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Improving understanding of the possible relationship between improving freshwater and coastal water quality and bird interest on designated sites – phase 1 review

Authors

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CONTENTS

Page No.

List of Tables 3

EXECUTIVE SUMMARY 5

1. INTRODUCTION 7

1.1 Background 7
1.2 Project Aims 8

2. METHODS 9

2.1 A Literature Review of Direct and Indirect Effects of Water Quality Change on Bird Communities 9
2.2 Recommendations for Further Work to Improve Understanding of this Subject Area 13

3. RESULTS 15

3.1 Coastal Waterbird Populations 15
3.1.1 Summary of Burton *et al.* (2002) 16
3.1.2 Species that feed directly on food resources from outfalls 18
3.1.3 Species that feed on invertebrates and algae 25
3.1.4 Piscivores 28
3.2 Freshwater Waterbird Populations 29
3.2.1 Species that feed on invertebrates and algae 29
3.2.2 Piscivores 31
3.3 Birds as Nutrient Sources 31

4. DISCUSSION 37

4.1 Summary 37
4.2 Species at Risk from Improvements to Water Quality 37
4.3 Recommendations 39

Acknowledgments 40

References 41

LIST OF TABLES

Page No.

Table 2.1 Wintering waterbird interest features of freshwater and coastal sites classified as Special Protection Areas (SPAs) in England under the EC Directive on the conservation of wild birds 10

Table 3.1 Principal studies investigating the effects of nutrient loading of coastal Waters on bird communities 20

Table 3.2 Principal studies investigating the effects of nutrient loading of freshwater Systems on bird communities...33

Table 4.1 Wintering waterbird interest features of freshwater and coastal sites classified as Special Protection Areas (SPAs) in England under the EC Directive on the conservation of wild birds (79/409/EEC) that may be affected by improvements to water quality 38

EXECUTIVE SUMMARY

1. Over the past 50 years there has been widespread improvement in water quality in many freshwater and coastal systems driven by domestic and European legislation, most recently the EU Water Framework Directive (EC Directive 2000/60/EC), but also including the Urban Waste Water Treatment Directive (EC Directive 91/271/EEC) and Bathing Water Directive (EC Directive 76/160/EEC). Over the same period, declines have been recorded in the populations of a number of non-breeding waterbird species in the UK. It has been suggested that the change to systems with more natural nutrient levels could be one of the contributory causes of these wintering bird population declines.

2. This work aims to provide a better understanding of the evidence for water quality change being a potential driver of bird population change at a whole site and site-network level. Five objectives have been identified by Natural England to meet this need:

    i. An update of a previous review by Burton et al. (2002) to provide a review of the global literature relating water quality change and its direct and indirect effects on bird communities;
    ii. A review of the global literature relating to water quality change and its impact on demersal and benthic communities used as food resources by non-breeding waders and wildfowl;
    iii. Identification of those species most at theoretical risk of population change from water quality improvement as a consequence of their foraging requirements;
    iv. Recommendations for further work to improve understanding of this subject area;
    v. Analysis of water quality data (if this can be sourced) and bird numbers for species identified in (iii) to see if there are any relationships.

    The present work focuses on the first and fourth of these objectives and informs assessment of the third.

3. Sewage discharged into coastal waters can provide a direct food source for bird such as gulls, scavenging on the effluent, but mostly it is the algal, plant, invertebrate and fish communities sustained by the outfalls that provide food for a variety of birds, such as dabbling ducks, waders, cormorants and grebes. As such, the presence and location of sewage discharge points has been linked to variation in numbers of Grey Plover *Pluvialis squatarola* and Lesser Black-backed Gull *Larus fuscus*, for example, and the structure and distribution of waterbird communities.

4. Nutrient enrichment of coastal waters from diffuse sources (e.g. from agricultural run-off) may also lead to increased food resources and may therefore be expected to be positively associated with waterbird abundance (especially waders and benthivorous species). In one of the only large scale studies of potential effects of diffuse pollution of coastal waters on waterbirds, the use of fertilisers in Denmark accounted for 15% of the variation in the winter population index of 15 species. Across Europe, 14 positive and 36 negative relationships were observed between fertiliser use and waterbird population indices, with indications that negative effects of fertiliser use may be reversible, over long timescales. While nutrient enrichment may increase food resources, it may also lead to the formation of macroalgal mats on mudflats, affecting the availability of invertebrate prey, and therefore the foraging strategies, abundances and distribution of waterbirds, particularly waders such as Curlew *Numenius arquata*, Redshank *Tringa totanus* and Black-tailed Godwit *Limosa limosa*.

5. Improvements to water quality of coastal systems, by reducing the nutrient content and organic matter available, may lead to shifts in waterbird community structure, and have been suggested as contributing factors in declines in wader abundance and the disappearance of some local diving duck populations. However, associations are correlative, or otherwise postulated, thus attributing changes in waterbird numbers solely to water treatment is unwise. Any effects of programmes to improve water quality are likely to be site- and species-specific.

6. The pathways by which nutrient loading affects waterbird communities in freshwater systems are likely to be similar to those in coastal waters, with nutrient enrichment leading to enhanced food resources and therefore positive associations with waterbird numbers (e.g. aggregations of Tufted Duck *Aythya fuligula* and Pochard *Aythya ferina* associated with sewage discharges into the Manchester Ship Canal and predicted positive effects of nutrient loading on piscivores). However, freshwater systems, and shallow lakes in particular, may be more sensitive to changes in nutrient loading than coastal systems, due to lower flushing and dilution of the system. Nutrient enrichment can reach a point where the system shifts from transparent, submerged macrophyte-dominated waters to a turbid, phytoplankton-covered state, which may impede the foraging behaviour of piscivores, and reduce food and habitat availability for dabbling ducks such as Gadwall *Anas strepera* and Teal *Anas crecca*, or benthivores such as Tufted Duck, Pochard and Goldeneye *Bucephala clangula*.

7. Effects of improvements to the water quality of freshwater systems on waterbirds will depend on the species (diet, foraging behaviour, etc.) and severity of nutrient loading. Programmes to reverse eutrophication of freshwater lakes have been shown to benefit Tufted Duck, Coot *Fulicra atra*, Mute Swan *Cygnus olor*, Goldeneye and Pochard, thought to be partly due to changes in the vegetation structure and water transparency.

8. Given that the impacts of nutrient enrichment of coastal or freshwater systems on waterbirds vary depending on natural water quality of the system, the severity of nutrient loading, and physical characteristics of the system, efforts to improve water quality will also have varying impacts, depending on the state of the system prior to improvement. Effects of changes in water quality are therefore likely to be both site- and species-specific and may lead to, and have been implicated in, both population increases and declines. Generally, species that are less flexible in their foraging strategy would be expected to be more vulnerable to any reductions in food resources resulting from reduced nutrient inputs. Improvements to water quality may be of greater benefit to waterbirds in freshwater or sheltered coastal systems than in more dynamic open coastal systems. A provisional list of wintering waterbird interest features of freshwater and coastal sites classified as Special Protection Areas (SPAs) in England under the EC Directive on the conservation of wild birds (79/409/EEC) that may be affected by improvements to water quality is provided.

9. Although there is evidence of impacts between changes in water quality and waterbird numbers at a local within-site scale, evidence for impacts at a site-level may be harder to discern, due to the number of other factors that might affect populations at this scale. Nevertheless, recent research has linked temporal changes in waterbird populations to changes in fertiliser use at national and European scales (Møller *et al.* 2015, Møller & Laursen 2015). To build on this research, it is recommended that the spatial and temporal variation in non-breeding waterbird numbers (both freshwater and coastal), derived from Wetland Bird Survey (WeBS: https://www.bto.org/volunteer-surveys/webs) data, should be explored in relation to spatial and temporal patterns in broad-scale metrics relating to fertilizer usage and water quality.

1. INTRODUCTION

1.1 Background

Over the past 50 years there has been widespread improvement in water quality in many freshwater and coastal systems in the UK driven by domestic and European legislation, most recently the Water Framework Directive (EC Directive 2000/60/EC), which, covers transitional and coastal waters up to 1 nm from the continental baseline and the Marine Strategy Framework Directive (2008/56/EC), covering all marine waters up to the limit of the Exclusive Economic Zone (EEZ), but also including the Urban Waste Water Treatment Directive (EC Directive 91/271/EEC) and Bathing Water Directive (EC Directive 76/160/EEC). This has included measures such as increased stringency in discharge consents, closure of direct sewerage discharges, development of nitrate vulnerable zones, and resource protection programmes such as catchment sensitive farming. Similar programmes have been initiated in many other European counties. One of the consequences of this direction of travel to a more natural state in water quality has been a reduction in anthropogenic nutrient loading, with an associated reduction in organic matter inputs into waterbodies.

In recent years declines in a number of non-breeding waterbird populations have been recorded in the UK. Many of these species are dependent on demersal and benthic communities for their food supply. It is theoretically possible that changes in biomass volume and species communities associated with demersal and benthic areas, as a consequence of changes in nutrient loading and supply of organic material, could have a knock on impact on bird numbers through impacts on food supply and foraging efficiency.

It has been suggested that one of the contributory causes of wintering bird population declines could thus be associated with this shift towards a system with more natural nutrient levels, i.e. former populations were being supported at an artificially high level by anthropogenic inputs and declines may reflect a rebalancing to more natural population numbers/density.

