Conservation of storm-petrels in the North Pacific

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Abstract

Storm-petrels are extremely difficult to census and population estimates are, therefore, crude. Only two species (Leach's *Oceanodroma leucorhoa* and Fork-tailed *O. furcata* storm-petrel) appear to be sufficiently abundant and widespread that conservation efforts are not needed at present. Four species (Ashy *O. homochroa*, Matsudaira's *O. matsudairae*, Tristram's *O. tristrami*, and Madeiran *O. castro*) are likely to number fewer than 10 000 individuals in the Pacific, and should be designated as threatened. Tristram's Storm-Petrel is known to be declining. Long-term conservation plans for these species should be developed and implemented. Black *O. melania* and Least *O. microsoma* storm-petrels may have populations of fewer than 20 000 individuals and should be monitored carefully. Storm-petrels are vulnerable to habitat destruction and mammalian predators. Modification of nesting areas by human development and livestock can greatly reduce breeding success in these species. Livestock should be prohibited in areas where threatened species breed. Removal of introduced predators from islands and restrictions on travel to breeding islands designed to reduce accidental or intentional introductions of domestic cats and rats should be given high priority in conservation plans.

Résumé

Les pétrels tempête sont difficiles à dénombrer, si bien que les données sur les populations sont des estimations brutes. Il semble que deux espèces seulement soient suffisamment abondantes et répandues pour ne pas exiger d'initiatives de conservation. Il s'agit du Pétrel cul-blanc *Oceanodroma leucorhoa* et du Pétrel à queue fourchue *O. furcata*. Compte tenu de leur population vraisemblablement inférieure à 10 000 individus dans le Pacifique, on peut considérer que le Pétrel cendré *O. homochroa*, le Pétrel de Matsudaira *O. matsudairae*, le Pétrel de Tristram *O. tristrami* et le Pétrel de Castro *O. castro* sont des espèces menacées. On sait que les effectifs du Pétrel de Tristram connaissent actuellement un déclin. Il y a tout lieu de préparer et d'exécuter des plans de conservation à long terme pour ces espèces. Les effectifs du Pétrel noir *O. melania* et du Pétrel minime *O. microsoma* comptent peut-être moins de 20 000 individus et devraient faire l'objet d'une surveillance attentive. Les pétrels tempête sont vulnérables à la destruction de l'habitat et aux mammifères prédateurs. La perturbation des lieux de nidification par les humains et le bétail risque de compromettre la reproduction de ces espèces. On devrait interdire le pâturage dans les lieux de nidification des espèces menacées. Les plans de conservation devraient insister sur l'élimination des prédateurs non indigènes dans les îles de reproduction et sur la restriction des déplacements en vue d'empêcher l'introduction accidentelle ou intentionnelle de chats domestiques et de rats.

1. Introduction

The North Pacific has the greatest diversity of storm-petrels in the world. Nine of the 20 species of storm-petrels (Leach's *Oceanodroma leucorhoa*, Fork-tailed *O. furcata*, Madeiran *O. castro*, Tristram's *O. tristrami*, Swinhoe's *O. monohris*, Matsudaira's *O. matsudairae*, Ashy *O. homochroa*, Black *O. melania*, and Least *O. microsoma*) have breeding ranges either wholly or partially in the North Pacific. In addition, three other species are occasionally seen foraging in the North Pacific *(Oceanites oceanicus, Oceanodroma markhami*, and *O. tethys)*, but none of these appears to breed above the Tropic of Cancer (see Huey 1952; Blake 1953; Lockley 1983; Harrison 1987). An extinct species, Guadalupe Storm-Petrel *Oceanodroma macrodactyla*, bred until the early 1900s on Guadalupe Island, off Mexico (Jehl 1972).

Although the breeding and pelagic ranges of all the species except Matsudaira's Storm-Petrel are fairly well documented, the exact locations and colony sizes of breeding populations, particularly in the western Pacific and off Baja California, Mexico, are not completely known. Storm-petrels are extremely difficult to census either on the breeding grounds or at sea. On their breeding grounds, their nocturnal swirling flights, cryptic coloration, and small size make counting them difficult. Their burrow locations often are difficult to find or unreachable, and even if all burrows can be found, simply counting the number of burrows exaggerates estimates of population sizes because occupancy rates are less than 100% and sometimes as low as 40%. Nests can have multiple entrances, and nest attendance is irregular, further complicating counting and identifying active nests. In some locations, several species of storm-petrels breed in the same areas. For example, on Isla Partida, Mexico, Black and Least storm-petrels nest together in different parts of the same rock crevices. On Hippa Island, British Columbia, and on St. Lazaria Island, Alaska, Leach's and Fork-tailed storm-petrels occur in adjacent nest sites (Vermeer et al. 1988; Boersma, pers. obs.). At sea, their small size, solitary nature, and large range make them difficult to detect and to accurately count; Leach's Storm-Petrels are known to fly 200 km/day while foraging (Billings 1968).

Because of the inherent limitations in censusing storm-petrels, most researchers are likely conservative in their abundance estimates. Most published data on abundance are

Table 1
Crude estimates of population sizes for nine species of storm-petrels known to breed in the North Pacific. Units are in thousands. Location names are as follows: Bonin = Bonin and surrounding islands; China = islands off China, including Taiwan; Japan = islands off Japan and Korea; Russia = islands in the Sea of Okhotsk, including Kuril Is.; AK = islands off Alaska, including Aleutian Is.; BC = islands off British Columbia; WA & OR = islands off the Washington and Oregon coasts; CA = islands off California coast; MX = islands off Baja California; CAm = islands off Central America; HI = islands in the Hawaiian Is. chain; ATL = breeding sites in the Atlantic.

	Location											
Species	Bonin	China	Japan	Russia	AK	BC	WA & OR	CA	MX	CAm	HI	ATL
Leach's	—	+	2000	200+	3500–6800	1100–2200	400	20	(+)	(+)	(+)	5000
Fork-tailed	—	—	—	100+	3000–5000	300–1300	5	+				
Madeiran	—	??	8?	(+)	—	—	—	—	(+)		0.1?	2?
Tristram's	+	??	3?	—	—	—	—	—			<10	
Swinhoe's	+	+	>8	>10	—	—	—					
Matsudaira's	3?	—	—	—	—	—	—					
Ashy	—	—	—	—	—	—	—	8.2				
Black	—	—	—	—	—	—	—	0.1?	20?	(+)		
Least	—	—	—	—	—	—	—		20?	(+)		

+ = breeding populations known from area, but no estimates of population sizes available;
(+) = nonbreeding populations have been sighted in area;
? = estimate of population size extremely crude;
?? = occurrence of species in area possible, but not documented.

