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Review Article

A horizon scanning assessment of current and potential future threats to migratory shorebirds

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We review the conservation issues facing migratory shorebird populations that breed in temperate regions and use wetlands in the non-breeding season. Shorebirds are excellent model organisms for understanding ecological, behavioural and evolutionary processes and are often used as indicators of wetland health. A global team of experienced shorebird researchers identified 45 issues facing these shorebird populations, and divided them into three categories (natural, current anthropogenic and future issues). The natural issues included megatsunamis, volcanoes and regional climate changes, while current anthropogenic threats encompassed agricultural intensification, conversion of tidal flats and coastal wetlands by human infrastructure developments and eutrophication of coastal systems. Possible future threats to shorebirds include microplastics, new means of recreation and infectious diseases. We suggest that this review process be broadened to other taxa to aid the identification and ranking of current and future conservation actions.

Keywords: anthropogenic change, Charadriidae, Charadriiformes, ecosystem health, horizon scanning, Scolopacidae, shorebirds, waders.

Maintaining and restoring biodiversity requires targeted responses to major threats. A recurring problem is failing to foresee and address forthcoming issues. One recent example is the promotion of biofuels by the United States and the European Union where the conservation community was inadequately equipped to examine the likely environmental, social and ecological consequences and took some time to establish effective responses (Buyx & Tait 2011). One option to reduce such risks is horizon scanning, defined as the systematic

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search for potential threats and opportunities that are currently poorly recognized (Sutherland & Woodroof 2009). Horizon scanning has been adopted in a range of fields, including medicine (Storz *et al.* 2007, Gwinn *et al.* 2011), epidemiology (Morgan *et al.* 2009), business (Brown 2007) and criminology (White & Heckenberg 2011). The aim of horizon scanning is to provide advance warning of issues so that there is the opportunity to plan ahead, thereby raising awareness of emergent issues among researchers and encouraging a more rapid accumulation of relevant knowledge, with the result that decisions made by policy-makers and actions taken by practitioners may be better informed (Sutherland & Freckleton 2012). There have recently been annual horizon scans of conservation issues (Sutherland *et al.* 2010, 2011a, 2012a), a scan of issues facing the UK (Sutherland *et al.* 2008) as well as a recent scan of forthcoming environmental legislation (Sutherland *et al.* 2011b, 2012b).

A sensible starting exercise can be to list all known threats for a particular topic. An inclusive review of threats provides the basis for a comprehensive assessment of possible responses and effective horizon scanning (Sutherland & Woodroof 2009, Sutherland *et al.* 2012c). In particular, listing currently known issues alongside summaries of forthcoming issues can help to prioritize actions and may highlight the need to develop tools to address future threats. Here we illustrate horizon scanning by examining the natural, anthropogenic and potential future issues facing migratory shorebirds (Charadriiformes). We have chosen this taxonomic group of almost 200 species because: (1) they are found throughout the world, and include some of the longest-distance migratory species that may therefore be at risk from conservation threats globally (Boere *et al.* 2007a,b); (2) their behaviour and ecology are well studied on breeding, migratory stopover and wintering sites, with intensive ringing, ranging and movement-related research and monitoring in place for many species; and (3) they exhibit a wide range of population sizes and threat levels – some are very common and widely dispersed species, whereas others are IUCN red-listed as critically endangered or endangered (e.g. Slender-billed Curlew *Numenius tenuirostris*, Nordmann's Greenshank *Tringa guttifer* and Spoon-billed Sandpiper *Eurynorhynchus pygmeus*).

We have restricted this review to issues that are likely to affect population sizes significantly through severe short-term or persistent processes. We acknowledge that many of these issues will have impacts far beyond temperate shorebirds and that some may have substantially greater importance for human populations. To avoid repetition, this message is not included in individual sections.

THE HORIZON SCANNING APPROACH

Our philosophy is to identify and describe environmental changes that might occur and are likely to affect shorebirds. We consider issues across the breeding, migratory and wintering areas of migratory shorebirds breeding in temperate or arctic regions. We restrict ourselves to those species that inhabit wetlands at some stage in their lives and we have thus excluded shorebird species of arid grassland (e.g. stone-curlews, pratincoles and coursers) and woodland (e.g. woodcocks). We assembled a team of scientists with widely ranging interests and geographical expertise in order to produce the summary of current and anticipated threats in a transparent and democratic manner (Sutherland *et al.* 2011c). The exercise was carried out largely by Email consultation.

We briefly outline some of the more important possible consequences for shorebird populations of these threats but we do not aim to provide a fully comprehensive review of all possible consequences. Some knowledge of shorebird ecology is assumed and therefore we do not necessarily explicate all intermediate stages through which these impacts may be manifest. In most cases there is the potential for both positive and negative changes. We did not formally score the threats according to the magnitude of their projected impacts as this is likely to vary between regions and species, and would therefore require substantial further review and assessment (Sutherland *et al.* 2011c).