Previous work (Burton *et al.* 2002) reviewed the importance of waste water discharges in providing food for waterbirds and identified species most likely to be at risk from changes to these discharges and sites where waterbirds may have been or may still be affected by the implementation of the EU's Urban Waste Water Treatment Directive and Bathing Water Directive, that preceded the Water Framework Directive. A second phase, focussing on coastal English Special Protection Areas (SPAs, classified under EC Directive 79/409/EEC on the conservation of wild birds), found suggestive evidence of correlations between water quality improvements and declines in bird numbers but no definitive relationships at the whole site level (Burton *et al.* 2003a).

A more detailed study on the Northumbria Coast SPA found clearer negative correlative evidence between changes in point sources of nutrient inputs and waterbird numbers at a local within-site scale (see Burton *et al.* 2005, Burton & Goddard 2006 and section 3.1.3).

As part of its work to better understand reasons for change, and provide conservation management advice Natural England needs to better understand the evidence for water quality change being a potential driver of bird population change at a whole site and site-network level. There is thus a need to revisit the previous work in the light of more recent studies, and to broaden it to consider both freshwater and coastal sites and the wider influence of changes to water quality from diffuse as well as point sources.

1.2 Project Aims

Five objectives have been identified by Natural England to meet this need:

i. An update of Burton *et al.* (2002) to provide a review of the global literature relating water quality change and its direct and indirect effects on bird communities;
ii. A review of the global literature relating to water quality change and its impact on demersal and benthic communities used as food resources by non-breeding waders and wildfowl;
iii. Identification of those species most at theoretical risk of population change from water quality improvement as a consequence of their foraging requirements;
iv. Recommendations for further work to improve understanding of this subject area;
v. Analysis of water quality data (if this can be sourced) and bird numbers for species identified in (iii) to see if there are any relationships.

The present work focuses on the first and fourth of these objectives and informs the third.

2. METHODS

2.1 A Literature Review of the Direct and Indirect Effects of Water Quality Change on Bird Communities

The main component of the present work is a literature review of the direct and indirect effects of water quality change on bird communities. This review updates that previously provided by Burton *et al.* (2002) in the light of more recent studies, and also broadens that review to consider both freshwater and coastal sites and the wider influence of changes to water quality from diffuse as well as point sources.

The review is restricted to waterbirds, defined as birds of the families Gaviidae, Podicipedidae, Phalacrocoracidae, Ardeidae, Ciconiidae, Threskiornithidae, Phoenicopteridae, Anatidae, Rallidae, Gruidae, Haematopodidae, Recurvirostridae, Charadriidae, Scolopacidae, Laridae, Sternidae, and Alcedinidae, following the Wetland Bird Survey (https://www.bto.org/volunteer-surveys/webs). Specifically, we focus on the species that comprise waterbird interest features of freshwater and coastal sites classified as SPAs in England. These are listed in Table 2.1 by habitat class as specified in the spreadsheet of UK SPA information as contained within the Natura 2000 standard data forms submitted to the European Union (http://jncc.defra.gov.uk/page-1409).

Within the review, we consider the potential impacts of water quality change on bird communities in coastal and freshwater habitats separately, this in part reflecting differences in the potential pathways through which they might be affected. For simplicity and for the purposes of drawing general conclusions, we also further classify bird species into guilds according to their dependence on different habitats and food resources and thus the potential pathways through which they might be affected by changes in water quality, e.g. species such as gulls and wildfowl that may feed directly on material from point sources, species that forage on intertidal invertebrates such as waders and Shelduck *Tadorna tadorna*, piscivores such as Cormorants *Phalacrocorax carbo* that may feed at both coastal and freshwater sites and herbivores, such as Wigeon *Anas penelope* that may forage on algal mats associated with nutrient loading. The review considers both recorded associations between birds and nutrient inputs (point and diffuse) and studies that have investigated changes to populations following changes to water quality (noting whether responses are positive or negative, the strength of species' responses, where possible, and whether results are purely correlative or if studies also record changes to food resources and thus demonstrate causal links to any changes observed).

Searches of key literature were carried out using Web of Science and also drew upon previous extensive reviews of the topic where available. Search terms included: "water quality", "eutrophic*","sewage", "fertiliser", "waste water" in combination with "bird", "wader", "shorebird" and "wildfowl", as well as the names of individual species that are features of freshwater or coastal SPAs in England. Reference lists of key papers were also searched for additional studies.

Through the review, we provide initial summary conclusions as to the potential importance of changes to water quality to species' populations and the species most at theoretical risk (objective iii). It is expected that this initial summary would be refined by subsequent review of the impacts of changes to water quality to species' demersal and benthic food resources (objective ii).

Table 2.1 Wintering waterbird interest features of freshwater and coastal sites classified as Special Protection Areas (SPAs) in England under the EC Directive on the conservation of wild birds (79/409/EEC). Habitat classes follow those provided in the spreadsheet of UK SPA information as contained within the Natura 2000 standard data forms submitted to the European Union (http://jncc.defra.gov.uk/page-1409). Species names here and in the text follow the British vernacular names provided in the British Ornithologists' Union's British List (BOU 2013; https://www.bou.org.uk/wp-content/uploads/2016/12/British-List-12-Dec-2016.pdf).

Species	Guild	Food	Inland water bodies (standing water, running water)	Marine areas, sea inlets	Tidal rivers, estuaries, mud flats, sand flats, lagoons (including saltwork basins)
Avocet	Generalist wetland	Invertebrates	y	(y)	y
Black-tailed Godwit	Generalist wetland	Invertebrates	y	(y)	y
Curlew	Generalist wetland	Invertebrates	y	(y)	y
Golden Plover	Generalist wetland	Invertebrates	y	(y)	y
Lapwing	Generalist wetland	Invertebrates	y	(y)	y
Ruff	Generalist wetland	Invertebrates	y	(y)	y
Snipe	Generalist wetland	Invertebrates	y		
Whimbrel	Generalist wetland	Invertebrates	y	(y)	y
Teal	Generalist wetland/dabbling	Omnivore	y		y
Bean Goose (Taiga)	Generalist wetland/dabbling	Vegetation	y		y
Bewick's Swan	Generalist wetland/dabbling	Vegetation	y		y
Coot	Generalist wetland/dabbling	Vegetation	y		y
Greylag Goose (Icelandic)	Generalist wetland/dabbling	Vegetation	y		y
Mute Swan	Generalist wetland/dabbling	Vegetation	y		
Pink-footed Goose	Generalist wetland/dabbling	Vegetation	y	(y)	y
White-fronted Goose (European)	Generalist wetland/dabbling	Vegetation	y	(y)	y
Whooper Swan	Generalist wetland/dabbling	Vegetation	y	(y)	y
Wigeon	Generalist wetland/dabbling	Vegetation	y	(y)	y

Species	Guild	Food	Inland water bodies (standing water, running water)	Marine areas, sea inlets	Tidal rivers, estuaries, mud flats, sand flats, lagoons (including saltwork basins)
Mallard	Generalist wetland/dabbling	Omnivore	y	(y)	y
Pintail	Generalist wetland/dabbling	Omnivore	y	(y)	y
Shoveler	Generalist wetland/dabbling	Omnivore	y		y
Barnacle Goose (Svalbard)	Generalist wetland/dabbling	Vegetation	y		y
Brent Goose (Dark-bellied)	Generalist wetland/dabbling	Vegetation	y	(y)	y
Pochard	Generalist wetland/diving	Omnivore	y		y
Tufted Duck	Generalist wetland/diving	Invertebrates	y	(y)	y
Knot	Intertidal bivalve specialists	Bivalves	y	(y)	y
Oystercatcher	Intertidal bivalve specialists	Bivalves	y	(y)	y
Bar-tailed Godwit	Intertidal invertebrate feeder	Invertebrates	y	(y)	y
Dunlin	Intertidal invertebrate feeder	Invertebrates	y	(y)	y
Purple Sandpiper	Intertidal invertebrate feeder	Invertebrates			
Redshank	Intertidal invertebrate feeder	Invertebrates	y	(y)	y
Ringed Plover	Intertidal invertebrate feeder	Invertebrates	y	(y)	y
Sanderling	Intertidal invertebrate feeder	Invertebrates	y		y
Shelduck	Intertidal invertebrate feeder	Invertebrates	y	(y)	y
Turnstone	Intertidal invertebrate feeder	Invertebrates	y	(y)	y
Grey Plover	Intertidal invertebrate feeder	Invertebrates	y	(y)	y
Bittern	Piscivore	Fish	y		y
Cormorant	Piscivore	Fish	y	y	y
Great Crested Grebe	Piscivore	Fish	y		y
Little Egret	Piscivore	Fish	y		y
Little Grebe	Piscivore	Fish	y	(y)	y

Species	Guild	Food	Inland water bodies (standing water, running water)	Marine areas, sea inlets	Tidal rivers, estuaries, mud flats, sand flats, lagoons (including saltwork basins)
Sandwich Tern	Piscivore	Fish	y		y
Slavonian Grebe	Piscivore	Fish			y
Red-breasted Merganser	Piscivore (diving)	Fish	y		y
Red-throated diver	Piscivore (diving)	Fish	y	y	
Smew	Piscivore (diving)	Fish	y		
Black (common) scoter	Diving benthivore	Invertebrates	(y)	y	y
Eider (except Shetland)	Diving benthivore	Bivalves	y	y	y
Goldeneye	Diving benthivore	Invertebrates	y		y
Scaup	Diving benthivore	Invertebrates	y		y
Velvet Scoter	Diving benthivore	Invertebrates			y
Gadwall	Freshwater/dabbling	Vegetation	y		y

The impacts of nutrient loading of aquatic system on the bird communities that they support, and therefore the impacts of efforts to reduce such loading, will vary according to the type of system. The amount of mixing, hydrological connectivity and flushing will affect the sensitivity of waters to nutrient inputs, so that isolated freshwater lake systems are likely to be affected by relatively minor changes in nutrient loads, compared with coastal waters, especially as these changes can lead to shifts in plant communities which further affect nutrient status (see section 3.2). Even within coastal systems, there will be variation in the response to nutrient loads, as estuaries and embayments are more likely to fill with nutrients than open coast systems, particularly those subject to regular flushing from tidal influences. The depth and stratification of the water column will also affect nutrient concentrations. Efforts to improve water quality may not necessarily lead to restoration of a system to its previous state, particularly if eutrophication of freshwaters has led to the development of stable algal-based communities, which may persist even at lower nutrient concentrations. System and biodiversity responses to changes in water quality will therefore vary between sites and according to scale, making large-scale or generalised patterns difficult to determine.

