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Creating a conservation network: Restoration of the critically endangered Chinese crested tern using social attraction

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ABSTRACT

Social attraction techniques have been demonstrated effective in restoring seabird breeding colonies, especially colonies of terns (Subfamily: Sterninae). The Chinese crested tern (*Thalasseus bernsteini*) is a critically endangered seabird with a global population of about 100 breeding adults and a breeding range restricted to the East China Sea and the Yellow Sea. In order to restore a breeding colony of Chinese crested terns in an archipelago where a former colony had been abandoned, social attraction (decoys and audio playback systems) was deployed on a small, uninhabited island with no history of seabird nesting. The objective was to establish a breeding colony of greater crested terns (*T. bergii*), a closely-related common species, in the hope that Chinese crested terns would follow. Thousands of greater crested terns and at least 19 Chinese crested terns colonized the island during the first breeding season after deployment of social attraction. After three years of successful breeding, the colony was abruptly abandoned early in the fourth breeding season because of invasive king rat snakes (*Elaphe carinata*), which consumed all tern eggs. Following removal of all snakes from the colony, terns resumed nesting the subsequent year. Recovery of this critically endangered seabird depends on repeating this process at multiple islands. Careful planning, in conjunction with habitat management, close colony monitoring, and deployment of social attraction, can establish a conservation network of suitable, secure colony sites where most breeding adults can reproduce successfully. This approach can be used to restore a variety of declining seabird species along the Chinese coastline.

1. Introduction

Nearly one-third of seabird species are threatened with extinction due to entanglement with fishing gear, reduction in marine food supplies, environmental contaminants, oil spills, overharvest, and introduction of invasive species that prey on breeding seabirds or destroy their nesting habitat (IUCN, 2017). Restoration of historical populations and the protection of seabirds from further threats are the major conservation goals for seabirds worldwide. Over the long-term, it has been assumed that if suitable nesting habitat and protection from anthropogenic disturbance could be provided, populations of threatened birds would recover (Ahlering and Faaborg, 2006). But this strategy may be inadequate in some cases, especially for colonial species, including most seabirds, whose selection of nesting habitat is largely determined by social cues whose absence may delay recovery, even when suitable habitat is available (Clout, 2001; Doligez et al., 2002).

Since the 1970s, new techniques have been developed and implemented to actively enhance seabird restoration efforts (Jones and Kress, 2012). These techniques, which can be classified into two major categories: social attraction and chick translocation, have been used in at least 171 different seabird restoration projects conducted in 16 countries/regions in an attempt to restore 64 seabird species (Zhou

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et al., 2017). With social attraction, decoys (models of adults, chicks, and eggs), playback of recordings of vocalizations, mirrors, scent, and artificial burrows are used to lure adult seabirds to restoration sites with the goal of establishing breeding colonies (Jones and Kress, 2012). More than 95% of seabird species, especially terns (Sterninae), can be attracted to breeding sites by the presence of conspecifics and other seabirds (Rolland et al., 1998). Also, terns feed their young and provide other parental care for extended periods post-fledging, suggesting that chick translocations would likely not result in fledged young that would survive to recruit into the breeding population.

To assure the success of a restoration project using social attraction, some important procedures should be followed, including nesting habitat enhancement, deploying social attraction before the nesting season, close monitoring of the incipient colony, and control of predators that may threaten the colony. A full understanding of the breeding biology of the targeted species is also crucial, especially social factors such as colony size, nesting density, and nesting synchrony, which can play key roles in restoration success (Kress, 1983; Roby et al., 2002). Jones and Kress (2012) listed 82 seabird restoration projects using social attraction techniques worldwide, and 44 of these projects (54%) were confirmed to have been successful. Restoration of a breeding colony of an endangered species using social attraction techniques, however, would likely face particular challenges due to small population size.

The Chinese crested tern (*Thalasseus bernsteini*) is perhaps the most threatened seabird species in the world. It was rediscovered in 2000 after a 63-year period with no confirmed sightings, when the species was presumed extinct (Liang et al., 2000). Total population size was estimated at no more than 50 individuals, and it was listed by the IUCN as Critically Endangered (BirdLife International, 2017). The most serious immediate threat to the survival of the species was exploitation – illegal harvest of eggs by fishermen (Chen et al., 2009). Beyond the direct take of eggs, the disturbance associated with fishermen landing on breeding islands to collect eggs or shellfish apparently caused breeding terns to abandon suitable nesting sites. Another documented cause of nest failure in Chinese crested terns is ill-timed summer typhoons (Chen et al., 2015). Long-term issues of conservation concern for the species include nesting habitat loss due to development on islands, the introduction of mammalian predators (e.g., rats [*Rattus* spp.]), and the degradation of foraging habitat in coastal areas due to sewage discharge, agricultural chemical runoff, and industrial pollution. These threats to the Chinese crested tern have not been adequately evaluated due to the lack of close monitoring and research since the species was rediscovered.

Considering the extremely small population size and severe threats to survival, the primary conservation action following rediscovery was safeguarding all Chinese crested terns. But fluctuations in population counts since rediscovery of the species implied that there might be other breeding adults besides those nesting at the two know breeding colonies. While the extensive known breeding range of the species made it extremely difficult to find additional breeding colonies, the frequent shifts among colony sites led to severe challenges in safeguarding the breeding population (Chen et al., 2011). If Chinese crested terns could be attracted to a site with suitable nesting habitat that is continuously monitored and secured against egg harvest and other human disturbances, however, the most serious immediate threats to the species might be quickly addressed, and the species could reverse recent declines and climb back from the brink of extinction.