THE THREATS

Punctuated threats

We here review five natural threats for which effects would be almost immediate.

Megatsunami

The 11 March 2011 and 24 December 2004 tsunamis in Japan and southeast Asia, respectively, illustrated the catastrophic and tragic consequences of such events. In particular, the threat of nuclear meltdown at the Fukushima I Nuclear Power Plant altered governmental and public attitudes to environmental risk. Tsunamis derive from tectonic activity, whereas megatsunamis, which typically exceed 100 m in height, are caused by landslides or the impact of celestial objects. Their effects can be massive: three huge underwater landslips in Norway (*c.* 3500 km^3 of debris) occurring about 8000 years ago had marked effects as far-reaching as the current southern North Sea (Bondevik *et al.* 2003). One current, but contentious, candidate for a possible future megatsunami is the result of the eruption and collapse of the western edge of Cumbre Vieja volcano, La Palma, Canary Islands. This could generate an initial kilometre-high wave, which is predicted to arrive in eastern North America and the Caribbean 8 h later as a 50-m high wave. Others argue that a single collapse is unlikely (Pararas-Carayannis 2002). Clearly, such events could cause a major transformation of wintering, passage and breeding grounds for shorebirds.

Volcanoes

Volcanic eruptions can destroy islands and lower global average temperatures by as much as 1 °C (e.g. Tambora in 1815, Krakatoa in 1883) (Diacu 2009). In Iceland, the Grímsvötn and Laki eruptions between 1783 and 1785 triggered widespread famine, killing one-quarter of the human population there. While the short-term effects of volcanism are largely lethal for biota, the long-term effects may be beneficial across broad geographical regions. Aeolian deposition from volcanic activity shows strong stratification across Iceland (Arnalds 2010) and shorebird abundance seems to be strongly and positively spatially related to deposition rates across the country (Gunnarsson 2010).

Earthquakes

Earthquakes can displace deltaic and intertidal zones via vertical uplift and subsidence of up to tens of metres, with effects extending across hundreds of kilometres (Atwater 1987). The resulting chronosequence of landform change can be either beneficial or detrimental to shorebird nesting and foraging habitat. Subsidence reduces habitat and diminishes food stores (Castilla *et al.* 2010). Uplift triggers short-term gains from exposed intertidal food sources and long-term habitat gain (Bodin & Klinger 1986, Boggs & Shepard 1999).

Asteroids

Asteroid impacts can severely reduce biodiversity; about 65 million years ago, one large impact may have caused the Cretaceous/Tertiary mass extinction (Bottke *et al.* 2007). Brown *et al.* (2002) estimated that collisions releasing about 5 kton of energy occur annually and that collisions on the scale of the Tunguska explosion in Russia (estimated as equivalent to 10 megatons of TNT) have a one in a thousand year probability of occurrence. Toon *et al.* (1997) state that collisions below 10 megatons of energy are unlikely to pose large-scale environmental hazards.

Hurricanes

The power of storm systems is well illustrated by Hurricane Katrina (2005) and the November 1970 cyclone in Bangladesh, which killed almost half a million people. Storms of these magnitudes can dramatically alter local ecosystems. Cyclones in northern Australia alter the balance of saltmarsh and mangrove ecosystems through storm surge and the landward expansion of tidal creeks (Winn *et al.* 2006).

Gradual change

Here we consider issues that will typically gradually increase in intensity. Some are clearly occurring now.

Climate change – major changes in weather patterns

Changes in temperatures, the timing and extent of precipitation, and the frequency and severity of extreme weather events all have the potential to influence shorebird populations both positively and negatively (Robinson *et al.* 2009). High levels of shorebird mortality can result from extremely cold weather conditions (Clark 2009) and the frequency of these events in temperate regions has decreased in recent years (IPCC 2007). However, in many cases the effects of natural or anthropogenic global climate change will be manifest through indirect effects on land-use change, prey availability, the condition of seasonal wetlands, changes in matching of the timing of arrival dates and prey dynamics, predation effects, disease and parasitism (Poulin & Mouritsen 2006, Boere *et al.* 2007a, Mustin *et al.* 2007, Thompson *et al.* 2012). Given the disproportionate impact that climate change may have on arctic ecosystems (IPCC 2007), changes in the timing of snowmelt and plant growth and invertebrate activity are likely to markedly influence shorebird productivity at higher latitudes and altitudes. However, some animals and plants may simply tolerate or adapt to various climatic effects, in which case the effects may be weaker than modelled hard-wired responses would assume (Dawson *et al.* 2011). Whilst it seems inevitable that there will be changes, the complexity of the interactions will make it difficult to predict the response (Mustin *et al.* 2007). Given the nature of climate changes experienced to date, we need more analyses of existing data and further work in order to assess the magnitude of this driver on shorebird populations (Pearce-Higgins 2011, Thompson *et al.* 2012).