Key studies investigating impacts of nutrient inputs from point and diffuse sources on coastal water and freshwater bird communities are summarised in this review in Tables 3.1 and 3.2, with details of the scale at which responses were observed.

Changes in the numbers of waterbirds and thus overall waterbird communities resulting from changes in water quality will be the result of demographic mechanisms, i.e. changes in survival rates or breeding productivity and recruitment, or emigration/immigration. Where such mechanisms have been investigated or postulated, these are also noted.

2.2 Recommendations for Further Work to Improve Understanding of this Subject Area

Previous studies have highlighted that although evidence might be found between changes in water quality and waterbird numbers at a local within-site scale (Burton *et al.* 2005, Burton & Goddard 2006), evidence for impacts at a site-level may be harder to discern, due to the number of other factors that might affect populations at this scale. Nevertheless, recent research has linked temporal changes in waterbird populations to changes in fertiliser use at national and European scales (Møller *et al.* 2015, Møller & Laursen 2015).

Draft recommendations are thus provided as to the potential for exploring how spatial and temporal variation in wintering waterbird numbers (both freshwater and coastal), derived from Wetland Bird Survey (WeBS: https://www.bto.org/volunteer-surveys/webs) data, may relate to spatial and temporal patterns in broad-scale metrics relating to water quality. Consideration is given in these recommendations to other factors important in explaining spatial and temporal variation in waterbird numbers (e.g. estuary morphology, climate change) and how the analyses might inform understanding of waterbird trends on individual SPAs (https://www.bto.org/volunteer-surveys/webs/publications/webs-alerts).

3. RESULTS

In the following review, we provide an overview of studies that have investigated the importance of water quality on waterbirds and the influence of changes in both point and diffuse sources of nutrients on coastal waterbird populations (section 3.1) and freshwater waterbird populations (section 3.2). We also provide a brief overview of studies that have investigated the importance of waterbirds themselves as a source of nutrients and influence on water quality.

3.1 Coastal Waterbird Populations

The importance of sewage as a foraging resource for waterbirds, whether direct or indirect has long been recognised, through observations at sewage farms, water treatment plants and waste stabilisation ponds (Fuller & Glue 1981, Maxson 1981, Evans & Harris 1994, Thompson 1998, Braithwaite & Stewart 2001, Hamilton *et al.* 2002, 2005, Gough *et al.* 2003, Waweru *et al.* 2005, Akinpelu 2006, Harebottle *et al.* 2008, Murray & Hamilton 2010, and others cited in Orłowski 2013). The high densities of waterbirds supported by these habitats has led to some being recognized as Globally Important Bird Areas, e.g. Phakalane sewage lagoons in Botswana and Samra sewage station in Jordan (Orłowski 2013). It follows, therefore, that where sewage effluent flows into coastal habitat, this foraging resource may influence the waterbird community it can support. There are two main pathways through which sewage affects food supply: the effluent itself provides a direct food source for some birds (gulls, some ducks, e.g. Campbell 1978, Ferns & Mudge 2000), and the increased nutrient availability may modify algae, plant, invertebrate and fish populations around sewage outfalls, thus indirectly affecting birds through impacts on their food resources (e.g. Pounder 1976, Ait Alla *et al.* 2006). These pathways will influence waterbirds in different ways, as discussed in sections 3.1.1, 3.1.3 and 3.1.4, but broadly, their impacts depend on the natural water quality of the system, the severity of nutrient loading, and physical characteristics of the system. Similarly, measures to improve water quality have varying effects on waterbird communities, but are expected to lead to reductions in some waterbirds due to reductions in food supply (e.g. Burton *et al.* 2002, Ait Alla *et al.* 2006, Smith & Shackley 2006). Fuller and Ausden (2008) cite modernisation of sewage treatment systems as one of the main changes affecting wetland birds. Effects will vary with species; diet, foraging strategy and habitat requirements will all contribute to the response of a particular species to nutrient loading, such that a piscivorous species requiring clear water to enable pursuit of prey, and a wader specialising in probing sediment of intertidal mudflats to forage for invertebrates will differ in their responses. For this reason, the review will summarise potential effects of changes in water quality in terms of species guilds (Table 2.1).

A recent horizon-scanning exercise identified eutrophication of coastal systems as a current threat to migratory shorebirds (Sutherland *et al.* 2012). In addition to sewage effluent, run-off from urban and agricultural landscapes makes a significant contribution to the nutrient content of a system (David *et al.* 1997, Jordan *et al.* 1997, Meissner *et al.* 2002). Eutrophication progresses through a number of stages. First, the nutrients within the run-off cause an increase in the productivity of the system, by enhancing nitrogen and phosphorous concentrations that previously limited growth. Increases in algae, invertebrates and fish follow, increasing the food resource available to the waterbird community (to be covered in a later review, but see e.g. Pounder 1976, Burton *et al.* 2002, Laursen & Møller 2014). Second, increased algal coverage will change the foraging habitat and resources available to birds; often macroalgal mats develop, covering the intertidal mudflats used by many waterbird species but providing a direct food resource to some herbivores. By reducing the oxygen content beneath them, these mats alter the density, availability and accessibility of prey items (Green *et al.* 2015 and section 3.1.4). In response, birds may change their foraging behaviours, shifting from a visual pecking strategy to tactile probing of available prey on the surface of mats, the changes in prey type, success rate and handling time all potentially having energetic consequences on foraging efficiency (Thornton 2016). If species are less able to adapt, or as resources become depleted due to predation and reduced oxygen levels, there may be impacts on the numbers of birds that the site is able to support. This can be realised both through mortality or emigration of individuals from the system. Finally, extreme nutrient loading may lead to hypereutrophic habitats, characterised by extensive macroalgal mats and algal blooms, the decomposition of which leads to anoxia and 'dead' zones. Responses to nutrient loading therefore often show a humped relationship, and effects of improved water quality will depend on how far eutrophication had progressed prior to treatment.

Below, we first summarise the previous findings of Burton *et al.* (2002). The following sections then summarise more recent studies on the importance of changes to waste water outfalls for coastal waterbird populations, and also consider the wider influence of changes to water quality from diffuse sources. Table 3.1 summarises the key studies investigating effects of nutrient inputs from point and diffuse sources on bird communities of coastal waters.

3.1.1 Summary of Burton *et al.* (2002)

Work by Burton *et al.* (2002) reviewed evidence of direct and indirect impacts of sewage and industrial effluent on waterbird communities, and potential impacts of improvements to waste water discharge in efforts to improve water quality. The review describes changes to invertebrate and fish densities concordant with improvements to waste water discharge, which will be touched on here in terms of their impacts on bird communities, but covered in more detail in a later review. Here, we provide a brief summary of the findings of that review and key literature.

Species feeding directly on outfalls:

Gulls will feed on a variety of items in sewage effluent: plant seeds, potato peelings, bread and meat (Ferns & Mudge 2000) and, as such, Herring Gull *Larus argentatus* and Black-headed Gull *Chroicocephalus ridibundus* abundances have been shown to be correlated with the volume of sewage discharged (Ferns & Mudge 2000). Improvements to sewage treatment may therefore lead to declines in gull populations as suggested for Common Gull *Larus canus* and Great Black-backed Gull *Larus marinus* in the Tyne Estuary (Fitzgerald & Coulson 1973) and other gull species in New Zealand (Robertson 1992), but limited evidence has been found of effects on other species (Fitzgerald & Coulson 1973). Some duck species, e.g. Goldeneye *Bucephala clangula* and Scaup *Aythya marila*, aggregate around sewage and industrial waste water outfalls, feeding on barley and grain maize husks discharged from breweries (Campbell 1978). Internationally important duck populations formerly dependent on these effluent discharges are likely to have been impacted by sewage treatment (Pounder 1976); local declines in Goldeneye and Scaup (Campbell 1984) and Mallard *Anas platyrhynchos* and Teal *Anas crecca (*Thom 1969) on the Firth of Forth, Goldeneye and Tufted Duck *Aythya fuligula* on the Moray Firth (Barrett & Barrett 1985), Mute Swan *Cygnus olor* on the Stour Estuary (Musgrove *et al.* 2001) and Goldeneye in Lancashire (Marsh 2000) have all been attributed to cessation or treatment of discharges. These studies focussed on observations in the vicinity of the (former) outfalls and although wider site-level declines have been seen in some instances – for example, in the numbers of Goldeneye and Scaup on the Firth of Forth (see Cook *et al.* 2013) – it is unclear whether the declines observed were due to the redistribution of birds to other sites or imply population level impacts.