In 2013, a tern restoration project was initiated in the Jiushan Islands (Fig. 1), the location of a former breeding colony of Chinese crested terns that was abandoned in 2007 after breeding failure due to illegal egg harvest. Tiedun Dao, which was selected for the restoration project, is near the original breeding island (Jiangjunmao), but was not known to have been occupied by breeding seabirds. Social attraction techniques were considered essential for establishing a breeding colony of Chinese crested terns on Tiedun Dao; however, these techniques had never before been used to restore a breeding colony of such an extraordinarily rare species. To improve the chances for success, we used social attraction techniques to try to establish a new breeding colony of greater crested terns (*T. bergii*). Since their rediscovery, Chinese crested terns had only been found nesting in large colonies of greater crested terns (Chen et al., 2011); therefore, we hoped that Chinese crested terns would subsequently recruit to a new breeding colony of greater crested terns.

Using this approach, and monitoring the restoration site closely, we sought to achieve three objectives: (1) attract greater crested terns to nest at a new breeding site by using social attraction techniques; (2) establish a new colony of Chinese crested terns within a colony of the common sympatric congener; (3) provide a more robust estimate the global population of Chinese crested terns; if the successful restoration of a mixed breeding colony of greater crested terns and Chinese crested terns in the Jiushan Archipelago did not negatively affect the size of the other two known breeding colonies for Chinese crested terns, it would indicate that there are other breeding-age Chinese crested terns and as yet undiscovered breeding colonies for the species somewhere in the northwestern Pacific. Achieving these objectives is a crucial first step for the longer-term goal of establishing a well-protected and closely-monitored network of breeding islands for greater crested terns and Chinese crested terns, which would address the difficulties in the conservation of this critically endangered species and save it from extinction.

2. Methods

2.1. Study species and area

The Chinese crested tern has been a poorly-known species since it was first described in 1863. Following the collection of 21 specimens in 1937 along the coast of Shandong Province, China, there were no confirmed records until four adults and four chicks were found among a large colony of greater crested terns in the Matsu Islands, Taiwan, along the Fujian Province coast of China in 2000 (Liang et al., 2000). Prior to this discovery, many ornithologists had presumed the Chinese crested tern was extinct.

Since rediscovery in 2000, breeding has now been confirmed in five locations. Three of these locations were found before 2013 and are along the Chinese coast: the Matsu Islands (Liang et al., 2000; Hung et al., 2019), the Jiushan Islands, and the Wuzhishan Islands (Chen et al., 2010; Fig. 1). In 2016, two other small breeding colonies of Chinese crested terns were confirmed for the first time: an uninhabited island off the southwestern coast of South Korea (Song et al., 2017), and the Penghu Islands of Taiwan (Liu and Hetherington, 2016).

The continental coastline of Zhejiang Province extends over 2200 km from 27°06′N to 31°11′N, and there are 3061 islands off the coast of Zhejiang Province, 2886 of which are uninhabited. The Jiushan Archipelago (29°26′N, 122°10′E) is situated 19 km off the coast of Xiangshan County, eastern Zhejiang Province (Fig. 1) and consists of 76 uninhabited islands that were included in the Jiushan Islands National Nature Reserve in 2011. In 2004, a breeding colony of Chinese crested terns, the first to be discovered after the rediscovery of the species nesting in the Matsu Islands, was found on Jiangjunmao Island in the Jiushan Archipelago. About 10–20 adult Chinese crested terns were found nesting among ca. 4000 greater crested terns (Chen et al., 2009). In 2005 and 2006, no Chinese crested terns were found nesting in the Jiushan Islands, but in 2007 eight Chinese crested terns were again observed breeding among nesting greater crested terns on Jiangjunmao Island. Illegal egg harvest apparently caused all crested terns to abandon the Jiushan Islands after the 2007 breeding season.

Tiedun Dao is a 2.58-ha island with a maximum elevation of 26.8 m asl that was chosen as a tern colony restoration site in the Jiushan Archipelago. Tiedun Dao is located about 1 km from Jiangjunmao Island, the site where nesting by Chinese crested terns was first detected