Changes in sediment flow

The impact of sea-level variation on the size and location of intertidal regions will be influenced by the rate of sediment inflow (Van de Kam *et al.* 2004). In China, sediment loads from the Yangtze River into the sea have dropped dramatically since the creation of the Three Gorges Dam (Chen *et al.* 2008) and those from the Yellow River have also declined due to basin-wide human activities and a decline in precipitation (Wang *et al.* 2007). The capacity of shorebirds to cope with such changes will depend on their ability to shift their migratory routes and possibly winter sites. This in turn will be influenced by whether rates of change in intertidal systems allow for adaptation and whether alternative areas provide sufficient resources to support potentially longer flights and higher densities of individuals. This is likely to have an effect on both the intertidal area and the type of sediment in the intertidal areas. Ongoing monitoring should reveal the nature of this response (Boere *et al.* 2007a,b).

Reduction of tundra habitat

Soja *et al.* (2007) reported that in the circumboreal region, warming-induced change has been progressing faster than predicted. There is evidence that the treeline has been migrating further north, colonizing arctic tundra habitat, which may further accelerate climate change through the liberation of labile carbon from tundra heath soils (Soja *et al.* 2007, Sjögersten & Wookey 2009). Furthermore, higher temperatures have been linked with increased pest insect outbreaks (Soja *et al.* 2007, Demain *et al.* 2009), more frequent and intense fire cycles (Soja *et al.* 2007) and the desiccation of wetland habitat (McMenamin *et al.* 2008), which may have a range of consequences for shorebirds breeding in this habitat (Pearce-Higgins 2011, Thompson *et al.* 2012). As with some of the above changes, detailed analyses are needed to provide an overview of changes; Pearce-Higgins (2011) gives an example for breeding Eurasian Golden Plover *Pluvialis apricaria*.

Anthropogenic sea-level rise

As a consequence of thermal expansion, average sea level is predicted to rise globally at a faster rate than ever observed (Watkinson *et al.* 2004). At the same time there are major concerns about the extent of polar ice melt and its effect on sea levels (Rignot 2011). The loss of ice has broadened the expanse of near-shore open water, providing much greater fetch for waves, thereby altering or sometimes even eliminating shorebird nesting and littoral feeding habitats (Jones *et al.* 2009). Manmade structures to prevent flooding and reclaim land are likely to impede the re-location of intertidal habitats. For example, sea walls may both reduce intertidal habitat and limit low tide emersion times (Ferns 1992).

Spread of algal species in intertidal habitats

The spread of algal species by invasion or eutrophication can restrict shorebird foraging habitat, because benthic prey may diminish with expanding algal coverage (Lopes *et al.* 2000). An outbreak of *Enteromorpha* in China in 2008 covered 13 000 km^2 (Leliaert *et al.* 2009). There is currently little evidence that algal mats affect shorebirds, although it should be noted that habitat patchiness or foraging behaviour adaptability may mask impacts of algal spread (Múrias *et al.* 1996, Cabral *et al.* 1999).

Algal blooms

More than 200 species of microalgae, including dinoflagellates, diatoms and cyanobacteria, can produce neurotoxins, hepatotoxins and dermatotoxins that can poison shorebirds through direct ingestion or bioaccumulation in filter-feeding invertebrate prey (Landsberg 2002). Harmful algal blooms have increased steadily due to climate warming and eutrophication (Sellner *et al.* 2003). The impact of algal blooms on shorebird mortality is probably underestimated due to carcass predation, decomposition and tide action, although there is evidence that algal blooms may have triggered several mass mortality events (Buehler *et al.* 2010). However, some shorebird species avoid prey or habitats contaminated by algal bloom toxins (Kvitek & Bretz 2005).

Botulism

Rocke and Bollinger (2007) reported that 64 species of shorebirds have been diagnosed with avian botulism, which has killed thousands of birds in every continent apart from the Antarctic. Newman *et al.* (2007) found that between 1971 and 2005, botulinum intoxication was a leading cause of death for aquatic birds. Given that the species responsible for botulism have resistant spores that can survive for years (Hofer & Davis 1972) these problems can persist, and may well have population-level impacts. This is most likely to be the case for species with small populations, such as the endangered Piping Plover *Charadrius melodus* at Sleeping Bear Dunes in the Great Lakes, where outbreaks are increasing in the vicinities of high-density nesting areas (USFWS 2009).

Infectious diseases

Avian influenza has raised the profile of avian diseases; for example, over 6000 birds, including more than 3000 Bar-headed Geese *Anser indicus*, died at Lake Qinghai in northern China during an outbreak in 2005 (Chen *et al.* 2006). Its prevalence in shorebirds is currently generally low (Olsen *et al.* 2006). Outbreaks may lead to calls for changes in attitude to wild birds. The infection rate by *Plasmodium* parasites (avian malaria) is rapidly increasing in many birds (Garamszegi 2011) and there are high infection rates of Campylobacteria in waders (e.g. 86% in Common Redshank *Tringa totanus*, Waldenstrom *et al.* 2007). The predicted changes in land use and global climate may result in a stronger concentration of shorebirds on remaining high-quality staging sites, making them potentially more vulnerable to infections (Krauss *et al.* 2010).