Species feeding on invertebrates and algae:

Waste water effluent affects algal and invertebrate communities in different ways, depending on the natural water quality of the system and the degree to which this alters with effluent discharge, proximity to outfalls, and the duration of discharge. High nutrient enrichment in the zone closest to outfalls is likely to stimulate high levels of productivity, resulting in the formation of dense algal mats, under which sediment becomes anoxic. At first, the reduced oxygen in the sediment forces invertebrates to move up to the surface, improving food accessibility for invertebrate-feeders (Pounder 1976). These resources will be rapidly depleted, leaving anoxic, invertebrate-poor conditions, which may lead to reductions in bird numbers (McLusky 1968, Tubbs 1977). Some birds will still be able to utilise the food resource provided by the algae itself, both directly – e.g. Wigeon and indirectly – e.g. Shelduck, Pintail *Anas acuta* and Dunlin *Calidris alpina* – by feeding on the invertebrates sustained by the algal mats. Further from outfalls, there are intermediate effects of increased nutrient enrichment enhancing food supplies, but at moderate levels that do not lead to such depletion of oxygen. In these areas, effects of sewage are expected to be more positive, for species such as Lapwing *Vanellus vanellus*, Curlew *Numenius arquata*, Redshank *Tringa totanus* and Turnstone *Arenaria interpres* (Goss-Custard 1969, 1970, Goss-Custard *et al.* 1977, Metcalfe 1985, Eaton 2000).

Burton *et al.* (2002) also examined more general relationships between nutrient loading and coastal waterbird populations. Increased algae as a result of increased input of sewage effluent and agricultural run-off has been suggested as a contributor to declines in shelduck, curlew, and redshank at Langstone Harbour (Tubbs 1977) and Oystercatcher *Haematopus ostralegus*, Dunlin, Bar-tailed Godwit *Limosa lapponica*, Curlew and Redshank on the Ythan Estuary (Raffaelli *et al.* 1999), where algal mats have reduced the abundance of *Corophium volutator* (Raffaelli *et al.* 1991, Raffaelli 2000). Conversely, nutrient enrichment of coastal systems from anthropogenic sources has been implicated (at least partly) in increased abundances of Dark-bellied Brent Goose *Branta bernicla bernicla*, Wigeon, Teal, Oystercatcher, Grey Plover *Pluvialis squatarola*, Knot *Calidris canutus*, Dunlin, Black-tailed Godwit *Limosa limosa* and Bar-tailed Godwit at Langstone Harbour (Tubbs 1977) and increased waterbird populations in Rogerstown Estuary, Ireland (Fahy *et al.* 1975). In the Lillo-Rilland area of Holland's Delta Region (van Impe 1985), abundances of Black-headed Gull, Oystercatcher, Avocet *Recurvirostra avosetta*, Grey Plover, Bar-tailed Godwit, Curlew, Spotted Redshank *Tringa erythropus* and Redshank increased over a period in which nutrient loading and polychaete abundance increased, while Ringed Plover *Charadrius hiaticula* decreased and Common Sandpiper *Actitis hypoleucos* remained stable.

Evidence of direct links between water quality variables and waterbird communities is scarce. Despite associations between the composition of wader communities on British estuaries and salinity, ammoniacal nitrogen concentration in the water, percentage dissolved oxygen and the biochemical oxygen demand (BOD), changes in nutrient status did not account for any changes in wader communities over a 16 year period (Green *et al.* 1990, Hill *et al.* 1993). Curlew and redshank abundance (numbers and biomass) were linked to ammoniacal nitrogen and percentage dissolved oxygen, while total wader biomass was positively related to the BOD of estuaries (Rehfisch & Austin unpublished, reviewed in Burton *et al.* 2002). Any changes resulting in decreased BOD may thus be expected to cause reductions in wader biomass.

Understanding the water quality prior to implementation of improvement measures is also important in assessing the potential effects of such improvements on the waterbird community. Improving sewage discharge to highly polluted waters is likely to benefit biodiversity, as formerly anoxic sites are colonised by invertebrates (Harrison *et al.* 1999, Kropp *et al.* 2000) thus providing enhanced food resources. Changes in waste water treatment will therefore have varying effects on waterbird communities. Waders on the Clyde Estuary initially appeared to increase following improvements to water quality (McKay *et al.* 1978) but Lapwing, Dunlin, Oystercatcher, Redshank, Shelduck and Pintail later declined, most likely due to a reduction in food availability (Furness *et al.* 1986). Although not explicitly tested, the reduction in food was postulated to have been caused by decreased nutrient loading of the system (Furness *et al.* 1986) and increased competition with fish (McKay *et al.* 1978, Henderson & Hamilton 1986), as suggested by the observed increase in the number of Cormorants (Furness *et al.* 1986). Sewage improvement programmes have also been implicated in the declines of Knot and Dunlin on the Firth of Forth (Bryant 1987), and Redshank on the Dee Estuary (Smith 2000), although other factors may also have contributed to declines. In contrast, Knot declines at Cleethorpes were not linked to sewage improvement, and neither Purple Sandpiper *Calidris maritima* nor Turnstone appeared affected by the cessation of sewage discharge into rocky shores around Hartlepool (in terms of numbers or survival rates: Eaton 2000, although see Burton *et al.* 2005). Again, direct effects on food resources were not examined, and the Hartlepool study involved only one year of data after the change in sewage discharge.

Piscivores:

Sewage outfalls may also increase food availability for piscivores, as fish concentrate in areas of enhanced invertebrate resource. Effects, will, however, depend on the prey species involved; benthic fish species tend to be low in abundance near outfalls (Gill & Frid 1995, Hall *et al.* 1997), while pelagic species increase with proximity to outfalls (Hall *et al.* 1997). Birds preying on benthic species are therefore expected to benefit from improvements to water quality, while those reliant on pelagic species may be disadvantaged. This is demonstrated by increased Cormorant numbers on the Clyde Estuary, thought to be linked to the increase in Flounders *Platichthys flesus* following improved water treatment (Furness *et al.* 1986). In contrast, a decrease in Australian Gannets *Morus serrator*, a pelagic feeder, was observed in a study in Wellington, New Zealand as sewages discharge declined (Robertson 1992).

Conclusions

Burton *et al.* (2002) concluded by suggesting that species most at risk from improvements to sewage and industrial waste water discharges are likely to be Brent Goose, Shelduck, Wigeon, Teal, Pintail, Oystercatcher, Avocet, Grey Plover, Lapwing, Knot, Purple Sandpiper, Dunlin, Black-tailed Godwit, Bar-tailed Godwit, Curlew, Spotted Redshank, Redshank and Turnstone. Duck species of more maritime habitats, e.g. Eider *Somateria mollissima*, Common Scoter *Melanitta nigra*, Velvet Scoter *Melanitta fusca* and Long-tailed Duck *Clangula hyemalis*, are likely to be less at risk than those that aggregate around artificial food sources, e.g. Scaup, Goldeneye, Pochard *Aythya ferina* and Tufted Duck, and there is some evidence communities inhabiting rocky shore environments may be less affected by nutrient enrichment from point sources and thus changes to sewage treatment than those in sheltered estuarine habitats, as on open coasts, currents may take nutrients away from the shore. An important caveat to the conclusions of the Burton *et al.* (2002) review is the correlative nature of the majority of the work presented. As such, many of the apparent relationships between bird numbers or behaviours and water quality summarised in the review cannot be proved. In many cases, other factors, external to the local system may be contributing to the associations.

3.1.2 Species that feed directly on food resources from outfalls

As noted above in the review by Burton *et al.* (2002), gulls often aggregate around sewage outfalls to feed directly on the effluent. The abundance of Lesser Black-backed Gulls *Larus fuscus* in the Tagus

Estuary, Portugal, was positively associated with the presence of non-treated sewage discharges (Rosa *et al.* 2003), although in the Mar Menor Lagoon in Spain, gulls and terns appeared to favour oligotrophic areas, rather than those directly affected by sewage effluent (Farinos & Robledano 2010). In Dutch Harbour, Alaska, large numbers of sea ducks were often observed feeding in areas close to outfalls discharging sewage and effluent from a seafood-processing plant. The high abundance of food in these areas was used as a possible explanation for the low foraging rates observed, as energy requirements were more easily met than in other areas (Reed & Flint 2007).

Table 3.1 Principal studies investigating the effects of nutrient loading of coastal waters on bird communities. These are studies in which nutrient loading is the focus, or at least features prominently in the discussion. The location of each study is given, together with details of the scale at which responses were observed, from international to local scales. Most studies either report effects at a local (i.e. within-site) scale or across a whole waterbody study site (or large section thereof).