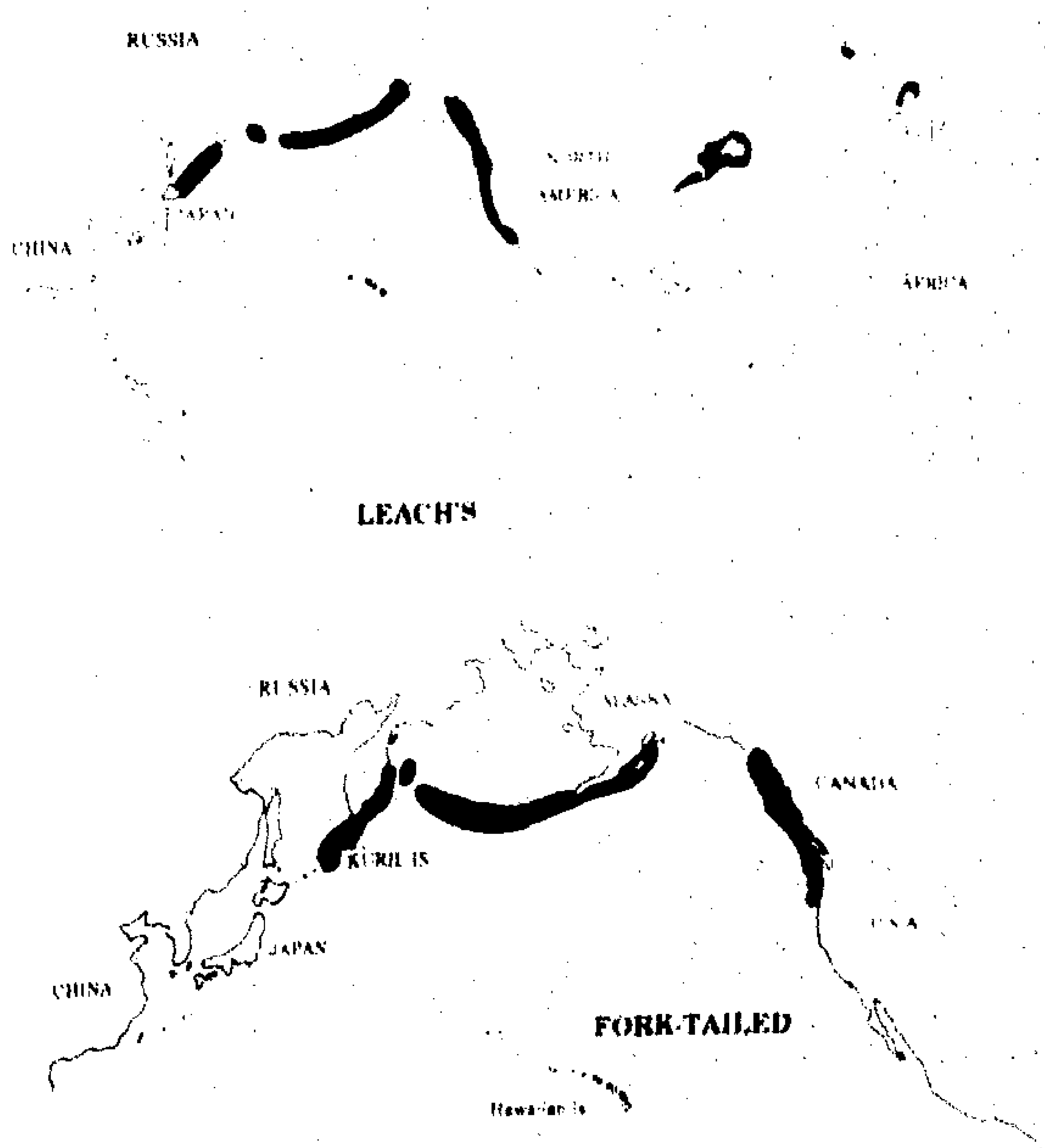
little more than crude estimates and probably accurate only to within an order of magnitude of true population size. In some locations, time and resources have permitted thorough censusing of populations (e.g., Ashy Storm-Petrels on the Farallon Islands), but this is rarely possible. For this reason, assessment of the current status of most species is crude (see Table 1). More importantly, tracking changes in storm-petrel populations is difficult: perhaps only gross differences such as changes in an order of magnitude of abundance of breeding populations may be detectable in most populations. For this reason, we feel it is prudent to err on the side of caution in planning for storm-petrel conservation. In this paper, we review the current status and threats to storm-petrels in the North Pacific and highlight issues that should be addressed in future work on the conservation of storm-petrels.

2. Species accounts: distribution and abundance

2.1. Leach's Storm-Petrel

This is the most abundant and widespread of the species breeding in the North Pacific (Fig. 1; Table 1). In the North Pacific, its breeding range extends from Hokkaido, Japan, across the entire North Pacific Rim to Baja California. A conservative total population size for the species is between 10 and 15 million (see Dement'ev and Gladkov 1951; Abe et al. 1972; Sowls et al. 1978; Golovkin 1984; Hasegawa 1984; Vermeer and Sealy 1984; Il'icev and Flint 1985; Watanuki 1985a; Byrd and Day 1986; Wilbur 1987; Watanuki et al. 1988 for greater detail). It is much rarer off the contiguous 48 states of the United States than elsewhere in its breeding range, and reaches peak abundance above 35°N latitude. Leach's Storm-Petrels are also widespread in the Atlantic, with large breeding populations off eastern Canada and smaller populations off Great Britain (Palmer 1962; Wilbur 1969; Tuck and Heinzel 1978). The largest breeding colony is located off Newfoundland and is estimated to have 3.36 million breeding pairs (Sklepkovych and Montevecchi 1989). Its nonbreeding range is extensive: in the Pacific it extends from the Bering Sea to 10°S, with rare sightings near the equator (see Fig. 1).

