vessel speed, wind and sea conditions, vessel structure, and deployment method can also influence the actual aerial performance of a tori line. In this study, the aerial extent of all three configurations increased with vessel speed, which was broadly consistent with the theoretical relationship whereby drag increases with the square of relative flow velocity. Higher vessel speeds may increase tail-section towing drag and line tension, thereby shifting the point at which the tori line contacts the sea surface farther astern and increasing aerial extent accordingly. Therefore, tori line performance should not be evaluated independently of the actual operating speed. Across different fleets, even tori lines of the same length or similar structure may show different aerial performance because of differences in line-setting speed. Goad[15] also noted in trials on small longline vessels that drag-section design should be matched to operating speed rather than relying solely on a fixed line length or a fixed type of attachment.

Current speed varied little during the trials, but the wind speeds corresponding to the different configurations were not completely consistent. Wind speed and direction may affect the movement and lateral displacement of the aerial backbone and streamers, as well as the stability of the point at which the tori line contacts the sea surface. Sea conditions may also affect the submerged state of tail-section attachments such as plastic cones and drogues. However, the plastic-cone configuration still produced the shortest aerial extent under relatively high wind speeds, whereas the drogue configuration maintained a relatively long aerial extent as vessel speed increased. This suggests that differences in wind speed alone are unlikely to explain the observed differences in aerial extent among the configurations. Given that fleets differ in attachment height, stern structure, retrieval methods, and entanglement-prevention requirements, the results of this study are more appropriately regarded as field-based evidence under the specific vessel type and configuration conditions tested. Further application should therefore include assessments of configuration suitability under the relevant operational conditions.

3.3 Management implications for optimizing seabird bycatch mitigation measures

This study shows that adding a towing configuration to the tail section of a tori line does not necessarily improve aerial performance. Its effectiveness depends primarily on the magnitude and stability of the hydrodynamic drag generated by the towing configuration. Under the conditions tested, the drogue configuration reached or exceeded the 100 m reference aerial extent recommended by regional fisheries management organizations, whereas the plastic-cone configuration remained below this reference value despite being fitted with an additional towing device. This indicates that the presence of a towing device alone is insufficient to ensure that a tori line achieves the intended deterrent coverage. The key requirement is whether the towing configuration can generate sufficient and stable hydrodynamic drag under actual operating conditions, thereby maintaining the target aerial extent. This performance-oriented approach to technical evaluation is also consistent with findings from other studies of bycatch mitigation in pelagic longline fisheries. Because mitigation effectiveness may vary among species and regions, the selection of bycatch mitigation technologies should be evaluated in relation to the target species, fishing operations, and regional conditions rather than being prescribed uniformly on the basis of device or measure type alone[19].

Accordingly, based on the findings of this study, future conservation and management measures or technical guidelines could further encourage fleets to assess the practical aerial performance and suitability of different towing configurations in relation to their vessel types and operational characteristics. Fleets should select towing configurations capable of providing sufficient and stable hydrodynamic drag under actual operating conditions, rather than being required to use one specific type of towing device. This performance-based approach, which emphasizes optimization rather than prescribing a particular device, can accommodate operational differences among fleets, improve the applicability and practical effectiveness of tori line measures, and provide scientific evidence for the continued revision of relevant technical guidelines.

3.4 Limitations and future research directions

This study provides data on the aerial performance of three tail-section towing configurations at actual operating speeds and uses scenario-based engineering estimates to support the interpretation of the observed differences. However, the findings remain subject to certain limitations in applicability. First, the trials were conducted on a single tuna longline fishing vessel, and the results therefore primarily reflect the relative performance of the different configurations under the vessel type, configuration parameters, and operational conditions tested. Further replicated trials are needed across different vessel types, attachment heights, sea conditions, and operating speeds to assess the stability and applicability of the aerial performance of different towing configurations. Second, this study used an engineering estimation approach to analyze the towing drag of the different configurations. Future studies could incorporate direct measurements of towing drag or line tension to further quantify the relationship between towing drag and aerial extent. In addition, this study focused primarily on the physical aerial performance of tori lines, and their actual effectiveness in reducing seabird bycatch requires further validation. Future research could combine observations of seabird approaches, attacks, or bait-taking behavior with actual bycatch records to comprehensively evaluate the effectiveness of different towing configurations in reducing seabird bycatch risk. Establishing a quantitative relationship between aerial performance and mitigation effectiveness would provide scientific support for the continued optimization of seabird bycatch mitigation measures by regional fisheries management organizations and for marine biodiversity conservation in areas beyond national jurisdiction (ABNJ).

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Appendix

Figure A1 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)