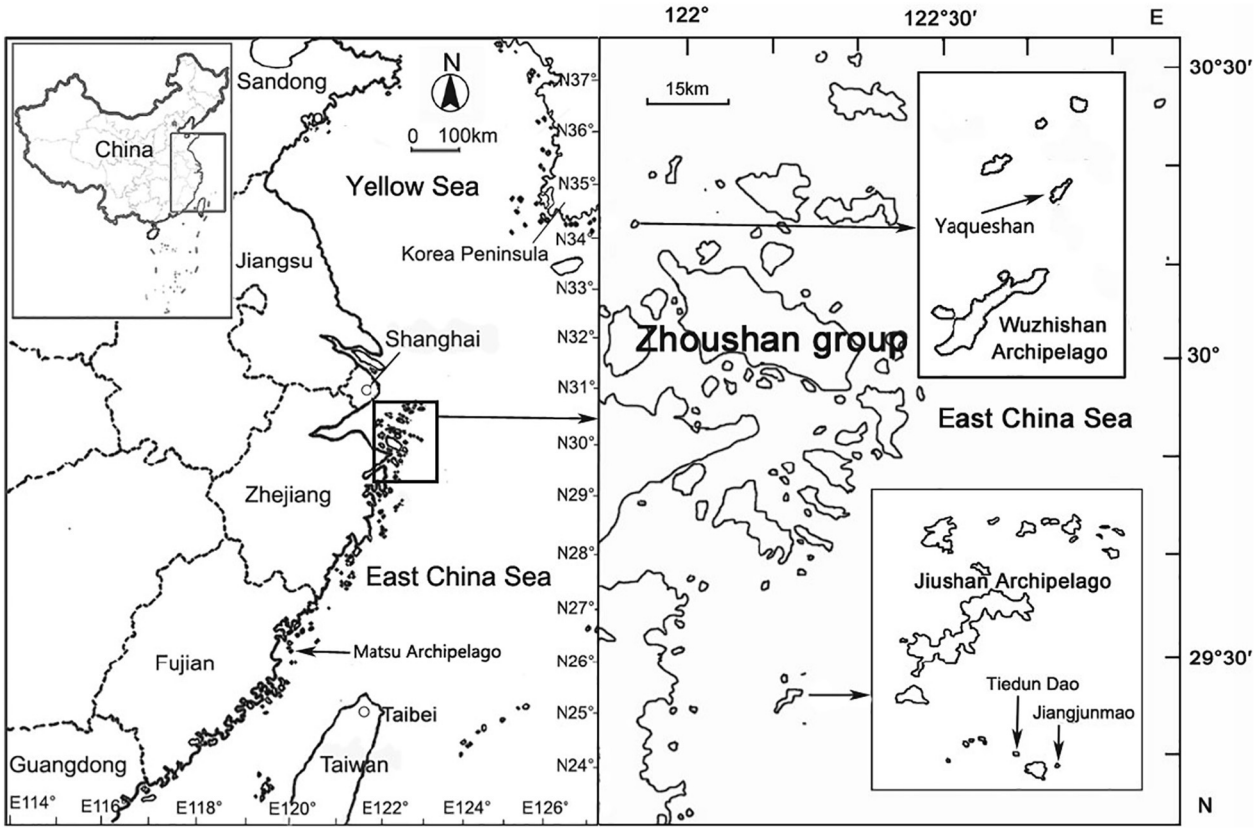

Fig. 1. The study area, including the two sites in Zhejiang Province where Chinese crested tern restoration projects have used social attraction techniques: Tiedun Dao in the Jiushan Archipelago and Yaqueshan in the Wuzhishan Archipelago.

in the Jiushan Islands, and is within the core protected area of the Nature Reserve (Fig. 1). It was selected based on several criteria, including (1) absence of human occupation and mammalian predators, (2) accessibility for site preparation and monitoring, (3) presence of dense vegetation on top of the island, allowing colony monitors to live on the island without disturbing nesting seabirds, and (4) proximity to Jiangjunmao Island, the former site of a mixed species tern colony.

The Wuzhishan Archipelago (30°13′N, 121°50′E) is located at the mouth of Hangzhou Bay, 7 km offshore of the largest island in the Zhoushan Group (Fig. 1). It consists of 7 uninhabited islands that were included in the Wuzhishan Islands Provincial Nature Reserve in 2001. Since 2008, two to six pairs of Chinese crested terns have been observed nesting among greater crested terns at large colonies in the Wuzhishan Islands (Chen et al., 2011). The tern colony shifted among four islands, depending on the breeding season, including Mantoushan, Yaqueshan, Longdongshan, and Wumaoshan. In 2014, however, this mixed-species breeding colony disappeared. In 2015, we chose Yaqueshan as a second restoration site where social attraction would be deployed in an effort to stabilize the breeding colony there. Yaqueshan is a 1.08-ha island with a maximum elevation of 18.5 m asl; the island is relatively flat and covered by short grass compared to the other islands in the Wuzhishan Archipelago.

2.2. Social attraction techniques

Social attraction aims to lure adult birds to restoration sites with the goal of establishing or re-establishing breeding colonies where none currently exists. Most seabird species are gregarious colonial nesters, excellent candidates for restoration because they can be lured using social attraction techniques that seek to replicate features of an established colony (Kress, 1983; Roby et al., 2002; Jones and Kress, 2012). Most tern species are amenable to the use of social attraction to lure them to a site where suitable nesting habitat is available. Decoys are deployed across a prospective colony site and recordings of calls are played using automated audio playback systems. The visual and audio cues cause prospecting adult terns to investigate the site and remain until other potential mates are also attracted. This technique, coupled with intensive monitoring and management of any problems that arise (e.g., predators) has been successful in restoring breeding colonies of nearly 50 different seabird species around the globe (Jones and Kress, 2012; Zhou et al., 2017).

In early 2013, before the breeding season, we used bait stations and track plates to survey for potential mammalian predators at Tiedun Dao. Lesser rice field rats (*Rattus losea*) were detected on Tiedun Dao; consequently, we used the rodenticide Bromadiolone dispensed at bait stations to eradicate rats from the island. According to Chen et al. (2011), the preferred nest substrate of mixed colonies of greater and Chinese crested terns includes grassy areas, bare rock, and a zone of interspersed bare rock and low grass devoid of tall vegetation. We identified the eastern part of Tiedun Dao as having substrate most suitable for nesting terns and the prospective site for a new tern breeding colony; this part of the island includes an extensive area of bare rock that slopes down to the shoreline, providing access to the water's edge for older chicks.

In late April of 2013, one month before the tern breeding season started, we dispensed rodenticide to eradicate rats from the island. Then we cleared vegetation, uprooted tall grasses, and cut shorter grasses in a rectangular area about 60 m × 200 m as the predetermined site for the prospective tern colony. To provide social attraction at the new colony site, we securely installed 350 plastic greater crested tern decoys and 50 Chinese crested tern decoys. We also deployed three audio playback systems (Murremaid Music Boxes, South Bristol, Maine, USA) on the prospective colony site, each including two patio speakers and powered by solar panels. The audio playback systems broadcast