Figure 1
Breeding (dark hatch) and nonbreeding (light hatch) range of Leach's and Fork-tailed storm petrels



2.2. Fork-tailed Storm-Petrel

This is the second most abundant and widespread of the storm-petrels of the North Pacific (Table 1). The core of its distribution is in the offshore islands of Alaska, particularly in the eastern Aleutian Islands (Fig. 1). In general, its range does not extend as far south as that of Leach's Storm-Petrel, with no breeding reported south of Korea or south of Eureka, California (Harris 1974; Sowls et al. 1980; Won and Lee 1986; Taoka et al. 1989). Its nonbreeding range is in subarctic and temperate waters (see Fig. 1). The total population size of the species is between five and 10 million (see Sowls et al. 1978; Golovkin 1984; Vermeer and Sealy 1984; Il'icev and Flint 1985 for greater detail).

Figure 2
Breeding (dark hatch) and nonbreeding range (light hatch) of Madeiran and Tristram's storm-petrels. Breeding islands for Madeiran Storm-Petrel in the Atlantic are, from north to south, the Azores, the Canary Islands, the Cape Verde Islands, Ascension Island, and St. Helena.

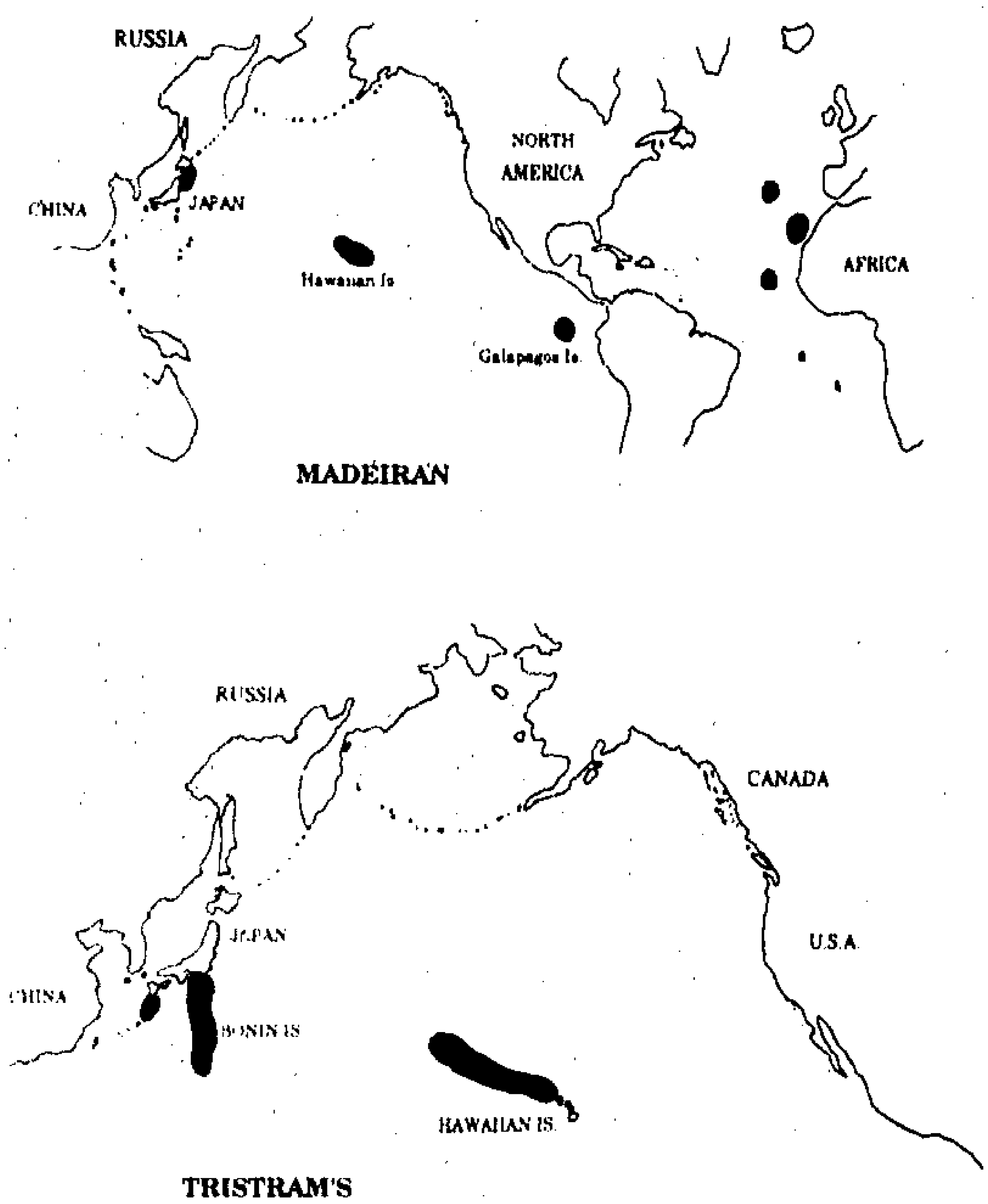
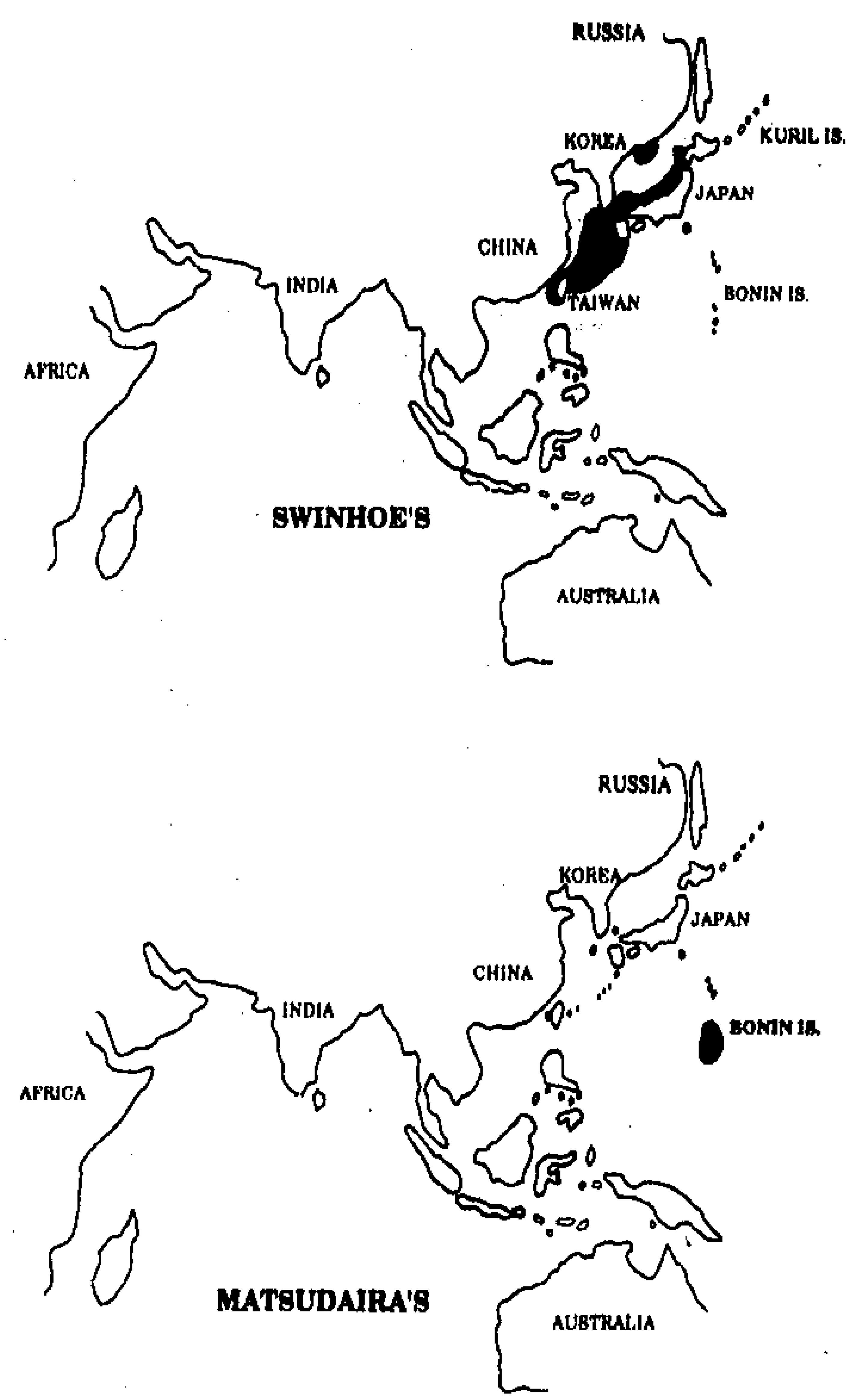