Current anthropogenic threats

We list 21 current issues, several of which seem likely to become increasingly important.

Drainage of breeding and wintering habitats

Drainage of breeding and wintering habitats, which typically constitutes the first step of agricultural intensification, has been implicated in the widespread decline of temperate breeding shorebird populations (Twedt *et al.* 1998, Higgins *et al.* 2002, Wilson *et al.* 2004, Boere *et al.* 2007b). Intensively managed grasslands generally have drier soils with reduced prey availability (Ausden *et al.* 2001), may be subject to mowing (Kleijn *et al.* 2010) and present homogenized habitat at the landscape scale (Benton *et al.* 2003). As pressure to increase grass yield continues to rise, drainage of current natural wet grasslands will probably accelerate. However, there is evidence in Iceland that low-intensity agriculture and limited drainage can improve conditions for some shorebirds (Thorhallsdottir *et al.* 1998, Gunnarsson *et al.* 2005).

Agriculture intensification

Agricultural development in the Neolithic era may have benefitted some temperate shorebirds by converting habitats such as woodlands to grasslands (Van Eerden *et al.* 2010). Nevertheless, it appears that species only profit from agricultural intensification up to some threshold level (Gunnarsson *et al.* 2005, Gill *et al.* 2008). Species that cannot persist in intensively managed lands have declined in Europe (e.g. European Golden Plover) and in North America (e.g. Marbled Godwit *Limosa fedoa*) (Beintema 1986). In Japan, shorebirds reliant on rice field staging sites have declined after the introduction of efficient drainage systems, which reduce fallow fields and habitat heterogeneity (Amano 2009, Amano *et al.* 2010).

Changes in grazing

Although grazing can promote plant species richness, particularly in saltmarsh habitats, overgrazing, usually by domestic livestock, may threaten breeding shorebird populations through trampling and severe reduction of vegetation cover. This risk is particularly acute with high densities of grazing sheep (Norris *et al.* 1998). However, low-intensity grazing may also reduce productivity through concomitant declines in insect density (Székely *et al.* 1993).

Changes in cutting date

Increased fertilizer use and rising temperatures permit earlier cutting and grazing dates for some agricultural grasslands (Kleijn *et al.* 2010). As a result, clutches and chicks of grassland-breeding shorebirds experience higher mortality (Teunissen *et al.* 2005). Early cutting and/or grazing can also adversely affect chick-rearing habitat, which further reduces chick survival (Schekkerman *et al.* 2008).

Changes in flooding patterns of rice fields

Flooded rice *Oryza sativa* fields provide shorebird habitat, especially in regions with severe wetland drainage and degradation, although they are generally inferior to existing natural wetland habitat (Elphick 2000, Bellio *et al.* 2009). However, rice-growing often requires extensive use of freshwater and produces high methane and nitrous oxide emissions (Xing *et al.* 2009). There have been proposals to produce dry rice (Ishizaki & Kumashiro 2008) and advance field drainage times for wet rice cultivars. Un-flooded rice fields are much poorer shorebird habitat and may increase predation pressure (Elphick 2000, Lourenço & Piersma 2009, Pierluissi 2010). Additionally, global warming may lead to altered flooding times in general, causing a mismatch between shorebird arrival and food availability. In Japan, for example, shorebird use of rice fields peaks during spring migration (Watanabe 1991) but farmers are increasingly delaying planting dates to avoid high temperatures at the ripening stage in midsummer (MAFF 2009).

Abandonment of rice fields

In west Africa, mangrove rice fields are important to a large variety of shorebirds (Bos *et al.* 2006). Cultivation of mangrove swamp rice is done manually. With increasing societal prosperity in west Africa, farmers are more likely to abandon mangrove swamp rice farming. Similarly, in Japan, rice fields have been abandoned at increasing rates (Japan Biodiversity Outlook Science Committee 2010). Abandoned rice fields are typically covered by tall vegetation and are thus less suitable as foraging habitats for shorebirds (Fujioka *et al.* 2001, Huner *et al.* 2002).

Afforestation of temperate and sub-arctic breeding habitat

The majority of shorebird species breed in open grassland, avoid forests and are displaced by forestry (Gunnarsson *et al.* 2006, Amar *et al.* 2011). Proximity to forests may increase predation impacts, although the evidence for such effects is not conclusive (Avery 1989, Reino *et al.* 2010, Amar *et al.* 2011). Large-scale afforestation schemes in important breeding wader habitat have been associated with population declines in the UK (Stroud *et al.* 1990, Amar *et al.* 2011). In other countries too, large-scale forestry threatens internationally important wader populations (Walsh *et al.* 2000, Gunnarsson *et al.* 2006, Reino *et al.* 2010).