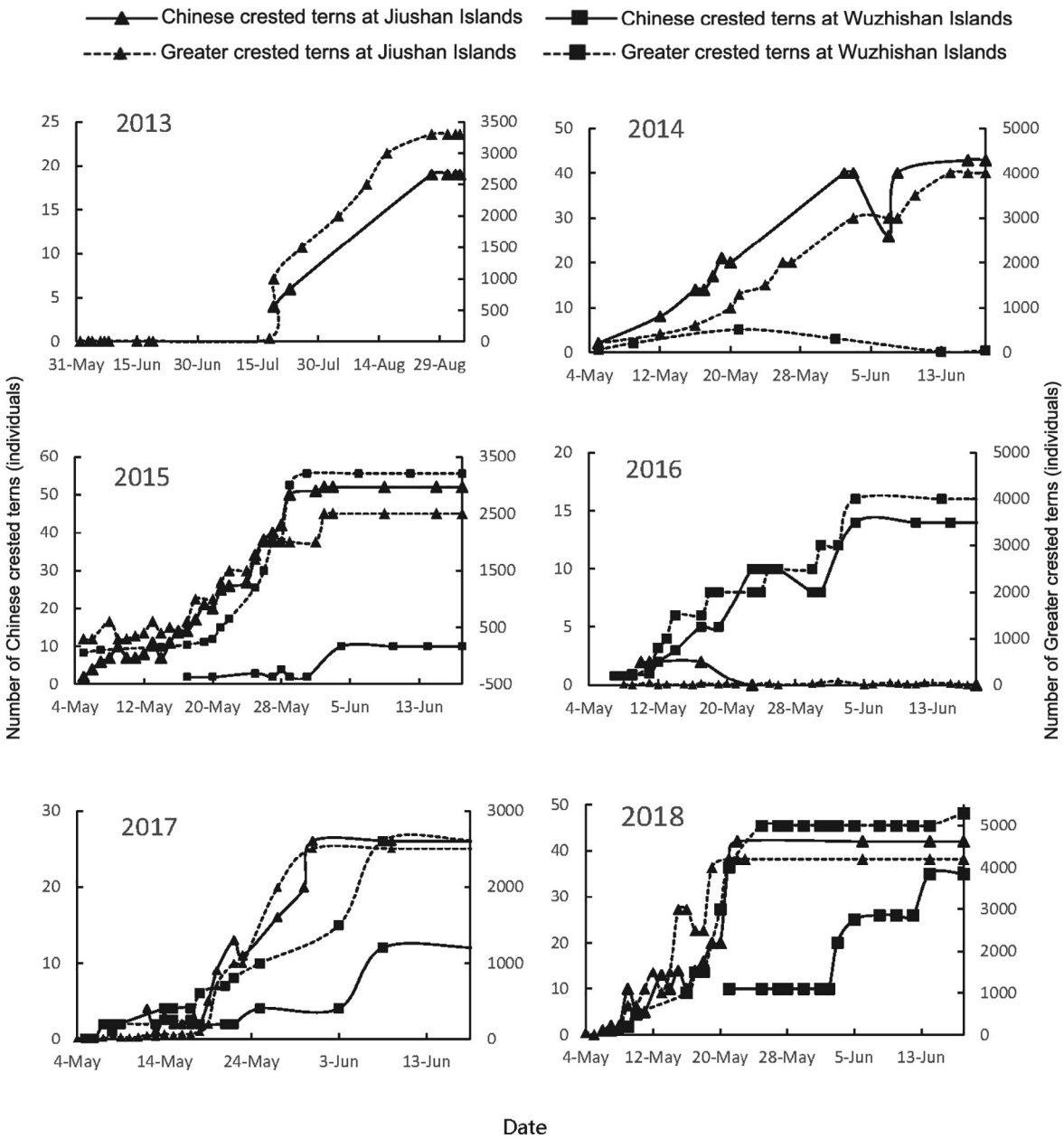

Fig. 2. Numbers of Chinese crested terns and greater crested terns attending the Tiedun Dao colony restoration site in the Jiushan Islands and the Yaqueshan colony restoration site in the Wuzhishan Islands, Zhejiang Province, China during the 2013–2018 breeding seasons. Restoration efforts were initiated on Tiedun Dao in 2013 and on Yaqueshan in 2015.

digital recordings of the calls of greater crested terns that had been recorded at a breeding colony on the Wuzhishan Islands. After the breeding season, we removed all decoys, audio playback systems, and solar panels from the tern colony site for cleaning, maintenance, and storage during the non-breeding season. We followed this procedure each year during 2014–2018.

2.3. Monitoring and data collection

In 2013, the first year of the restoration effort in the Jiushan Islands, we set up a video surveillance system at the restoration site on Tiedun Dao, and the colony monitors lived on a nearby island, Jigushan, and monitored the colony site with binoculars and spotting scopes from a distance of about 600 m. Because of the difficulty of closely monitoring the restoration site from such a distance, beginning in 2014 the colony monitors lived in tents or portable buildings set up on the opposite side of Tiedun Dao from the tern colony site and separated by a dense patch of vegetation.

The resident colony monitors monitored the restoration site and breeding colony from observation blinds that were installed at the periphery of the nesting area. Ingress and egress from the observation blinds was via concealed pathways cut in dense vegetation adjacent to the area cleared as nesting habitat. This set-up facilitated the close monitoring of the breeding colony without disturbing nesting terns. The tasks of the resident colony monitors included (1) deterring disturbance to the tern colony due to illegal egg harvest or other human visitation to the island; (2) detecting other potential factors that might limit colony restoration, such as disturbance from predators; (3) monitoring use of the island by greater and Chinese crested terns, including visitation, breeding behavior, egg-laying, incubation, and chick-rearing; and (4) responding to any factors that might limit colony restoration as appropriate (e.g., predator removal).

At the Wuzhishan Islands, the colony monitors did not live on the nesting island, but visited Yaqueshan, the nesting island, during the day via watercraft, weather permitting. The colony monitors observed the nesting area and tern colony from an observation blind set up on the northeastern side of Yaqueshan.

Data on the estimated number of greater and Chinese crested terns present on each colony and the causes of any tern nesting failure were collected daily on Tiedun Dao and, weather-permitting, on Yaqueshan. The numbers of greater crested terns on the breeding colonies were estimated from the blinds by counting the numbers of incubating and non-incubating terns in plots (3 m × 3 m) that were marked on the nesting area prior to the breeding season. Because the entire breeding colony could not be observed from the blinds, these estimates were extrapolated to the entire colony area by adjusting the plot counts based on the ratio of terns in plots to the total number of active tern nests counted during walk-throughs on each colony in mid-June, late in the incubation period, when peak numbers of breeding pairs were incubating eggs.