Refs	Guild	Habitat	Site	Variable	Scale	Results	Pathway	Quality of evidence
Rosa *et al.* (2003)	Waterbirds (gulls, waders, piscivores)	Estuary	Tagus Estuary, Portugal	Presence of sewage discharge points	Local (28 sectors 0.4-16.4 ha in size)	No effect on species richness, or on **Avocet** or **Black-tailed Godwit** abundance. Presence of sewage discharge points positively related to **Grey Plover** and **Lesser Black-backed Gull** abundance	Sewage outfall provides direct and indirect food source	Correlative association between sewage and birds, limited dataset
Farinos & Robledano (2010), Robledano *et al.* (2008)	Waterbirds (gulls and terns, piscivores, coots)	Lagoon	Mar Menor Lagoon, Spain	Nutrient loading from sewage and run-off	Local (whole or part of lagoon divided into sampling stations at varying distance from discharge channel)	Birds distributed in zones apparently related to nutrient discharge. In areas directly affected by nutrient input, high abundance and low diversity	Distribution of food	Correlative association between distribution and environmental gradient or position of outfalls, no examination of food resources. May be entangled with effects of disturbance
Robledano *et al.* (2011), Fernandez *et al.* (2005)	Waterbirds	Lagoon	Mar Menor Lagoon, Spain	Nutrient loading from sewage and run-off	Whole waterbody	Increases in **Great Crested Grebe, Black-necked Grebe** and **Cormorant** at first, **Coot** increased at later stages. **Red-breasted Merganser** tolerant to nutrient loading during study period, negatively affected in long term	Increased food resources	Long-term monitoring, correlative associations between nutrient loading and bird abundances, no examination of food resources
Farinos *et al.* (2013)	Waterbirds	Lagoon	Mar Menor Lagoon, Spain	Nutrient loading from sewage and	Whole waterbody	Change in species community, all guilds increased with increasing nutrient inputs. The	Changes in food resources	No formal testing of associations between nutrient loading and food

Refs	Guild	Habitat	Site	Variable	Scale	Results	Pathway	Quality of evidence
				run-off		proportion of **ducks** increased, and the proportion of **shorebirds** decreased, **specialists** give way to **generalists**		or bird abundance, but trends in waterbirds superimposed over trends in nutrient status
Alves *et al.* (2012)	Intertidal invertebrate feeder	Estuary	Tejo Estuary, Portugal	Sewage discharge and treatment thereof	Local (six areas at varying distance from sewage outfall)	Higher prey intake rate by **Black-tailed Godwit** closer to sewage outfalls, but sewage treatment predicted to have little effect on godwits on estuary	Increased polychaete resources close to outfalls	Association between outfalls, food resource and birds
MacDonald (2006)	Gulls, shorebirds, diving ducks	Coastal	Review	Nutrient loading		Predicted increase, except some specialist shorebirds (e.g. shelduck).	Increased food resources, some interference from algal mats.	Predicted based on review of effects on vegetation, food resources and therefore birds
MacDonald (2006)	Dabbling herbivores and omnivores	Coastal	Review	Nutrient loading		Predicted decrease	Loss of food in phytoplankton-dominated state	Predicted based on review of effects on vegetation, food resources and therefore birds
Møller & Laursen (2015)	50 waterbird species	Freshwater and coastal	Europe	Fertiliser use	International	Abundance of 14 species positively related to fertiliser use, 36 species negatively related. Similar changes in decrease or increase phase of fertiliser use, but changes in decrease phase much slower	Delayed recovery could be due to stored phosphorous in sediment	Long-term, correlative associations between fertiliser use and bird populations, partial controls for climate change and temporal trends
Møller *et al.* (2014)	20 waterbird species	Freshwater and coastal	Denmark	Fertiliser use	National	Significant linear and quadratic effects of fertiliser use on population indices. Linear effect of fertiliser use accounted for 12% of variance in population abundance, quadratic effect accounted for 3%. Humped relationships for some species indicate peak at intermediate	Increased food resources followed by oxygen depletion	Long-term dataset, includes analysis of trends in nutrient load, food resources and waterbird abundance, partial controls for climate change and temporal trends

Refs	Guild	Habitat	Site	Variable	Scale	Results	Pathway	Quality of evidence
						fertiliser use		
Lewis & Kelly (2001), Lewis *et al.* (2014)	Intertidal invertebrate feeder	Coastal	Clonakilty Bay, Ireland	Presence of macroalgal mats	Local (two study areas within bay)	**Black-tailed Godwit** distribution and foraging negatively associated with mats, but success of foraging actions not affected. **Redshank** densities increased through winter as mats receded and foraging success rate was higher on clear sediment. Showed preference for both clear sediment and mats, depending on site	Mats affect food resources and accessibility	Short-term studies, small plot size and maximum algal coverage 55%. Associations between mats, prey abundance and bird distributions
Metzmacher & Reise (1994)	Intertidal invertebrate feeders	Tidal flats	Wadden Sea	Macroalgal mats	Local	**Dunlin** and **Ringed Plover** attracted to newly placed mats, but did not use existing mats	Mats affect food resources and accessibility	Experimental study, in which macroalgal mats were transferred between locations, and distribution of birds on existing and moved mats were compared.
Thornton (2016)	Waders	Estuary	Poole Harbour	Presence of macroalgal mats	Local (varying algal coverage at three areas within bay)	**Curlew, Black-tailed Godwit, Redshank** and **Oystercatcher** distribution and/or feeding behaviours associated with mat coverage. Direction of effects varied with site	Mats affect food resources and accessibility	Associations between mats, invertebrates and waterbirds
Múrias *et al.* (1996)	Waders	Estuary	Mondego Estuary	Macroalgal mats	Local	No variation in **Dunlin, Curlew** or **Grey Plover** density with mat coverage. **Avocet** avoided mats	Mats affect food resources and accessibility	Limited mat coverage, so effects of extensive algal mat coverage unknown
Lopes *et al.* (2006)	Intertidal invertebrate feeders	Estuary	Mondego Estuary	Macroalgal mats	Whole waterbody and local	**Dunlin** increased as mats receded, and avoided mats at higher coverage (25%)	Mats affect food resources and accessibility	Long-term monitoring of mat coverage, prey biomass and dunlin abundance. Maximum mat coverage was 43% so effects of extensive algal mat coverage unknown

Refs	Guild	Habitat	Site	Variable	Scale	Results	Pathway	Quality of evidence
Cabral *et al.* (1999)	Intertidal invertebrate feeder	Estuary	Mondego Estuary		Local (three 1ha areas within site)	**Grey Plover, Ringed Plover** and **Dunlin** negatively associated with mats, peck rate of **Kentish Plover** positively associated with macroalgal biomass	Mats affect food resources and accessibility, but here prey abundance not negatively impacted by mat coverage	Examined prey density and waterbird abundance/behaviour in relation to macroalgal mats. Maximum mat coverage was 36% and affected areas were surrounded by algal free-areas that may contribute to renewal of food sources.
Green *et al.* (2015)	Intertidal invertebrate feeder	Estuary	Mugu Lagoon, California		Local (four areas, ~2500m^2 each within lagoon)	**Marbled Godwit** and **Least** and **Western Sandpiper** changed from pecking on bare sediment to probing on algal mats. **Grey Plover, Marbled Godwit** and **Willet** all avoided macroalgae	Mats obscure visual foraging cues	Correlative associations between mat coverage, prey abundance and bird habitat selection and foraging behaviour
Philippart *et al.* (2007)	14 waterbird species	Estuary	Dutch Wadden Sea	Variation in nutrient loading	Whole waterbody	Change in community structure, concurrent with changes in macrozoobenthos, phytoplankton and nutrient loads	Change in food resources	Long-term dataset, includes analysis of trends in nutrient load, food resources and waterbird abundance. Other factors may be involved
Atkinson *et al.* (2010)	Waterbirds	Estuary	The Wash	Declines in rates of P and N discharge	Whole waterbody	Change in community structure away from bivalve specialists towards worm-eaters	Reduction in bivalves	Long-term monitoring of nutrient discharge, shellfish abundance and waterbird abundance. Nutrient effects cannot be disentangled from others, such as removal of mussel beds by shellfisheries
Burton *et al.* (2003a)	Waterbirds	Coastal/ Estuary	UK SPAs	Improvements to sewage treatment	Whole waterbody	Most birds declined on more sites where improvements to sewage treatment had been implemented than increased. This was only significant for	Decreased food resources (assumed)	Waterbird trends before and after sewage treatment. Some trends matched national trends or pre-dated sewage

Refs	Guild	Habitat	Site	Variable	Scale	Results	Pathway	Quality of evidence
						Shelduck and **Grey Plover**		improvements. Some sites involved only a short monitoring period after changes to sewage treatment. No analysis of prey
Burton & Goddard (2006)	Intertidal invertebrate feeder	Coastal	Northumbria Coast SPA	Improvements to sewage treatment	Whole site and local	**Turnstone** and **Purple Sandpiper** declined, especially at the site where outfall directly affected most of the intertidal habitat. **Turnstone** survival declined	Decreased food resources (assumed)	Trends before and after improvements to sewage treatment. No analysis of prey
Burton *et al.* (2005)	Intertidal invertebrate feeder	Coastal	Northumbria Coast SPA	Cessation in sewage discharge	Local	Wintering **Turnstone** left site where sewage no longer discharged	Decreased food resources (assumed)	Postulated based on the re-sightings. Small sample size
Holm & Clausen (2006)	Waterbirds	Coastal lagoon	Western Denmark	Improved water quality	Whole waterbodies	No change in diversity in one treated lagoon but decreased on another. Increase in bird days for **herbivores, piscivore**s and **diving benthivores**, decrease in bird-days for **benthivores**	Changes in food resources	Water quality improved by opening floodgate allowing greater flushing but affects water depth, and salinity which also affects bird abundances. Associations between habitat use, changing vegetation, and water levels