Figure 3
Breeding (dark hatch) and nonbreeding range (light hatch) of Swinhoe's and Matsudaira's storm-petrels



2.3. Madeiran Storm-Petrel

This species is found breeding on oceanic islands in the tropical Pacific and Atlantic oceans (Fig. 2). In the Pacific it is known to breed on islands off the eastern coast of Japan (about 8000 pairs: Hasegawa 1984), on Kauai in the Hawaiian Archipelago, where perhaps 100 pairs breed (although estimates are difficult to obtain: Pratt et al. 1987; Harrison et al., in press), and in the Galapagos (about 15 000 pairs: Harris 1969). Madeiran Storm-Petrels are rarely seen in waters off Russia, but they do not breed there (A. Golovkin, pers. commun.). The species' total population size is on the order of 50 000 individuals, although less than half that number may be breeding in the Pacific (Table 1). The Hawaiian subspecies is considered endangered by the State of Hawaii, and the U.S. Fish and Wildlife Service (USFWS) is currently considering a proposal to list the subspecies as endangered (Harrison et al., in press).

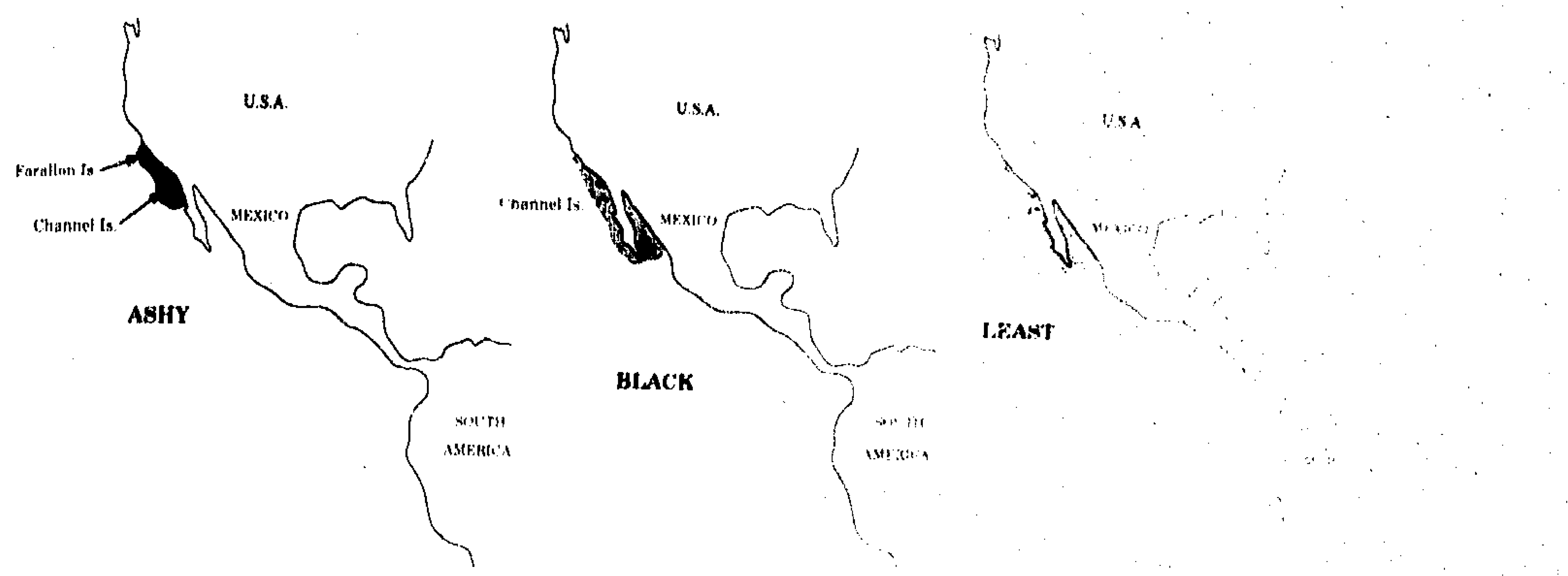
2.4. Tristram's Storm-Petrel

Tristram's Storm-Petrel breeds on a restricted number of islands in the west-central Pacific (Fig. 2). Large nesting colonies (>1000 individuals) are known from Laysan and Midway islands, the Bonin Islands, Volcano Island, and several other small islands on the eastern coast of Honshu, Japan (Harrison et al. 1984; Hasegawa 1984). The species may be declining due to reduction of breeding colonies in the western Pacific following introduction of rats and cats onto several islands (see Hasegawa 1984). The population centre for the species may be in the Hawaiian Archipelago where it is known to breed on five islands and likely to be breeding on an additional three islands with a total population size of <10 000 (Rauzon et al. 1985; Table 1). Because of its relatively small population size and few sites for breeding, Tristram's has been designated a "sensitive species" by the USFWS (Rauzon et al. 1985). Due to recent declines in populations near Japan and overall small breeding populations in the central Pacific, Tristram's is also listed as a "near-threatened" species by the International Council for Bird Preservation (ICBP) and is under consideration for inclusion in the World Conservation Union (IUCN) Red Data Book (Collar and Andrew 1988).

2.5. Swinhoe's Storm-Petrel

This species breeds from the Sea of Japan to islands near Taiwan (Fig. 3). Its nonbreeding range is mostly tropical and subtropical, extending through the Indian Ocean to Saudi Arabia (Lockley 1983). The total population size is probably fewer than 30 000 individuals (Table 1). The greatest concentration of Swinhoe's Storm-Petrel appears to be in the Sea of Japan where over 10 000 pairs are thought to breed on Verkhovski Island (Golovkin 1984, pers. commun.). Another large colony of about 7900 pairs has been reported on Ch'ilbal Islet off the southwest coast of Korea (Taoka et al. 1989). Other small colonies (about 100 pairs) are known from islets around the Sea of Japan and off Korea, although total population sizes are unknown (Won and Lee 1986; Taoka et al. 1989; A. Golovkin, pers. commun.). Swinhoe's Storm-Petrel is included in the Red Data Book of Russia as of 1984 (Golovkin 1984).

Figure 4
Breeding (dark hatch) and nonbreeding (light hatch) range of Ashy, Black, and Least storm-petrels



2.6. Matsudaira's Storm-Petrel

This is the least known of the storm-petrels found in the North Pacific. Although its range extends eastwards into the western North Pacific, it is known to breed only on several of the Bonin Islands in colonies thought to number more than several thousand individuals (Fig. 3). Its winter range extends into the Indian Ocean to Africa, generally farther south than Swinhoe's Storm-Petrel. There are no estimates of the population size of this species (Table 1).