Land-claim of tidal flats and marshes

There have been extensive losses of coastal wetlands globally (e.g. in the UK, Davidson *et al.* 1991, in USA, Dahl 2006, for global reviews see Boere *et al.* 2007a). Currently, development of coastal mudflat and wetland habitat is especially prevalent throughout eastern Asia, particularly in the Yellow Sea, where about 37% of the inter-tidal areas in the Chinese and 43% of the South Korean portions have been reclaimed for agriculture (Barter 2006). South Korea has reclaimed 40 100 ha of tidal flats in Saemangeum, a key site for shorebirds, leading to declines in 19 of the most numerous species in 2 years (Birds Korea 2010), and China has reclaimed 19 000 ha from Bohai Bay, which has concentrated migratory populations in the remaining habitats (Yang *et al.* 2011). There are ongoing plans for further development on both sides of the Yellow Sea (Rogers *et al.* 2010) and species dependent on the Yellow Sea have declined in Japan (Amano *et al.* 2010).

Restoration of coastal wetlands through managed realignment

The restoration of coastal habitats through realignment of coastal defences is being increasingly implemented in northwest Europe and North America (Atkinson *et al.* 2004), although not in areas with rapidly growing human populations and economies such as East Asia. These actions can result in the creation of new mudflats and saltmarshes, and thus provide key resources for shorebird species. Mander *et al.* (2007) reported that within 3 years of creation, a realigned site on the Humber estuary supported a waterbird community with the same functional assemblage as on nearby natural intertidal zones.

Conversion of mangroves

Mangroves provide foraging and sheltering habitat to shorebird populations that winter in the tropics. However, across Asia and in Thailand, the Philippines and India in particular, mangrove forests have been extensively converted to building development, agriculture and commercial shrimp farms, reducing shorebird species richness and abundance (Sandilyan *et al.* 2010).

Expansion of mangroves onto saltmarshes

In New Zealand and Australia, mangroves have colonized saltmarsh habitat (Saintilan & Williams 1999) and tidal mudflats (Morrisey *et al.* 2007), leading to the loss of large areas of open intertidal zones critical to waders during the austral summer. In Lake Man, a Ramsar site in Japan, the expansion of mangroves has similarly reduced intertidal habitats (Japanese Ministry of the Environment 2009). Mangrove distribution may be limited by minimum critical temperature thresholds (Spalding *et al.* 2010), with increased temperatures potentially removing limits on the growth of mangroves and enabling them to expand into temperate saltmarshes or intertidal habitats currently used by waders.

Pollution from aquaculture

Shrimp farming results in the release of antibiotics and other pollutants to the environment (Holmström *et al.* 2003, Xie *et al.* 2004, Visuthismajarn *et al.* 2005, Cao *et al.* 2007, Xie & Yu 2007). Farming of Japanese Spiky Sea Cucumbers *Apostichopus japonicus* is growing rapidly in northeast China and uses large quantities of antibiotics that may be discharged into the environment (Sui 2004). In India, the organophosphate insecticide Dipterix (trichlorfon) (James 2004) is used to control predators of another sea cucumber, the Sandfish *Holothuria scabra*, and may be ecotoxic to the aquatic environment and terrestrial vertebrates (ERMA 2011). It is likely that shorebird prey will be impacted by these pollutants, although impacts on birds are not clear.

Eutrophication of coastal systems

With some similarities in impacts to the above, industrial and domestic effluent discharge accumulates in estuarine and coastal sites where the slow water flows enhance sedimentation. Agricultural fertilizers promote nutrient run-off in downstream areas. Eutrophication in coastal systems has complicated consequences; whereas some macrobenthos profit from nutrient augmentation, continued nutrient discharge can lead to anoxia from aerobic bacteria hyperactivity (Nedwell *et al.* 1999). The consequences of eutrophication for waders are shown by the discharge of effluent from sewage treatment outfalls being associated with artificially high local wader populations, which may then receive unwarranted conservation designation (Burton *et al.* 2004). Wastewater provides substantial food resources through directly edible matter and/or enhancing invertebrate density (Alves *et al.* 2012).

Spread of Spartina and other angiosperms

Many countries have introduced species of cordgrasses *Spartina* spp. for flood control but *Spartina* depresses mudflat accessibility and alters communities through sediment trapping (Wang *et al.* 2010). *Spartina* spread has been linked to declines in the abundance of wintering Dunlin *Calidris alpina* in Britain (Goss-Custard & Moser 1988) and breeding and wintering shorebirds in China (Ma *et al.* 2009). However, Van de Kam *et al.* (2004) reported that Dunlin abundance has increased even on sites where *Spartina* persists. Other invasive plants, such as Black Locust *Robinia pseudoacacia* in Japan, are also known to reduce early-successional habitats available to waders (Katayama *et al.* 2010).