3.1.3 Species that feed on invertebrates and algae

A study of the factors affecting waterbird abundance in the Tagus Estuary, Portugal found the presence of sewage discharge points was positively associated with grey plover abundance, but was not associated with Avocet or Black-tailed Godwit abundance, or species richness (Rosa *et al.* 2003). Black-tailed Godwit densities were not found to be affected by sewage outfalls on the Tejo Estuary in Spain either, despite attaining significantly higher prey intake rates closer to outfalls (Alves *et al.* 2012). Although polychaetes, the main prey of godwits, declined with distance from sewage outfalls, the area in which this was most evident was used by only 17% of the total godwit population of the estuary. Of these 17%, only a small number of longer-billed individuals were expected to be able to access the very large polychaetes that were most abundant in these areas. The authors therefore concluded, that even if polychaete abundance declines as expected following improvements to sewage treatment (Ait Alla *et al.* 2006), sufficient resources will be available throughout the estuary to sustain current Black-tailed Godwit populations on the Tejo estuary. At a coastal lake in Spain, fed by a channel containing both sewage discharge and agricultural run-off, coots aggregated around the point of channel discharge and were found almost exclusively in this area, rather than in other parts of the lagoon (Robledano *et al.* 2008, Farinos *et al.* 2013). The total abundance of waterbirds increased with increasing nutrient enrichment, but shifts in the waterbird community were apparent. The proportion of shorebirds and waders declined whilst ducks formed an increasing contribution to the total abundance (Farinos *et al.* 2013). Nutrient enrichment from sewage discharges is cited as a possible reason for the high numbers of Redshank foraging at one site in Cardiff (Burton & Armitage 2005) , and was also associated with presence of Pochard (Burton *et al.* 2003b).

The effects of nutrient loading from diffuse sources on populations in coastal waters have been examined in a number of studies. A review of the effects of nutrient loading of aquatic systems predicted that diving benthivores and gulls will increase as nutrient inputs into coastal systems increase, due to greater food availability (MacDonald 2006). Shorebirds are also expected to increase, except where the formation of macroalgal mats disrupts foraging behaviour and food availability, leading to the decline of some specialists. Dabbling herbivorous and omnivorous species are expected to decline as nutrient loads increase, due to loss of their preferred food where increased productivity causes shifts towards phytoplankton dominated waters (although this is more likely to be the case in freshwater sites, see section 3.2). Møller and Laursen (2015) explored long-term associations between changes in fertiliser use and winter population indices of 50 freshwater and coastal species, across Europe. The numbers of fourteen species, including Scaup, pochard, Oystercatcher, Bewick's swan *Cygnus bewickii*, Purple Sandpiper (the five strongest relationships), Avocet, Brent Goose, Mallard, Eider, Long-tailed Duck, Redshank, Shelduck and Black-headed Gull, were positively related to fertiliser use. Numbers of 36 species showed negative relationships with fertiliser use, those of Eurasian Spoonbill *Platalea leucorodia*, Greylag Goose *Anser anser*, Gadwall *Anas strepera*, Golden Plover *Pluvialis apricaria* and Pink-footed Goose *Anser brachyrhynchus* showing the strongest effects. The effects of fertiliser use were similar regardless of the phase of use (increasing or decreasing), and thus reversible. However, when fertiliser use was in the decreasing phase (use was lower than the previous year), the effect on population size was much slower. The authors suggest, therefore, that reversing the effects of fertiliser use would take three times longer than the time taken for the initial change in response to increasing fertiliser use. Restricting the analysis of effects of fertiliser use to Danish waterbirds, significant linear and quadratic effects of fertiliser use accounted for 12% and 3% respectively of the variation in the winter population index of 15 species (Møller *et al.* 2014). The quadratic relationship indicates that abundances peaked at intermediate fertiliser use, suggesting a pattern of response similar to that exhibited by birds in the vicinity of sewage outfalls (section 3.1.2). Only mallard exhibited a contrary effect of fertiliser use to that found in the European study (Møller & Laursen 2015), the Danish population declining as fertiliser use increased (Møller *et al.* 2014).

One of the main ways in which increased nutrient loading from diffuse sources can affect waterbirds, is through the formation of macroalgal mats. As mats develop on mudflats, conditions within the sediment become more anoxic and invertebrates move upwards towards the surface (Lewis & Kelly 2001). These items, formerly only available to long-billed specialists, then become accessible to smaller species. Whilst this may be beneficial to these smaller species, both inter- and intra-specific competition may then increase, which may disadvantage the larger specialists. After an initial increase in the food resource, an aggregation of predators is likely to lead to a rapid depletion of resources, as demonstrated by a transfer experiment undertaken in the Netherlands. Black-tailed Godwit, Dunlin and Ringed Plover preferred to forage on macroalgal mats that had been recently transferred to the area, rather than on bare sediment, but did not select existing mats (Metzmacher & Reise 1994). At higher levels of macroalgal coverage, the prey community shifts towards smaller-bodied, less profitable prey (Brooks & Bell 2001), which may be an issue for larger waders (Thornton 2016, Sutherland *et al.* 2000). Conversely, longer bills may confer a competitive advantage by allowing penetration through mats, although in the case of curlew, this is debatable (Finn *et al.* 2008, Davidson *et al.* 1986). The structure of the mats themselves may support larger body-weights, enabling use of new areas by larger birds (Thornton 2016).

In a study of the effects of algal mats on waterbird populations in Poole Harbour, Curlew densities were affected by mat coverage, but effects were site-specific, while Oystercatcher, Black-tailed Godwit and Redshank distributions were unaffected (Thornton 2016). Oystercatchers were present at relatively low densities throughout the study and therefore more observations of this species may be needed to determine effects on Oystercatcher activity. In contrast, work in Portugal found no effect of algal mats on Curlew distribution (Múrias *et al.* 1996), and in Clonakilty Bay, Ireland, Black-tailed Godwits avoided areas of high algal coverage, and did not repopulate areas as mats receded (Lewis & Kelly 2001). Distribution was correlated with the distribution of *Hediste diversicolor and Scrobicularia plana*, which themselves decreased as algal coverage increased (Lewis *et al.* 2014). Redshank have been shown to increase as algal cover decreases through the winter, but also to preferentially forage on mats (Lewis & Kelly 2001), showing some flexibility in behaviour. Effects of macroalgal mat coverage on Dunlin densities have thus far been mixed, with positive, negative and no associations documented (Múrias *et al.* 1996, Lopes *et al.* 2006, Thornton 2016). This is likely to be an artefact of the paucity of studies at levels of very high levels of algal coverage, which species such as Dunlins are likely to avoid (Cabral *et al.* 1999, Lopes *et al.* 2006, Thornton 2016), possibly due to their small bills being unable to penetrate dense mats. Perhaps for similar reasons, Grey Plover and Ringed Plover were less abundant on mudflats covered by macroalgal mats in Portugal (Cabral *et al.* 1999). In Poole Harbour, associations between winter bird populations and macroalgae coverage in the preceding autumn suggest that effects persist after mats recede (Thornton 2016). Curlew foraged at higher densities on areas without any prior algal coverage, while Black-tailed Godwits were found at higher densities on areas where preceding algal coverage was high. The effects on Oystercatcher densities were variable, sometimes foraging at higher densities where previous algal coverage had been high, and sometimes where no algae had been present.

It is likely that some birds will change their foraging strategy to adapt to the presence of algal mats (i.e. move from visual to tactile foraging, or change feeding rate). For example, in the United States, Least Sandpiper *Calidris minutilla*, Western Sandpiper *Calidris mauri*, and Marbled Godwit *Limosa fedoa* changed from pecking bare sediment to probing the sediment underneath mats (Green *et al.* 2015). The feeding rate of Curlews was not affected by macroalgal coverage in Poole Harbour, but there was some evidence of shifts in behaviour from visual to tactile foraging, and the adoption of new foraging techniques, including shaking the mats themselves to dislodge prey (Thornton 2016). In contrast, Black-tailed Godwits attained higher feeding rates on areas covered with algal mats than on bare sediment. Higher foraging rates could be an adaptation to the shift in available food resource, to take more, less-profitable items that were found at greater abundance in sites with greater macroalgal coverage (Thornton 2016). Godwits in Clonakilty Bay, however, made fewer foraging attempts in algal patches (Lewis *et al.* 2014). This variation in godwit response between the studies could be due to the lower levels of algal coverage on Clonakilty Bay; perhaps the birds have not had to adapt to foraging on the mats, which can still be avoided. It also highlights the variation in response according to site and even individuals. Redshank and Oystercatcher are also thought to be able to change foraging strategies, although this may be at reduced success, as postulated for Redshank (Lewis *et al.* 2014). American Oystercatcher *Haematopus palliates* in San Antonio Bay, Argentina, changed to a tactile foraging strategy during algal blooms, and appeared to shift away from less detectable but more profitable prey in favour of items that could be encountered at a higher rate (Garcia *et al.* 2010). Species that are less able to adapt, or for which the higher energetic costs of tactile foraging are unsustainable, will be more likely to avoid mats than the more generalist species, as has been postulated for Grey Plover, Avocet and Shelduck (Múrias *et al.* 1996, Green *et al.*2015).