2.7. Ashy Storm-Petrel

The species breeds only on five islands off California and Mexico, and most of the population (approx. 4000 individuals: Ainley et al. 1990) is restricted to the Farallon Islands (Fig. 4). There is one small colony in Los Coronados Islands, Mexico (Sowls et al. 1980). The total population size is about 8300, probably an accurate estimate based on extensive mist-netting on the Farallons and monitoring of the islands within its breeding range (Table 1). The total population size is certainly fewer than 10 000 birds (Sowls et al. 1980). Enigmatically, Ashy Storm-Petrels have not been given "threatened" status, although more abundant and widespread species have been considered for "threatened" designation (see below). Given its confined breeding range and small population size, this species clearly warrants designation as "threatened."

2.8. Black Storm-Petrel

This species breeds on the Channel Islands off California, and islands off both coasts of Baja California, Mexico, and the species "winters" as far south as Panama (Fig. 4). Published estimates of the breeding abundance are generally vague and vary considerably. Approximately 150 birds breed in the Channel Islands (Hunt et al. 1979; Spendelow and Patton 1988; although Briggs et al. [1987] roughly estimate that 100 000 may occur in California waters), but large numbers may breed on the islands off the eastern and western coasts of Baja California (Davis 1972; Briggs et al. 1987; Table 1). Although no complete censuses of this species have been done, population sizes probably range from 10 000 to 100 000 individuals. Due to the paucity of information concerning this species, it has been listed as a candidate for inclusion in the IUCN's Red Data Book (Collar and Andrew 1988).

2.9. Least Storm Petrel

Least Storm-Petrels appear to be as abundant as Black Storm-Petrels, and are as widespread, although they do not breed in the Channel Islands (Fig. 4). The species probably numbers between 10 000 and 50 000 (Briggs et al. 1987, Table 1). They often co-occur with Black Storm-Petrels on islands in the Gulf of California. They have a similar nonbreeding range to Black Storm-Petrels, although they do not move as far north on a regular basis (Fig. 4). Like the Black Storm Petrel, the Least Storm-Petrel has been listed as a candidate for inclusion in the IUCN's Red Data Book pending further research (Collar and Andrew 1988).

3. Storm-petrel breeding biology

Extensive studies of the breeding biology of storm petrels have been carried out on only a few of the species in a few locations. Only Leach's, Fork-tailed, Ashy, and Madeiran storm-petrels have been studied in detail, although some information about the biology of all but Matsudaira's Storm Petrel is available (see summary in Ainley et al. 1990).

All the species appear to have a very similar breeding biology: adults do not begin breeding until they are three to four years old; courtship lasts for several weeks and consists of vocalizing during elaborate aerial swoops and circles over the colony. Males attract females to the nesting site by calling. After copulation in the burrow the birds depart for sea for several weeks. Upon return the female lays a single large egg, up to 20% of her body weight (Boersma 1982). Both sexes incubate and feed the young. The egg and young can be neglected for several days during the long incubation period (Boersma and Wheelwright 1979; Boersma 1986a, Vermeer et al. 1988). Egg-laying and hatching are not highly synchronous and may extend for several months. The typical interval between laying and hatching is 40–50 days and the interval between hatching and fledging is between two and three months (Harris 1969; Boersma et al. 1980; Zhao-qing 1988; Vermeer et al. 1988).