To count the total number of tern nests on-colony, 6–8 team members walked through the entire colony and took photographs of all eggs in each nesting plot. From the photography, we could distinguish active nests from abandoned ones because unattended eggs were generally covered in mud and rolled together in windrows. By comparing photography taken during mid-June with photography taken in late August, once all terns had finished nesting and left the breeding colony, we could also estimate the number of eggs that hatched in each plot and throughout the entire colony as well. This estimate is likely a minimum because a few eggs were laid on the colony after mid-June by adults that had lost eggs earlier in the season. The numbers of hatched eggs minus those taken by predators and those addled on the nesting area were considered the best estimate of the numbers of young greater crested terns raised to fledging age at each tern colony. The number of Chinese crested terns was accurate to the nearest individual, while the number of greater crested terns was considered accurate to the nearest 100 individuals.

3. Results

3.1. Size and productivity of breeding colonies

The estimated numbers of adult Chinese crested terns and greater crested terns on the two colony restoration sites during the study period are shown in Fig. 2. In 2013, two colony monitors began monitoring the Tiedun Dao colony site on 7 May. On 1 June, five greater crested terns were first observed on the colony site near the social attraction. From 3 June to 19 June, 2–8 greater crested terns were occasionally observed on the Tiedun Dao colony site, but a breeding colony failed to form. One month later, on 18 July, about 50 greater crested terns suddenly appeared on the Tiedun Dao colony site and, in the following days, the numbers of terns increased rapidly and egg-laying was initiated. The numbers of greater crested terns continued to increase throughout much of August, peaking at an estimated 3300 individuals on 27 August. By 23 July at least six Chinese crested terns had joined the newly formed colony of greater crested terns, and the number of Chinese crested terns counted on Tiedun Dao peaked at 19 individuals on 27 August (Fig. 2). More than 800 pairs of greater crested terns and at least two pairs of Chinese crested terns laid eggs. Ultimately, this newly established tern colony successfully produced over 600 greater crested tern fledglings and at least one Chinese crested tern fledgling by early October.

In 2014, terns arrived at Tiedun Dao in early May and most laid their eggs by the end of May. At its peak, the Tiedun Dao colony included about 4000 greater crested terns and 43 Chinese crested terns (Fig. 2), and at least 13 young Chinese crested terns and about 1000 young greater crested terns were fledged by the end of the 2014 nesting season. At the Wuzhishan Islands in 2014, as many as 500 greater crested terns appeared in May, but all abandoned the nesting ground later in the month. This was the first year that the mixed species breeding colony of crested terns abandoned the colony in the Wuzhishan Islands since the colony was first discovered in 2008.

In 2015, in an effort to restore a crested tern breeding colony at the Wuzhishan Islands and stabilize it, we deployed social attraction on Yaqueshan in the Wuzhishan Archipelago. Yaqueshan had been the site of a mixed species breeding colony of greater and Chinese crested terns in 2008, 2010, and 2012; in 2009, 2011, and 2013 the tern colony was on a different island in the Wuzhishan Archipelago. The social attraction at Yaqueshan consisted of installing 300 greater crested tern decoys and two audio playback systems distributed over the former nesting area. At the peak of the nesting season about 3200 greater crested terns and 10 Chinese crested terns were attracted to the colony site on Yaqueshan (Fig. 2), and about 1200 young greater crested terns and 4 young Chinese crested terns were fledged by the end of the 2015 nesting season. During the same nesting season, a total of about 2500 greater crested terns and 52 Chinese crested terns attempted to nest on Tiedun Dao in the Jiushan Islands (Fig. 2). About 1000 young greater crested terns and 16 young Chinese crested terns were fledged from the Tiedun Dao colony in 2015.

In 2016, as many as 100 greater crested terns appeared at the colony site on Tiedun Dao in early May, but the Tiedun Dao colony was unexpectedly abandoned by the end of the month (Fig. 3). The earliest arriving greater crested terns laid two small batches of eggs, 15 and 7 eggs each, but these eggs disappeared soon after they were laid, and adult terns did not attend the colony overnight. Using video surveillance equipment, we discovered that the tern eggs were being consumed by king rat snakes (*Elaphe carinata*) at night, and that this predator disturbance was likely the cause of colony abandonment early in the 2016 breeding season. Meanwhile at Yaqueshan in the Wuzhishan Islands, a total of about 4000 greater crested terns and at least 14 Chinese crested terns were counted during the peak of the nesting season (Fig. 2), and the colony at Yaqueshan produced about 1200 greater crested tern fledglings and 6 Chinese crested tern fledglings by the end of the 2016 breeding season.

In 2017, after 18 king rat snakes were trapped and removed from Tiedun Dao before the tern breeding season, the mixed species tern colony reformed on Tiedun Dao amidst the deployed social attraction. About 2500 greater crested terns and 26 Chinese crested terns were counted on the Tiedun Dao colony during the peak of the breeding season, and about 1100 greater crested tern fledglings and 6 Chinese crested tern fledglings were produced by the end of the 2017 nesting season. Concurrently at Yaqueshan, about 2600 greater crested terns and at least 12 Chinese crested terns nested amidst and near social

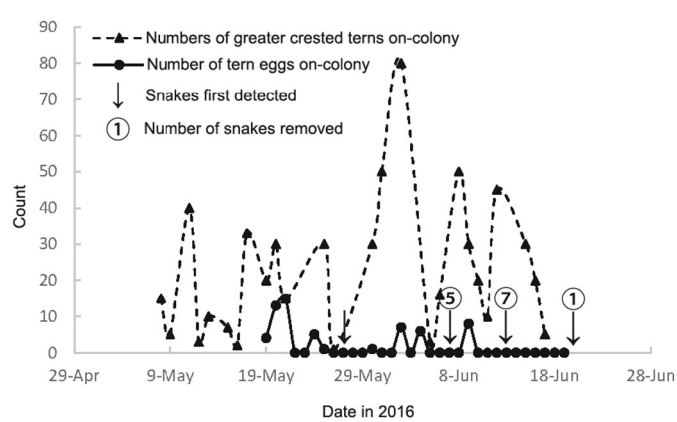

Fig. 3. Timeline of attendance by greater crested terns of the colony restoration site on Tiedun Dao, Jiushan Islands during the 2016 breeding season, when invasive king rat snakes were detected on and removed from the colony site. The numbers of greater crested tern eggs present on the colony restoration site each day are also shown.

attraction, and about 1000 greater crested tern fledglings and 4 Chinese crested tern fledglings were produced by the end of the nesting season.