Suppression of natural disturbance by river regulation

Fluvial plains that are seasonally or irregularly inundated by floodwater provide critical wildlife habitat (Nilson & Dynesius 1994). Some wader species specialize in such early successional habitats. A large proportion of the world population of Whimbrel *Numenius phaeopus* occupies river plain habitats in Iceland (Gunnarsson *et al.* 2006) and vulnerable species such as the Wrybill *Anarhynchus frontalis* in New Zealand are dependent on such habitats (Hughey 1997). Regulation of many large river systems worldwide has interrupted the natural disturbance patterns needed to maintain dynamic floodplain habitats (Nilson *et al.* 2005).

Disturbance

Although shorebirds may waste time and energy responding to human disturbance, the consequences for individuals and populations are difficult to determine (Gill *et al.* 2001) as are the consequences for disturbance on roost sites. Temporary loss of foraging habitats can occur (Dias *et al.* 2008) and the capacity to compensate by foraging for longer periods may vary between individuals (Urfi *et al.* 1996). During the breeding season, human disturbance may influence nest incubation and chick rearing, and very high levels of human activity may prevent the use of suitable breeding or foraging habitat (Finney *et al.* 2005, Liley & Sutherland 2007).

Harvesting and collection of shorebird prey

Although anthropogenic exploitation of shellfish stocks at low intensities may have little impact on shorebirds (Dias *et al.* 2008), shellfish harvesting in some areas can be much more intensive (Melville 1997, Niles *et al.* 2009). Extensive mechanical harvesting may increase shorebird mortality and suppress productivity (Camphuysen *et al.* 1996, Atkinson *et al.* 2003, Verhulst *et al.* 2004). Mechanical dredging can severely degrade intertidal habitat through the loss of mussel and cockle beds (Van de Kam *et al.* 2004).

Hunting

Hunting by humans has severely threatened several shorebird species to the point of endangerment or even possible extinction (e.g. Eskimo Curlew *Numenius borealis*, Gill *et al.* 1998, Graves 2010). Although hunting of shorebirds is banned in some developed countries, hunting and poaching elsewhere may undermine conservation measures (Gill *et al.* 2008, Ottema & Ramcharan 2009, Zöckler *et al.* 2010). In the European Union (EU), for example, many waders listed under Annex II of the EU Birds Directive (quarry list) are hunted. Reporting and monitoring of the 'take' of these birds will clearly be important to determine any wider impacts in the future.

Predators and predation

Raptors are key predators of adult shorebirds outside of the breeding season (Cresswell & Whitfield 1994) and raptor abundance has increased globally due to protective measures implemented in the 1990s (Kirk & Hyslop 1998, Kjellén & Roos 2000). There has been no substantial evidence that higher raptor abundance has reduced adult shorebird survival but there have been reports of abbreviated migratory stopovers (Ydenberg *et al.* 2004), inadequate weight gain during the wintering period (Piersma *et al.* 2003) and predation–starvation risk trade-off, as in the case of Common Redshanks in Scotland, which experience higher mortality risk in cold weather because they are obliged to move from safer, but less profitable, areas to risky foraging areas with more profitable prey (Cresswell & Whitfield 2008). A number of mammalian predators have recently increased in abundance and these can have an impact on breeding success (Smith *et al.* 2010, Fletcher *et al.* 2012).

Invasive animals

Introduced predators, particularly mammals, may threaten breeding populations to the point of extirpation (Dowding & Murphy 2001, Blackburn *et al.* 2004). For example, introduced Hedgehogs *Erinaceus europaeus* substantially reduced shorebird abundance on the Western Isles of Scotland (Jackson *et al.* 2004). Exotic marine organisms, dispersed worldwide by ballast water, compromise coastal habitats. The rapid spread of the Pacific Oyster *Crassostrea gigas* exemplifies the dramatic changes invasions can impose (Troost 2010). Introduced rats and mice have been shown to deplete insect populations in the Falkland Islands (St Clair *et al.* 2011) and the Antipodes Islands (Marris 2000), which could affect shorebirds.

Possible future threats

We list 13 issues that could be important in the future.

Microplastics

Microplastics are plastic particles under 5 mm long. Their persistence is compounded by the continuous breakdown and wide distribution of plastic waste (Ryan *et al.* 2009). Microplastics can adsorb various types of organic pollutants and, in general, plasticizing compounds are toxic to a variety of fish, amphibians and molluscs (Frias *et al.* 2010). Bhattacharya *et al.* (2010) demonstrated that the adsorption of nanoplastic impeded algal photosynthesis. The loss of specific food items could be directly detrimental to specific shorebirds, or disrupt the wider food chain that supports wader populations at sites affected by microplastics.