Nesting habitat is variable, ranging from exposed cliffs to forest floors where storm-petrels use either natural crevices or excavate burrows (Allan 1962; Harris 1969; Boersma et al 1980). Burrows can be as deep as several metres (Lockley

1983), but the average is probably 30–60 cm. Some individuals nest in talus slopes penetrating several metres by using existing openings among the rocks, others may dig side chambers off existing Tufted Puffin *Fratercula cirrhata* burrows (Boersma, pers. obs.). Soil erosion is believed to cause birds to be displaced (see Sowls et al. 1980).

Most species are active at the colony only at night, and often stay at sea on moonlit nights (Boersma, unpubl. data; Watanuki 1986). The diets and feeding ranges when on the breeding colonies may be variable among the species. Black, Ashy, Least, Fork-tailed, and Tristram's storm-petrels all have been reported feeding close to their breeding grounds (Ainley et al. 1975), and Leach's and Madeiran storm-petrels have been reported feeding further offshore (Lockley 1983). Although the proportions of different prey may vary among the storm-petrels and within species depending on the location and season, the principal components of their diets are amphipods, copepods, euphausiids, decapods, cephalopods, and small fish (Watanuki 1985b; Croxall et al. 1988; Vermeer and Devito 1988; Ridoux and Offredo 1989). Storm-petrels have well-developed olfactory systems (Bang 1966; Wenzel 1980) and find their food and perhaps their nest site by odour (Grubb 1974).

The key to population stability in storm-petrels appears to be their high adult survivorship. Most species have a very low reproductive output (e.g., 0.3 chicks/pair for Madeiran Storm-Petrels in the Galapagos: Harris 1969; 0.7 for Ashy Storm-Petrels on Farallon Islands: D. Ainley, pers. commun.). Any perturbations that greatly depress storm-petrels' low reproductive output could lead to population decline, particularly if lowered output results in low recruitment into the adult life stage. Evidence from Leach's Storm-Petrel (Gross 1947) suggests that storm-petrels are extremely long-lived birds for their body size. Annual adult survivorship was estimated to be 0.94 for breeding Leach's Storm-Petrels in Maine (Morse and Buchheister 1977). It is probable that adults of most species often live more than 20 years. Given their low reproductive output, it is likely that the key to population stability in storm-petrels is their high annual adult survivorship, allowing a relatively long life span. Threats that severely reduce adult survivorship or greatly lower reproductive success have the potential to cause storm-petrel populations to decline.

4. Predation

A large variety of species are known to eat storm-petrel adults or nestlings. Most of the major predators of storm-petrels are mammals, particularly introduced mammals that hunt by sense of smell. Storm-petrels may be particularly susceptible to predation by such predators because they have such a pungent and unmistakable odour.

Mammalian predators and gulls, in particular, can devastate storm-petrel colonies. Medium-sized mammals, such as otters and foxes, can dispose of a large number of storm-petrel adults (Quinlan 1983). These types of predators can have dramatic effects even when in low numbers. For example, Boersma et al. (1980) reported that several hundred storm-petrel wings were found at the entrance to a single otter den. Gulls, as their populations increase, are becoming serious predators on small seabirds such as storm-petrels (e.g., Parslow 1965; Angles 1973; Boersma et al. 1980; Watanuki 1986, 1988). Other avian predators, such as owls (Harris 1969; French 1979; Holt 1987; Vermeer et al. 1988) and crows and ravens (Watanuki 1985a, 1986; Paine et al. 1990; Boersma, unpubl. data), are regular predators of storm-petrels.

The most severe threat to storm-petrel populations is from predation by small introduced mammals—particularly rats and cats (Moors and Atkinson 1984; Imber 1987). Rats and cats are both extremely efficient predators on burrow-nesting birds and difficult to eliminate once introduced to an island (Kepler 1967; Crossin 1974; Jones and Byrd 1979; Moors and Atkinson 1984). Cats appear to have been responsible for the extinction of the Guadalupe Storm-Petrel (Jehl 1972) and, along with introduced rats, they contributed to the elimination of a "huge" colony of Tristram's Storm-Petrels from the Izu Islands off Japan in less than 20 years (Hasegawa 1984). On Whaler Island, California, a colony of 20 000 storm-petrels was destroyed in less than 40 years by the construction of a breakwater to the island. This allowed rats to colonize the island (Osborne 1972).

Besides threatening the survival of particular breeding colonies or populations, predation pressures can result in dramatic changes in species distribution and the composition of seabird communities. For nine islands with introduced foxes and nine islands without foxes in the Shumagin Islands, Alaska, a total of 3150 Fork-tailed and 6750 Leach's storm-petrels nested on islands free of introduced foxes. In contrast, *no* storm-petrels nested on islands with foxes (data from Bailey 1978). In general, the distribution of storm-petrels tends to be negatively correlated with the distribution of mammalian predators.

Increases in gull populations that are tolerant of human-altered habitats (such as the Slaty-backed *Larus schistisagus* and Glaucous-winged *L. glaucescens* gulls) may cause decreases in smaller seabird species (Paine et al. 1990), particularly storm-petrels and alcids (Watanuki 1986, 1988). For example, for 174 Alaskan islands reported in Sowls et al. (1978), both Fork-tailed and Leach's storm-petrels were less likely to be found on islands with greater than the mean number of gulls for all the islands. Species that cause and accelerate soil erosion, such as puffins and introduced livestock, can destroy storm-petrel nesting habitat and cause birds to desert (Sowls et al. 1980). Introductions of livestock can be particularly harmful to storm-petrel populations by opening up breeding habitat, thereby making storm-petrels more vulnerable to capture by avian or mammalian predators. The changes likely in storm-petrel populations over the next century are somewhat unpredictable due to the complex interplay between species and the community effects that accompany changes in predator populations (see Paine et al. 1990). However, it is most likely that storm-petrel populations will decline overall.