By reducing the nutrient content and organic matter available, programmes to improve water quality might be expected to negatively affect waterbird populations that were previously enhanced by the artificial enrichment. Generally, as improvements to water quality are made, reducing the nutrient load to the system, shifts in community structure are observed (Phillipart *et al.* 2007, Atkinson *et al.* 2010), with generalists likely to be better able to adapt to reduced foraging availability than the more specialist feeders. Shifts away from bivalve feeders towards worm-eaters have been recorded, although these changes are also likely to be attributable to other factors, notably the removal of mussel beds by shellfisheries (Atkinson *et al.* 2010). A Spanish case study suggests the reverse, that specialist are replaced by generalists along an increasing nutrient gradient (Farinos *et al.* 2013). At sites in Denmark, use by diving benthivores, herbivores and piscivores all increased on at least one treated site, while waders and Shelduck (decreased. This ‘treatment’ involved opening a floodgate to improve water quality by diluting the effects of nutrient loading, but will have also raised the water level (Holm & Clausen 2006). This is likely to explain the response of benthivores; the water levels becoming too deep for these waders.

In the Ems Estuary in the Netherlands, sanitation schemes in the 1980s reduced the organic loading of the system, resulting in a reduction in macrozoobenthic biomass, especially polychaetes (Essink 2003). The author suggests that improvements to waste water effluent could help to explain the decline in waders observed over the period (Prop *et al.* 1999, cited in Essink 2003). Other evidence of impacts of improvements to sewage treatment on waterbirds comes from a study of winter population indices on UK SPAs, following such improvements (Burton *et al.* 2003a). For most species analysed, populations declined on more sites than increased, although this difference was only significant for shelduck (declines on six out of eight sites, $p = 0.03$) and grey plover (eight out of eleven sites, $p = 0.04$), two intertidal invertebrate specialists. The lack of significant effects could be due to small sample sizes; the maximum number of sites for which indices of the non-significant species were compared was eight. Of the declines observed, some matched regional trends, while others began before the implementation of changes to sewage treatment, and for some sites, insufficient time had elapsed since the changes to determine trends. Attributing the declines solely to water quality improvements in any of these cases is therefore unwise. The timing of the decline and the contrast with regional trends suggests the sewage treatment was an important factor in declines of Grey Plover, Bar-tailed Godwit, Black-tailed Godwit, Curlew, Knot, Oystercatcher, Redshank, Dunlin, Turnstone, Pintail, Wigeon, Shelduck, Goldeneye and Brent Goose. Ringed Plover, Sanderling *Calidris alba* and Turnstone each increased on one site receiving improved sewage treatment although for Sanderling, this increase mirrored the regional trends. No direct link was found between effluent quality, measured using Biochemical Oxygen Demand (BOD), ammonia and suspended solids, and waterbird indices, or between site-level changes in BOD concentration and changes in waterbird numbers (Burton *et al.* 2003a).

Following improvements to sewage discharges into the Northumbrian coast SPA (completed in 2000/01), Turnstone and Purple Sandpiper numbers across the study area declined (Burton & Goddard 2006). The timing of decline and within site-patterns were strong indicators that the declines were a direct result of sewage improvements. Numbers increased prior to improvements, in contrast to regional trends, and, within the study area, declines were far greater at a site where a sewage outfall directly affected most of the intertidal habitat (37% and 50% declines for Turnstone and Purple Sandpiper respectively over four- to-five years) than at a site where sewage was discharged downstream and further offshore (no significant trend for either species). The authors attribute the turnstone decline at least in part to reduced survival rates observed, as a result of depleted food resources increasing competition. Birds could also be responding to lower food supplies by switching wintering sites as suggested by Burton *et al.* (2005) to explain the appearance of Turnstones in Northumberland that had previously wintered in Hartlepool. The results of these two studies are in contrast to those of Eaton (2000), who found no significant response in Turnstone numbers to the changes in sewage treatment in Hartlepool. This suggests a time lag between changes in sewage treatment and impacts on waterbird communities. Purple Sandpiper also declined on the Moray Firth where sewage treatment improved, mainly due to reduced recruitment to the site. Declines pre-dated the change in sewage treatment regime, and therefore could not be attributed solely to the nutrient reductions, but instead were possibly due to climate change enabling birds to winter closer to their breeding grounds, rather than migrate to Scotland (Summers *et al.* 2012).

It is harder to determine how improvements to water quality that lead to reductions in algal mat coverage may affect waterbirds. Effects will depend on the extent of the mat coverage, and whether species can adjust back to their previous behaviours. In the interim period, when mats have disappeared, but conditions remain anoxic, there is likely to be a period of reduced food availability (Thornton 2016).

3.1.4 Piscivores

In the Mar Manor Lagoon, Spain, Great Crested Grebes *Podiceps cristatus* were found at their highest densities around the point of discharge of a channel containing sewage and agricultural run-off (Robledano *et al.* 2008), while Black-necked Grebes *Podiceps nigricollis* were distributed more evenly throughout the site. A later study of the same system looked in greater detail at the waterbird community and its distribution amongst zones within the lagoon (Farinos & Robledano 2010). In the zone closest to the mouth of the channel discharging run-off and sewage effluent, species diversity was low but those that were present were in high numbers. Generally, diving piscivores favoured the more confined, nutrient enriched waters closer to points of discharge, although Great Crested Grebe appeared to select waters indirectly affected by diffuse run-off rather than areas directly affected by sewage discharge. On several SPAs undergoing improvements to sewage discharge in the UK, Cormorant, Great Crested Grebe and Little Grebe *Tachybaptus ruficollis* all declined (Burton *et al.* 2003a). For each species, two declines occurred after treatment changes were implemented and did not match regional trends, suggesting a contribution of the treatment to the declines.

Effects of nutrient loading from diffuse sources on piscivores in coastal waters have been mixed. Across Europe, fertiliser use was negatively correlated with winter population indices of Cormorant, Goosander *Mergus merganser*, Red-breasted Merganser *Mergus serrator*, Great Crested Grebe and Little Egret *Egretta garzetta* (Møller & Laursen 2015), and these relationships were also true for cormorant and goosander wintering in Denmark (Møller *et al.* 2014). The opening of floodgates to improve water quality in western Denmark, by diluting the nutrient load, resulted in an increase in number of bird-days that piscivorous species spent on one out of two treated sites. This could also be due to the associated increase in water level at the site (Holm & Clausen 2006). These results appear to contradict the findings of work in the Mar Menor Lagoon, Spain. Estimated nitrogen input to the lagoon was a good predictor of Black-necked and Great Crested Grebes, and cormorant, all of which were positively correlated to N input (Fernandez *et al.* 2005), and increased with moderate levels of nutrient loading (Robledano *et al.* 2011). The response was more likely to reflect the conditions of the lake than external influences for the grebes than the more mobile cormorant. Red-breasted merganser, however, was thought to be far less associated with eutrophication (Fernandez *et al.* 2005, Robledano *et al.* 2011). A jellyfish bloom resulting from the increased productivity of the system highlights another way in which high nutrient loading can affect waterbirds; by limiting the nutrients cascading through the food chain, a decline in predators may follow.

3.2 Freshwater Waterbird Populations

The pathways by which nutrient loading affects waterbird communities in freshwater systems are likely to be similar to those in coastal waters, although diffuse sources (agricultural run-off especially) may be relatively more important, as point sources are less prevalent at freshwater sites. Nutrient enrichment in the short term is likely to lead to enhanced food resources, thereby increasing bird populations, but the duration of this period of excess and thus the effects on the waterbird community will vary according to site, habitat and species. Freshwater systems, and shallow lakes in particular, may be more sensitive to changes in nutrient loading than coastal systems, due to lower flushing and dilution of the system (MacDonald 2006). Increased nutrient inputs often lead to shifts in vegetation community from submerged macrophyte vegetation, to surface macroplankton. This can mean a loss of food resources for herbivorous birds, and food and habitat for invertebrates and fish (MacDonald 2006). Macrophyte dominated-waters also tend to be more transparent than the more turbid phytoplankton covered lakes, thus affecting diving waterbirds (benthivores or piscivores; see sections 3.2.2 and 3.2.3). It is important to note here that water transparency is not only governed by nutrient status, but other factors such as changes to water levels, abundance of fish, damage to vegetation, amongst others (MacDonald 2006). Nutrient loading, whether from diffuse or point sources may affect piscivores through changes to food supply; fish may be attracted to areas of increased productivity but will then be depleted or die-off as conditions become anoxic. Increased productivity will also have an impact on water transparency, thus affecting the ability of piscivores that rely on visual cues to find prey.

3.2.1 Species that feed on invertebrates, plants and algae

Just as nutrient loading can be advantageous to waterbirds in coastal systems, the same has also been shown for freshwater environments. Table 3.2 summarises the key studies investigating effects of nutrient inputs on bird communities of freshwaters. The highly polluted Manchester Ship Canal supports nationally important tufted duck and pochard populations in winter, which concentrate in areas receiving large sewage discharges, where benthic organic carbon content and oligochaete density were high (Marsden & Bellamy 2000). The authors suggest that modernizing sewage treatment works, thereby improving water quality in the canal may negatively impact ducks using the canal. The closure of raw sewage outfalls and implementation of water treatment in 1978 has been cited as the reason for the disappearance of Pochards from Duddingston Loch, once the most important site for wintering Pochards in Britain (Fox & Salmon 1988). In Sweden, waterbird density across 11 shallow lakes was positively correlated with P concentration, and bird species richness was higher in naturally eutrophic lakes than oligotrophic lakes, although there was no difference in species richness between formerly oligotrophic lakes that had become eutrophic through nutrient loading, and oligotrophic lakes (Nilsson & Nilsson 1978).