In 2018, the tern breeding colonies formed at the colony sites in the two island groups in early May, as in 2017. About 4200 greater crested terns and 42 Chinese crested terns were counted at the Tiedun Dao colony by mid-June, and about 5300 greater crested terns and 35 Chinese crested terns were counted concurrently at the Yaqueshan colony (Fig. 2). By late August, about 1600 greater crested tern chicks and 13 Chinese crested tern chicks had fledged at Tiedun Dao, and about 1900 greater crested tern chicks and 12 Chinese crested tern chicks had fledged at Yaqueshan.

3.2. Threats to breeding Chinese crested terns

Illegal egg harvest and associated disturbance to breeding adults have been identified as the greatest threat to Chinese crested terns (Chen et al., 2015); however, no tern egg collection occurred at either the Tiedun Dao or the Yaqueshan colonies during the 6-year restoration period. During the breeding seasons of 2013–2018, the colony monitors for the Tiedun Dao restoration site prevented a total of 13 attempts by fishermen to land on the island, including one instance in 2014 when a fisherman fled the island just after entering the breeding colony and noticing a colony monitor was in an observation blind. The colony monitors also deterred an additional 28 vessels from approaching the colony site so closely as to flush adult terns.

On 11 July 2015, a Super Typhoon named Chan-hom (Category 4 storm with 210 km/h winds) passed near both Tiedun Dao and Yaqueshan, killing at least six greater crested tern chicks at Tiedun Dao and at least 184 greater crested tern chicks at Yaqueshan, but no Chinese crested terns were known to have been killed during this typhoon.

A single lesser rice field rat was detected on Tiedun Dao in both 2015 and 2016, and three lesser rice field rats were detected at Yaqueshan in 2015 and 2016. Despite the presence of small numbers of this widespread and omnivorous rat species on Tiedun Dao and Yaqueshan, no harm to the tern breeding colonies on these islands from invasive rats was detected or documented during our study.

One or more peregrine falcons (*Falco peregrinus*) were observed visiting the tern breeding colony on Tiedun Dao during the breeding seasons of 2014, 2015, 2017, and 2018, and falcons were documented depredating at least six adult greater crested terns on or near the colony. No Chinese crested terns were observed being depredated by peregrine falcons during the study period, however.

King rat snakes were observed on Tiedun Dao during both the 2014 and 2015 breeding seasons, but this common and widespread species was not documented to eat tern eggs until 2016. The first 23 eggs that were laid by greater crested terns on the Tiedun Dao colony in 2016 were all apparently eaten by king rat snakes, and the breeding colony was subsequently abandoned during the 2016 nesting season (see Fig. 3). Only after 18 king rat snakes had been trapped and removed from Tiedun Dao before the 2017 nesting season did the mixed-species tern breeding colony reform on Tiedun Dao. No king rat snakes were subsequently detected on Tiedun Dao during the 2017 nesting season. However, snake trapping early in the 2018 nesting season revealed that at least four king rat snakes had re-colonized Tiedun Dao.

4. Discussion

4.1. Social attraction and the conservation challenges for the Chinese crested tern

Since Chinese crested terns were rediscovered in the Matsu Islands in 2000, the species was regarded for 13 years as breeding in only two large colonies of greater crested terns, and the global population of Chinese crested terns was considered very low, likely less than 50 individuals (Chen et al., 2009; Chen et al., 2015). Small population size and severe threats to reproductive success from illegal egg harvest and typhoons apparently drove the species to the very brink of extinction (Chen et al., 2015). Although alarm over the species' status has attracted worldwide conservation attention, saving this critically endangered species still faces many challenges.

On the one hand, the breeding range of the Chinese crested tern is large and extensive, across most of the East China Sea, making it extraordinarily difficult to detect and monitor all breeding attempts by the species. Even for the three known larger breeding colonies in the Matsu, Jiushan, and Wuzhishan archipelagos, large fluctuations in numbers of breeding individuals have been recorded among years, and frequent shifts occur among different islands within each archipelago (Chen et al., 2009; Hung et al., 2019; this study). These nesting characteristics make it very difficult to monitor and safeguard the very few known breeding individuals.

On the other hand, two major threats to the species' persistence, egg harvest and human disturbance, are still widespread at islands along the coast of the East China Sea. Elimination of these threats depends on increased public awareness of the conservation needs of the species, which requires a long-term effort toward public education and outreach. In the short term, however, saving such a critically endangered seabird requires a more immediate and active restoration effort. Our results indicated that social attraction techniques can provide an important tool to address the immediate challenges for conservation of the Chinese crested tern.

First, it is possible to attract Chinese crested terns to nest at selected islands. Even so, the Chinese crested tern is so rare that the success of social attraction depends on using the technique to restore large breeding colonies of greater crested terns, which then lure Chinese crested terns to recruit to those colonies.

Second, the use of social attraction techniques to establish or restore mixed species tern colonies on particular islands provides an opportunity for close monitoring of those colonies, if the islands are selected carefully to facilitate monitoring efforts. Close monitoring of active tern colonies can effectively deter illegal egg harvest and other human disturbance, enhancing the prospects for breeding success at the colony. Furthermore, close monitoring provides an opportunity to identify those factors that limit colony size and nesting success. For example, close monitoring at Tiedun Dao allowed the detection and elimination of a major threat to that colony, the invasion of king rat snakes, which is a widely-distributed species on islands along the coast of the East China Sea (Huang, 1990) that can cause abandonment of tern colonies.