4.1. Long-term effects of predation on storm-petrel populations

In the future, several species could submit to the fate of the Guadalupe Storm-Petrel. Ashy and Matsudaira's storm-petrels are particularly at risk due to their extremely limited distribution amongst a few separate islands: Ashy Storm-Petrels are concentrated on the Farallon Islands, and Matsudaira's Storm-Petrels are known to nest only on the Bonin Islands. Other species that nest on relatively few islands (Tristram's, Madeiran, Black, Least, and Swinhoe's) may also be vulnerable because with increasing visitation by humans, introduction of predators is more likely. Nests in rock crevices may be less sensitive to predation (see Hatch 1983), and thus species such as Fork-tailed and Madeiran storm-petrels may be somewhat less vulnerable to predation. The location of the crevice is also a factor: nests on steep slopes are less accessible to many predators (Boersma, pers. obs.). Some species, such as Madeiran Storm-Petrels (Harrison et al., in press), are particularly site faithful. This being the case, it is unlikely that populations once extirpated from an island will easily be reestablished by birds from other distant locations.

The extinction in a mere 20 years of what appears to have been the largest colony of Tristram's Storm-Petrels by introduced cats and rats shows how vulnerable many of these species may be to population decline and extinction via predation. These examples of the rapidity with which introduced predators can decimate storm-petrel populations suggest that islands where mammalian predators have become established recently will require intense and active management if storm-petrels are to survive and breed at these sites. In the long term, it will be of the utmost importance to prevent future introductions in order to preserve most of the storm-petrel species of the North Pacific.

5. Pollution

5.1. Plastics

Storm-petrels, like other procellariiform birds, are prone to ingestion of plastics due to their foraging mode. All storm-petrels are surface feeders, seizing primarily amphipods, squid, euphausiids, copepods, and small fish from the surface. Their food items are mostly pale, semi-translucent items that float at the surface of the water, much as plastics do—hence storm-petrels can and do ingest a large quantity of plastics (Rothstein 1973; Furness 1985a, 1985b; Day et al. 1985; Zonfrillo 1985; Boersma 1986b; Ryan 1987; van Franeker and Bell 1988). The incidence of plastic ingestion in adult storm-petrels can be extremely high: Ryan (1987) estimated that 88% of White-faced Storm-Petrel *Pelagodroma marina* adults and 38% of White-bellied Storm-Petrels *Fregetta grallaria* had plastics in their digestive tracts. Thirty-three percent of the relaxed gizzard volume of Leach's Storm-Petrels in the North Atlantic was found to be composed of plastics (Furness 1985a). In contrast, 1% of the food samples regurgitated by Fork-tailed Storm-Petrels contained plastic particles (Boersma 1986b). It is likely that all storm-petrel species ingest quantities of plastics, although the amount should vary with the overlap in their foraging ranges and major shipping regions (Day et al. 1985).

Ryan and Jackson (1987) found that the average half-life of plastics in seabird digestive systems was one year. It may be less for storm-petrels because they can eject their stomach contents and often do at predators. However, if plastics accumulate in storm-petrel guts they may decrease digestive efficiency, and weigh the bird down. At present there are no data on the effects of plastic ingestion on flight or digestive efficiency in storm-petrels. Ryan's studies of larger seabirds suggest that negative effects over the short term are small, although long-term consequences are not known. For example, Ryan and Jackson (1987) found no cases of obstructions and little physical damage from plastic ingestion in their examination of over 400 seabird carcasses. A detailed and experimental study of effects of plastic ingestion by Laysan Albatross *Diomedea immutabilis* showed that only in a few instances ingestion causes chick death, although ingestion of large plastic volumes slowed growth of chicks significantly (Fry et al. 1987; L. Sileo, pers. commun.).

If plastics interfere with storm-petrel digestive efficiency, expected effects include elevated mortality (particularly at times of stress such as breeding or moult), and decreased breeding success via limitation either of the female's ability to form eggs or of the parents' ability to feed their young. Obstruction of the digestive system by plastics has been reported as a contributing cause of death in Wilson's Storm-Petrels *Oceanites oceanicus* (Zonfrillo 1985; van Franeker and Bell 1988). Chicks receive plastics in feedings from their parents (Ryan 1988) and can die from obstructions (Ryan 1988; van Franeker and Bell 1988). However, because storm-petrels generally ingest small particles (Ryan 1987), they may not be particularly susceptible to this sort of problem.

5.2. Petroleum

Storm-petrels are less susceptible to direct oiling than most seabirds, largely because they infrequently land on the water. Nevertheless, storm-petrels were found oiled after the March 1989 *Exxon Valdez* oil spill (E. Bailey, pers. commun.). Thus, such large oil spills could have adverse effects on storm-petrel populations. However, a more constant and potentially more serious threat comes from ingestion of petroleum. Because their food is often embedded in surface slicks, storm-petrels likely ingest surface pollutants, such as oil, frequently with their meals (Boersma 1986a). Studies on a variety of seabirds have shown that oil ingestion can impact endocrine functions (Peakall et al. 1981; Butler et al. 1988), interfering with ovulation (Cavanaugh and Holmes 1987) or even with immune functions (Peakall et al. 1981; Fry and Lowenstine 1985; Lowenstine and Fry 1985). Other toxic effects include inducing anemia (Leighton et al. 1983, 1985) and interference with normal renal function (Lee et al. 1985). Ingestion of even small quantities of oil can cause elevated metabolic rates in adult Leach's Storm-Petrels (Peakall et al 1981; Butler et al. 1986), and chicks of oil-dosed parents suffer from lowered hatching and fledging success, perhaps because the adults' increased energetic demands reduce the efficiency with which they can tend and feed their young (Trivelpiece et al. 1984; Butler et al. 1988). Trivelpiece et al. (1984) also found that Leach's Storm-Petrel chicks had greater morbidity and mortality when fed by oil-dosed parents, but in another study by Boersma et al. (1988), Fork-tailed Storm-Petrel chicks dosed directly showed little or no effects from their exposure. It appears that storm-petrels suffer primarily from changes in basal metabolic rate associated with oil ingestion. We suggest that storm-petrels are less susceptible than many species of seabirds to oil toxicity because their diets contain large amounts of n-hexanes that are similar to oil (Obst 1986; Boersma et al. 1988). More studies need to be conducted to fully understand the range of effects of oil ingestion in storm-petrels, although the available evidence suggests that oil ingestion may depress storm-petrel populations.