Nanosilver

Nanosilver denotes aggregates of silver atoms $\leq$ 100 nm and is currently being developed due to its antibacterial properties, which may be widely used in food preparation, disease control in medical processes and reducing the smell of sweaty clothes. Mueller and Nowack (2008) calculated that the concentration of nanosilver particles is currently < 80 ng/L, far below the concentration at which effects have been observed. It is unknown how long nanosilver persists in aquatic media or if it can be directly bioaccumulated. Research on nanosilver toxicity has been inconclusive. Although low concentrations of nanosilver have been shown to cause DNA damage and reduce immunocompetence, other studies have reported either neutral or even positive effects such as increased intestinal bacteria in Japanese Quails *Coturnix c. japonica* (Sawosz *et al.* 2007, Hackenberg *et al.* 2010). The consequences, if any, for shorebirds remain extremely uncertain.

New means of recreation

Waterskis, kite-surfing and kite-buggying have changed coastal recreation. The engines of water-craft discharge up to 30% of their fuel (Davenport & Davenport 2006). Kite-surfing and kite-buggying use large kites (up to 5–8 m^2) flown 30 m high. The potential impacts of novel sports such as waboba® (throwing a ball in near-shore environments), paddle boarding or Coasteering®, which involves jumping and scrambling across rocky shores and pulling on kelp to climb out of the surf, are unknown (Davenport & Davenport 2006).

Artificial meat

Several research teams are developing *in vitro* meat from skeletal muscle stem cells. This research has only produced tissues $< 1.5 \times 0.5$ cm^2 thus far (Marloes *et al.* 2010). However, given that the FAO (2009) forecasts that the global demand for food will rise by 70% by 2050, and the fact that about 80% of agricultural lands worldwide are dedicated to grazing and feed crops, synthetic meat could not only greatly reduce the conversion of natural lands to pasture but also reduce the availability of pasture as a breeding habitat for shorebirds in temperate zones.

Impact of global hydro-security and water wars

Globally, there are approximately 263 internationally shared watercourses, draining the territories of 145 countries. Although there are over 400 international agreements between watercourse states, 60% of these international basins do not have any co-operative management framework (Rieu-Clarke & Loures 2009). The development of large dams, river diversions and inter-basin transfers have been the principal drivers of flow regime change to the point where major rivers sometimes do not reach the sea and some are now dry for much of their length (UNEP 2006). Water scarcity threatens to become a potent fuel for wars and conflict. Fuelled by poverty, trade disputes and climate change, water security and governance may have a major impact on wetland habitats.

High-latitude volcanism

The Laki eruption in 1783 triggered an aberrantly cold winter in the northern hemisphere and acid rain in Iceland (Robock 2000). The climatic effects of the Laki eruption, although extreme, are characteristic of the impact of high-latitude volcanism (Schneider *et al.* 2009). High-latitude eruptions can cause glacial melt and have been implicated in weaker Asian monsoons, reduced rainfall and even droughts in the Palaearctic and northern Africa (Oman *et al.* 2006). Although the impact of high-latitude eruptions tends to be fairly short lived, modelling exercises suggest that higher latitudes are disproportionately sensitive to volcanic activity (D'Arrigo *et al.* 2008, Schneider *et al.* 2009). There are suggestions that global warming could increase the likelihood and impact of high-latitude volcanism (Sutherland *et al.* 2010). Increased volcanism could devastate wader habitat in the high latitudes through faster glacial melt, and in the tropics by weakening the Asian monsoon and leading to reduced rainfall and drying of saltmarsh currently used by shorebirds.

Change in nitrogen fixing in high-latitude estuaries

There is some evidence that changes in nutrient cycling in high-latitude estuaries may impact the food supply of shorebirds. These estuaries tend to be oligotrophic and nitrogen-limited. In general, estuaries divert nitrogen from the ocean shelf, thereby reducing the effect of anthropogenic N-loading (Filippino *et al.* 2011). However, there is evidence that high-latitude estuaries have recently switched from denitrification to nitrogen fixation because less resource-rich organic matter is delivered to the benthos (Filippino *et al.* 2011); phytoplankton biomass has reduced and the peak grazing pressure on phytoplankton has shifted to the summer, which is the main season for cyanobacterial nitrogen fixation (Borkman & Smayda 2009, Fulweiler *et al.* 2010, Thad & McCarthy 2010). These changes could lead to an overall or at least seasonal reduction in food sources for particular shorebirds; we have no evidence of examples to date.

Changes in sediment with forest loss

Kirwan *et al.* (2011) reported evidence that widespread deforestation in North America promoted saltmarsh accretion through increased sedimentation. However, higher rates of sediment delivery may suppress nitrogen fixation activities (Moseman-Valtierra *et al.* 2010). Furthermore, continued sediment loading can compromise water clarity and eventually cause wetland loss (Van Hengstum *et al.* 2007).