Third, through the use of social attraction, we obtained a more accurate understanding of the size of the population of Chinese crested terns. Using a relatively complete survey of potential nesting islands along the coast of Shandong, Zhejiang, and Fujian provinces, the total number of Chinese crested terns was estimated to be no more than 50 individuals in 2008 (Jiang et al., 2005; Liu et al., 2009; Chen et al., 2009; Hung et al., 2019). Because these surveys were conducted over multiple breeding seasons, however, the accuracy of this population estimate was somewhat in question. The number of breeding individuals that were recorded during the six-year restoration project (2013–2018) was considerably more than the previous estimate (Fig. 4). For example, in 2015 the minimum total number of breeding adult Chinese crested terns reached 75 individuals, based on data collected during monitoring at the Matsu (Hung et al., 2019), Wuzhishan, and Jiushan archipelagos. The dramatic increase in the census number of breeding adults since 2012 implies that restoration projects at the Jiushan and Wuzhishan archipelagos attracted breeding individuals from colonies other than the three known colonies. Two new breeding sites that were discovered in 2016 support our hypothesis that other previously undetected breeding colonies of Chinese crested terns were the source of the unprecedented numbers of adults counted in 2015. In 2016, five Chinese crested terns were discovered nesting in a large black-tailed gull colony on a small island off the southwest coast of South Korea, and two pairs of Chinese crested terns were discovered at

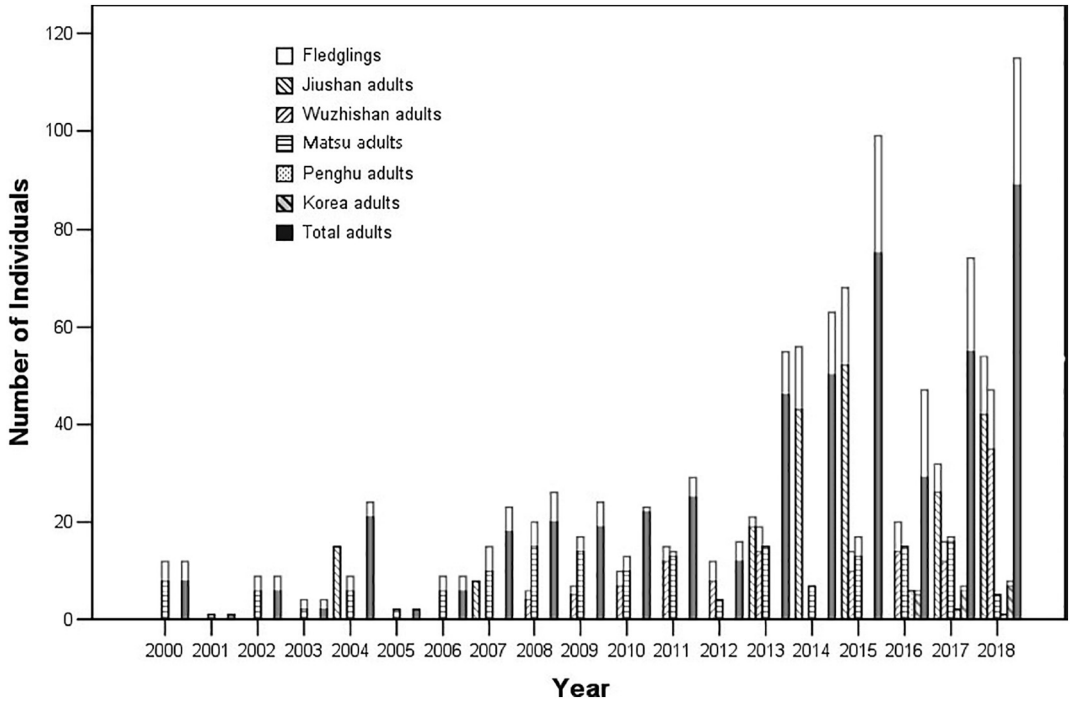

Fig. 4. Counts of individual adult and fledgling Chinese crested terns at extant breeding colonies during the 2000–2018 breeding seasons. Data from the Matsu Islands is courtesy of Hung (2018), data from the Penghu Islands is courtesy of Qianxun Zheng, and data from Korea is courtesy of Yunkyoung Lee.

the Penghu Islands in Taiwan (Song et al., 2017; Liu and Hetherington, 2016). Regardless, the breeding colonies at the Jiushan, Wuzhishan, and Matsu archipelagos still included most of the known breeding individuals of Chinese crested terns.

Finally, the success of the restoration projects using social attraction at the Jiushan and Wuzhishan archipelagos generated considerable public attention. A four-episode documentary film on this tern restoration project was televised by China Central Television (China Central Television, 2016). This publicity greatly enhanced the awareness of this conservation project by governmental agencies, scientists, and the general public in a short period of time, and contributed enormously to the conservation of the Chinese crested tern in China and its prospects for future recovery. The seabird breeding colonies in the Jiushan Islands Nature Reserve were frequently subjected to illegal egg harvest and human disturbance before 2013 (Fan et al., 2011; Chen et al., 2015), but intrusion by boats into the protected area decreased significantly following the initiation of tern colony restoration and illegal egg harvest has not been reported since then.

The recorded number of adult Chinese crested terns has increased dramatically since we initiated the restoration project in 2013 (Fig. 4). In 2018, we attracted a total of 77 breeding adult Chinese crested terns to the Tiedun Dao and Yaqueshan colony sites, or 88.5% of the known number of breeding adults in the global population in that year. Also in 2018, 25 Chinese crested tern chicks fledged from the Tiedun Dao and Yaqueshan colonies, which accounted for 96.2% of the known number of Chinese crested tern fledglings produced range-wide in that year. Consequently, we now know for the first time in history that the global population of Chinese crested terns exceeds 100. The population increase from less than 50 to more than 100 individuals is a cautiously hopeful sign that this critically endangered species can be brought back from the very brink of extinction.

A new threat to the Chinese crested tern has, however, been revealed based on molecular studies (Yang et al., 2018). Evidence from this study indicates that hybridization between Chinese crested terns and greater crested terns has occurred, and that the hybrid descendants are likely fertile. Genetic introgression may represent a serious threat to such a critically endangered species. That hybridization has occurred is perhaps not surprising given the very small population size of Chinese crested terns and their habit of nesting in large greater crested tern colonies. For this and other reasons (avoiding genetic drift and inbreeding depression), rapid population expansion is fundamental to the conservation of Chinese crested terns and survival of the species in the long-term.