5.3. Toxic contaminants

Toxic chemicals frequently become trapped in surface slicks, and thus storm-petrels due to their foraging method are particularly prone to ingesting these kinds of toxins. Organochlorine contaminants are common in storm-petrel eggs, although the level of contamination varies (Ohlendorf et al. 1978; Pearce et al. 1979; Elliott et al. 1989). DDT and its derivatives have been shown to promote eggshell thinning in Leach's, Fork-tailed, and Ashy storm-petrels (Coulter and Risebrough 1973; Ohlendorf et al. 1978; Pearce et al. 1979; Henny et al. 1982; Lukowski 1983). Bull et al. (1977) and Murton et al. (1978) have reported heavy metal contamination in the tissue and eggs of Leach's Storm-Petrels. The principal source of such contaminants is not known: they may pick up heavy metals from their foods or from traces trapped in oil slicks that are inadvertently ingested while foraging. Few other effects of toxic chemicals have been reported, but it is likely that storm-petrels would be at greater risk than many other species to direct, inadvertent ingestion of floating toxins (Bourne 1976; Lukowski 1983).

5.4. Long-term effects of pollutants on storm-petrel populations

In general, pollution problems are likely to affect all species, but to have greater impacts on populations with small population sizes (e.g., Ashy and Matsudaira's storm-petrels). The species may be differentially susceptible according to the degree of overlap of their foraging and breeding ranges with the distribution of pollutants on the ocean's surface. Species that follow ships to take advantage of their castoffs (Fork-tailed, Black, Matsudaira's, and possibly Least and Swinhoe's storm-petrels, Lockley 1983) may be particularly susceptible to oil and plastic ingestion.

6. Other threats

Four additional types of disturbance may have some negative impacts on storm-petrel population stability. First, grazing and farming may injure storm-petrel populations both because they increase soil erosion, which may increase burrow collapse, and also because they can make burrows and returning adults more visible to predators. Second, human disturbance may not affect all species equally. For example, Leach's Storm-Petrel appears to be less sensitive to investigator disturbance than Fork-tailed Storm-Petrel. Increased tourism near breeding grounds of sensitive species may reduce nesting success.

Thirdly, global climate change could have adverse effects on storm-petrel breeding success. Both short- and long-term changes in rainfall patterns may have substantive effects on storm-petrels. Fork-tailed Storm-Petrels are less likely to return to feed and brood their chicks under rainy and windy conditions, and chick mortality is correlated with rainfall (Boersma et al. 1980). Climate changes that bring more rain to breeding areas will increase maintenance costs of storm-petrel chicks and increase mortality.

Finally, storm-petrels may experience problems from competition with commercial fisheries. Storm-petrels probably do not suffer much from commercial fishing because they do not often become entangled in nets and do not compete directly with most fisheries for food. However, the taking of small bait fish such as capelin or sand lance could prove damaging to storm-petrel populations because they depend heavily on fish during the breeding season. At present it is unknown if such competitive interactions exist.

7. Recommendations

Of the nine storm-petrel species in the North Pacific, two (Leach's and Fork-tailed) are so widespread and abundant that they do not appear to be threatened. The remaining seven species are all of some concern either because they have limited breeding distributions and relatively small population sizes, or because little is known about their actual numbers and present status. Black and Least storm-petrels both may number 20 000 individuals, and are under consideration for listing as threatened (Collar and Andrew 1988). Many species of storm-petrels are known to nest on only a small number of islands (e.g., Ashy and Madeiran storm-petrels), and several species (Ashy, Matsudaira's, Tristram's, and Madeiran storm-petrels' Hawaiian subspecies) likely number fewer than 10 000 individuals worldwide. Consideration should be given to designating at least Ashy, Matsudaira's, Tristram's, and Madeiran storm-petrels as threatened, and long-term conservation plans for each species should be developed as well. Tristram's Storm-Petrel is known to be declining and is already being considered for inclusion in the IUCN's Red Data Book as a threatened species (Collar and Andrew 1988). The remaining species, Swinhoe's, Black, and Least storm-petrels, should be considered sensitive species: breeding colonies and overall population sizes should be monitored.

Overall, there are insufficient data in most cases to determine if population sizes in any of the species are stable. Given the fact that most of the species have relatively small population sizes (5000–10 000 individuals), have a limited number of breeding sites, and may be vulnerable to a wide array of threats, it would be wise to begin planning for their conservation now.

Specifically, several steps need to be taken to assess the present status of the most threatened of the storm-petrel species. First and foremost, a survey to determine the Matsudaira's breeding grounds and estimate their population size needs to be done. The breeding grounds of all storm-petrels in the western Pacific and of the Black and Least storm-petrels in the Gulf of California should be determined and an effort made to improve the estimate of population sizes. In general, protocols for determining population size, which can be used to track changes in storm-petrel populations, need to be developed. Comparisons should be made among the existing methodologies—aerial nocturnal colony counts, mark and recapture mist-netting, burrow counts, and counts of calling at burrows—to determine their accuracy.

Given the threat posed by a wide variety of pollutants, efforts should be increased to adopt and enforce more restrictive guidelines against discharge of plastics, petroleum, and other toxic compounds into the world's oceans.

The most potent and serious threat to storm-petrel populations at present is predation, particularly by introduced predators. Storm-petrels are successful breeders on remote and isolated islands largely because these sites lack predators. As islands are visited and altered by humans, storm-petrels will be increasingly at risk.

Efforts to prevent introductions of mammals and removal of these mammals on islands where they have become established should be given the highest priority. In particular, guidelines to reduce the chances of ships and boats making introductions need to be developed and implemented. The most easily controlled and damaging predators (such as cats and foxes) should be immediately removed from any islands where they threaten storm-petrel breeding colonies, and from islands where they have recently eliminated colonies, in hopes that the birds will recolonize. Recordings and nesting boxes are known to be effective in attracting storm-petrels (Podolsky and Kress 1989; Boersma, unpubl. data). At present, because rats are so difficult to remove, efforts should be directed toward preventing introduction of these predators to seabird islands.

In conclusion we must emphasize that, overall, the impacts of pollutants and habitat disturbances pale in comparison with the impacts of predation, particularly by introduced mammals. Although successful management of storm-petrel populations will depend on efforts to reduce adverse effects from all classes of threats, the key to storm-petrel survival over the long term will lie primarily in careful predator management.

Acknowledgements

We thank D. Ainley, A. Golovkin, S. Sealy, and K. Vermeer for critical comments that have improved the manuscript.

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