Changing atmospheric circulation patterns

Atmospheric conditions that are favourable for migration are a key component of the evolution of bird migration routes and patterns (Åkesson & Hedenström 2000). In particular, wind strength and direction can directly affect the capacity of shorebirds to migrate between stopover locations (Shamoun-Baranes *et al.* 2010). Much of the climate change research on wind systems has focused upon changes in stormtracks (McDonald 2010) but changes in typical weather patterns may also influence the capacity of shorebirds to migrate between key locations along migratory routes.

Changes in primary productivity on wintering and migratory staging areas

Shorebird wintering and staging sites tend to be concentrated on intertidal flats with high levels of near-shore primary productivity and generally exclude sites with low productivity (Butler *et al.* 2001). With the exception of the Pacific Americas Flyway, most shorebird flyways have wide separations between these localities, which led Butler *et al.* (2001) to posit that migratory strategies had evolved to capitalize on these specific locations. Rapid changes in ocean current circulation and/or onshore winds could change the distribution of such sites. Arctic-breeding shorebird species are disproportionately likely to be long-distance migrants and are especially reliant on key high-quality staging sites for fattening (Gill *et al.* 2009).

Shutdown or slowdown of the thermohaline circulation

A shutdown or slowdown of the thermohaline circulation has been suggested as a possible, but unlikely, consequence of global warming, which might induce significant short-term or long-term climate oscillations (Pross *et al.* 2009, Elmore & Wright 2011). Pross *et al.* (2009) proposed that a previous slowdown of the thermohaline circulation triggered significant species turnover in terrestrial ecosystems.

Impact of acidification on marine nitrogen cycles and shellfish

Currently, the world's oceans store up to 50% of anthropogenically produced CO_2 (Sabine *et al.* 2004). Ocean acidification from CO_2 dissolution poses a severe threat to the marine nitrogen cycle. Huesemann *et al.* (2002) observed experimentally cessation of nitrification at a pH of 6. Beman *et al.* (2011) warn that continued ocean acidification could reduce nitrification rates up to 44%. The risks posed by disruptions to the marine nitrogen cycle are compounded by threats to shellfish that are an important food for many shorebirds. Calcification in *Mytilus edulis* and *Crassostrea gigas* declines linearly with increasing pCO_2 (Gazeau *et al.* 2007). In contrast, *Amphiura filiformis* exhibited the capacity to compensate for acidification by accelerating their metabolism and calcification rates, although these processes are likely to be unsustainable for extended periods of time (Wood *et al.* 2008).

Increases in pharmaceutical discharges as human populations age

An ageing human community and a change in the availability of prescription practices is likely to result in marked increases in the quantity and diversity of pharmaceuticals (including new types such as nanomedicines) and in the subsequent release of metabolites into the environment (Depledge 2011, Sutherland *et al.* 2012a). The impact of these changes is poorly understood.

DISCUSSION

This review demonstrates the wide breadth of issues facing shorebirds, ranging from unlikely but highly catastrophic events such as megatsunamis to ongoing problems such as the spread of invasive angiosperms to novel developments such as nanosilver. The merit of such an exercise is that it exposes the range of possible problems, and can thus aid the formation of policy and scientific experimentation to identify solutions. We suggest that this exercise be broadened to other taxa, particularly those of high conservation concern with limited research.

For migratory shorebirds, many of the current and future threats relate to changing availability of wintering, stopover and breeding locations along their migratory pathways (Boere *et al.* 2007a). Migratory species differ from other species because individuals depend on multiple locations that may be spread over continents, and individual sites can support substantial proportions of entire populations during the course of annual migrations. The loss of key locations at any point on migratory routes can therefore have far-reaching consequences for whole populations. The capacity of migratory species to alter migratory routes in response to environmental changes is not well understood. Examples of the range of species that have recently changed their migration route (Sutherland 1998, Newton 2007) suggest some degree of flexibility. Shorebirds have persisted throughout previous glaciation events, and migratory behaviour clearly has the capacity to respond to large-scale environmental changes. However, the success of any shifts in migratory behaviour would also be contingent upon the diminishing prospect of alternative locations being available for these species to exploit.

Horizon scanning can be a component of 'adaptive foresight', a process that challenges policy-makers to examine the uncertainties and the unexpected, to develop more resilient policies (Van Rij 2010). We expect that policy-makers and practitioners will use this by considering the implications for the region and group of species relevant to their concerns. Thus the priorities will differ between organizations. Organizations will also differ in the extent to which it is appropriate for them to respond to horizon scanning, depending upon the breadth of their interests and the extent to which they wish to concentrate upon immediate issues or ensure they are prepared for those that may arise in the future.

We suggest that consideration of the urgency and importance of the issues listed here will help to identify whether current levels of preparation are appropriate. For many issues, such as the development of artificial meat, implementation is likely to be sufficiently gradual that research and policy development can be delayed until required. Other issues, such as the widespread environmental changes currently occurring in the Yellow Sea, are likely to require more urgent action.

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