4.2. Conservation networks: a restoration approach for Chinese crested terns and other breeding seabirds in China

An effective population recovery plan for an endangered species relies on complete knowledge of its life history, ecology, and genetics (Campbell et al., 2002). For some critically endangered species, direct management intervention, such as artificial propagation and ex situ conservation, are necessary (Fiedler & Groom, 2006). Among terns in general, and Chinese crested terns in particular, extended post-fledging parental care is a life history trait that poses nearly insurmountable obstacles for captive breeding programs. In the case of the Chinese crested tern, whose breeding population is so small and widely distributed over an extensive breeding range, and the severity of the threats still facing the species, creating a conservation network of monitored breeding sites to safeguard all nesting attempts is regarded as the best immediate conservation action.

Our results indicated that it is possible to establish new mixed species breeding colonies of greater and Chinese crested terns using social attraction techniques. Close monitoring and safeguarding of these new colonies can protect the colonies from most major threats and thereby enhance breeding success. Although the use of social attraction at one colony site might impact the numbers of breeding adults at another site, it is possible to achieve balanced colony sizes through cooperation and coordination of social attraction efforts. This approach was successfully used to sustain mixed species breeding colonies on both Tiedun Dao and Yaqueshan in 2015 and 2017. With the populations of both greater crested terns and Chinese crested terns apparently increasing, more new breeding colonies could be created using social attraction. By persisting in this approach, a well-protected, closely-monitored, and extensive conservation network of tern breeding islands

could be developed in the East China Sea, and potentially in the Yellow Sea as well, where the Chinese crested tern was originally described. Such an extensive conservation network of protected colony sites would help spread the risk from major typhoons in the East China Sea during the nesting season, typhoons whose strength, frequency, and overlap with the tern nesting season are known to be increasing with climate change (Chen et al., 2015).

In the future, a conservation network should include migratory stopover sites and wintering sites across the Australasian-East Asia Flyway, as well as breeding sites in the East China Sea and Yellow Sea. Currently, there is still only a very limited understanding and knowledge of the migratory stopover sites and wintering range of the Chinese crested tern, and more research efforts are needed to elucidate the species' habitat requirements during the non-breeding period. Although restoration of a critically endangered species is usually a difficult, long-term, and systematic mission with many risks of failure along the way, creating a conservation network through social attraction offers an opportunity to consolidate conservation achievements step by step, and enhance the prospects of saving the Chinese crested tern from extinction.

Managing a conservation reliant species like the Chinese crested tern in the long term will always be a major challenge, especially sustaining the funding support for crucial research and conservation efforts. In recent years, however, as social attraction has been applied to more sites in an effort to restore the population of Chinese crested terns, the funding streams from governmental and non-governmental organizations for the conservation of this critically endangered species have increased substantially. We remain optimistic that as the public becomes more aware of the plight of Chinese crested terns and as conservation awareness increases in China generally that the resources to sustain this restoration effort will be available.

There are various ways to create a new breeding colony for different species depending on their specific breeding ecology. It could be achieved through social attraction, or chick translocation, or even by a combination of these two techniques. It could also be achieved by focusing on just one species independently or, as in the case of Chinese crested terns, by focusing on species that are closely-related or colony associates. Nevertheless, we have shown that establishing a well-monitored and protected network of breeding sites has widespread conservation implications for most seabirds. Among the 171 active seabird restoration projects conducted in 16 countries/regions, at least 75 projects were determined to be successful in helping restore 34 different seabird species (Zhou et al., 2017). Through the use of active restoration techniques, robust conservation networks of breeding sites have gradually been developed for some seabird species, including Atlantic puffins (*Fratercula arctica*), Caspian terns (*Hydroprogne caspia*), roseate terns (*Sterna dougallii*), common terns (*Sterna hirundo*), and Arctic terns (*Sterna paradisaea*) (Roby et al., 2002; Kress et al., 2009; Jones and Kress, 2012; Zhou et al., 2017).

China's coastline extends over 18,000 km, spanning temperate, subtropical, and tropical regions. It includes rocky coasts and islets, rapidly accreting soft shorelines, mangroves, and coral reefs. There are a total of ca. 6500 uninhabited islands along the China coast within the Bohai, Yellow, East China, and South China seas in 13 different provinces or districts. These islands provide a wide variety of potential breeding habitats for seabirds. Currently, a total of 77 seabird species have been recorded along the China coast. Among these species, 37 (48%) have been documented as breeding (Chen et al., 2018). As with those of the Chinese crested tern, most breeding habitats and colonies are facing severe threats, including illegal egg harvest, human disturbance, habitat degradation and loss, marine pollution, declining food availability, and increasing frequency and severity of typhoons. These threats have resulted in the widespread loss of breeding colonies and population declines (Chen et al., 2009; Fan et al., 2011; Chen et al., 2015; Chen et al., 2018). The restoration project for the critically endangered Chinese crested tern is the first attempt in China at active restoration of a seabird population. It promises to provide much invaluable experience for the conservation of breeding seabirds and facilitate seabird restoration throughout China.

CRediT authorship contribution statement

Yiwei Lu: Conceptualization, Investigation, Data curation, Writing - original draft. **Daniel D. Roby**: Conceptualization, Methodology, Writing - review & editing. **Zhongyong Fan**: Conceptualization, Methodology, Investigation, Data curation. **Simba Chan**: Conceptualization, Investigation, Funding acquisition. **Donald E. Lyons**: Conceptualization, Methodology. **Chung-Hang Hong**: Investigation, Data curation. **Siyu Wang**: Investigation, Data curation, Resources. **Jia Yang**: Investigation, Data curation, Resources. **Xiao Zhou**: Investigation, Data curation. **Dongdong Chen**: Investigation, Data curation. **Hsiao-Wei Yuan**: Supervision. **Shuihua Chen**: Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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