Effects of water treatment will depend on the species (diet, foraging behaviour, etc.) and severity of nutrient loading, as shown by investigations of the responses of waterbirds to eutrophication. The accompanying increased productivity as a result of increased nutrient inputs often leads to a shift in the vegetation community, away from submerged macrophytes, to algal blooms instead (MacDonald 2006). It has been suggested that this decline in submerged vegetation may initially benefit diving benthivores, such as Tufted Duck and Goldeneye which have clearer access to foraging sites (Allison & Newton 1974, MacDonald 2006). However, the disappearance of submerged vegetation can also cause a reduction in benthic invertebrates (Andersson & Nilsson 1999), thus contributing to declines of Goldeneye, Pochard and Tufted Duck on Hickling Broad (Harper 1992, reviewed in Macdonald 2006). In Lough Neagh, Tufted Duck, Pochard and Goldeneye have declined dramatically since the 1990s, attributed both to declines in eutrophication-sensitive prey (in contrast, Scaup, which prey on larger, deeper dwelling items remained stable: Allen *et al.* 2004, Maclean 2006), and more recently to changes in the macroinvertebrate community following improvements to water quality (Tománková *et al.* 2013, 2014). The decline in Tufted Duck was also thought to be in part due to increased competition with fish (Allen *et al.* 2004). Roach *Rutilus rutilus*, the diet of which overlaps strongly with tufted duck, benefit from eutrophication, but when a control programme was implemented, Tufted Duck numbers recovered (Winfield & Winfield 1994). Removal of fish has also been shown to benefit waterfowl in the US, by increasing food resources, whether through the removal of competition, or the return to a clear-water state that accompanies the fish control (Hanson & Butler 1994).

Birds that feed directly on vegetation might also be expected to decline as the macrophytes disappear (Allison & Newton 1974). This shift in vegetation has been implicated (at least partly) in disappearances of wintering gadwall and teal flocks from Loch Leven (Allison & Newton 1974), declines in Mute Swans at Hickling Broad (Harper 1992) and reduced summer populations of Mute Swans and Pochards on Loch Leven (Allison & Newton 1974). A decrease in *Egeria densa* following the start of discharge of pulp mill effluent into the Rio Cruces Wetland in Chile was postulated to have led to declines in numbers of herbivores, including those of Black-necked Swans *Cygnus melancoryphus* through increased mortality and emigration (Lagos *et al*. 2008). In Japan, however, it is improvements to water quality of lakes and rivers that have been implicated in their decreased use by Gadwall and other dabbling ducks over a period of 13 years (Kasahara & Koyama 2010), although wigeon populations may have benefitted. It was postulated that birds move to more productive estuarine habitats as nutrient loading of freshwater habitat decreases. Declines across a variety of habitats for many species indicated, however, that factors besides water quality contributed to changes in populations (Kasahara & Koyama 2010).

Long-term studies of freshwater systems undergoing periods of eutrophication and recovery indicate potential impacts of improvements to water quality on the waterbird community. Population declines in a number of species using shallow freshwater lakes in Sweden coincided with periods of eutrophication, and a detailed study of these patterns on Lake Ringsjön (Andersson & Nilsson 1999) indicated three phases of population change for Coot, Mute Swan, Whooper Swan, Mallard, Wigeon, Goldeneye, Pochard and Tufted Duck. High numbers in the 1970s rapidly declined to low levels or absences during a period of eutrophication, before slowly recovering in the early 1990s after the introduction a restoration programme to reduce nutrient inputs. These changes may be partly due to national population changes (Whooper Swan, Wigeon, and more so for Mallard), but mostly the changes were thought to be due to local changes in trophic status of the lake, and the associated effects on food abundance (Andersson & Nilsson 1999). Coot, Mute Swan and dabbling ducks also increased on Lake Krankesjön after macrophytes increased on the lake during natural recovery from a eutrophic state (Hargeby *et al.* 1994). Similar patterns were observed on Lake Veluwemeer in the Netherlands, where bird numbers recovered after efforts were made to restore the lake to its pre-eutrophic state. These measures led to an increase in *Chara* spp, and other associated food resources, all of which were correlated with waterbird populations on the lake. Long-necked waterfowl (Bewick's and Mute Swans), and diving ducks (pochard, red-crested pochard and tufted duck) were more strongly correlated with these food supplies than short necked, non-diving species such as gadwall and pintail, although a strong relationship was found for coot (Noordhuis 2002). Coverage of *Chara intermedia* also appears to be important in affecting the distribution of waterfowl at Hickling Broad, which feed extensively on *Chara* beds (Armitage *et al.* 2000, 2001).

3.2.2 Piscivores

Nutrient enrichment of freshwater systems is likely to lead to increased fish abundance due to greater availability of their prey, which in turn would benefit piscivorous species (MacDonald 2006). Fish size increases as nutrient loading increases, which may have both positive and negative effects on the species that predate them (MacDonald 2006). Increased productivity also leads to changes in water transparency, thus affecting ability to detect prey, and for diving species, this is expected to lead to declines in abundance as nutrient loading increases (MacDonald 2006). In support of this hypothesis, Black-throated Diver *Gavia arctica* density across 11 shallow lakes in Sweden was negatively related to chlorophyll and phosphorous concentrations (Nilsson & Nilsson 1978) and showed a preference for breeding in transparent lakes (Eriksson & Sundberg 1991). Greater transparency may also explain the increase in Red-breasted Merganser populations on rivers and lakes in Japan coincident with improvements to water quality (Kasahara & Koyama 2010). Goosander populations on Lake Ringsjön appeared to be influenced by patterns of eutrophication and recovery of the lake, but this was not true for Cormorant or Great Crested Grebe (Andersson & Nilsson 1999). Breeding great-crested grebes were more abundant on rivers with poor water quality, but it is unclear exactly how this quality was assessed (Rushton *et al.* 1994). Changes in vegetation due to increased productivity may also affect piscivores; the higher abundance of pied-billed grebes in sites free of nutrient enrichment was attributed to their requirement for open water, while rails and bitterns preferred the more heavily vegetated nutrient enriched sites (Crozier & Gawlik 2002). MacDonald suggested in his review (2006), however, that the effect of eutrophication on Bitterns *Botaurus stellaris* would be negative, as the reedbed habitat is lost due to direct weakening effects of nitrates on the reed stems, and their main food, Rudd *Scardinius erythrophthalmus*, are negatively affected by eutrophication.

3.3 Birds as Nutrient Sources

Waterbirds themselves may act as a source of nutrients, affecting water quality. Where large numbers of geese, gulls and other waterbirds aggregate, they can make a significant contribution to the nutrient content of the water (Manny *et al.* 1994, Portnoy 1990, Post *et al.* 1998, Telesford-Checkley *et al.* 2017, Hahn *et al.* 2008, but see Pettigrew *et al.* 1997, Mukherjee & Borad 2001, Gwiazda 2014). At Brown Moss, a freshwater pool in the UK, birds contributed 73% of the phosphorous input from external sources, and 11% of the nitrogen input (Chaicana *et al.* 2010), while 88-92 % of the phosphorous entering Lake Ardensee was attributed to geese (Rönicke *et al.*

2008). In particular, staging and wintering geese may be important nutrient sources, transporting nutrients from terrestrial foraging sites to aquatic roosting sites (Kitchell *et al.* 1999).

By contributing to the nutrient content of aquatic systems, birds may alter the trophic status of waters. The effect of this guanotrophication will depend on the system; birds could contribute important nutrients that would otherwise limit productivity (Dessborn *et al.* 2016), or the additional nutrient load in already eutrophic waters could lead to hypertrophy (Manny *et al.* 1994). Effects on the biotic community are therefore likely to follow those described for eutrophication from other nutrient sources, with enhanced productivity, increased diversity, shifts in community structure, reductions in dissolved oxygen, accumulation of organic matter, decline in benthic fauna (Signa *et al.* 2015). Separating ornithogenic inputs as the cause of eutrophication is difficult, but comparisons of waters near and far from seabird colonies or experimental additions of guano have attributed higher chlorophyll, ammonia, phosphorous, nitrogen, higher plankton biomass and reduced dissolved oxygen (Kitchell *et al.* 1999, Soliman *et al.* 2000, Shatova *et al.* 2016) to guanotrophication. Stable isotope analysis has also enabled identification of guano-derived nutrients in algae and higher trophic levels (Payne & Moore 2006, Gagnon *et al.* 2013, Vizzini *et al.* 2016,). Higher phytoplankton biomass, and shifts in the algal community as rapidly growing species out-compete others have been observed close to seabird colonies (Powell *et al.* 1991, Payne & Moore 2006, Signa *et al.* 2012, Gagnon *et al.* 2016), which in turn may affect the macrobenthic community (Signa *et al.* 2015). Changes in polychaetes, nematodes and isopods have all been observed (Bosman & Hockey 1986, Palomo *et al.* 1999, Kolb *et al.* 2010, Gagnon *et al.* 2013, but see also Marmen *et al.* 2017), but evidence of ornithogenic nutrient loading affecting higher trophic levels is difficult to determine, due to top-down effects from birds consuming prey items. On the shores of seabird breeding islands in South Africa, extensive algal mats formed due to inputs from guano, which in turn provide food for invertebrate and bird communities. Persistence of the mats is likely to be a function of the nutrient enrichment from bird faeces, but also their role in controlling invertebrates feeding on the mats (Bosman & Hockey 1986). Changes in the fish communities near piscivorous bird colonies could be due to both nutrient enrichment and predation by the birds (Powell *et al.* 1991, Vizzini *et al.* 2016, Gagnon *et al.* 2015). Birds may also alter the nutrient status of waters through physical disturbance of sediment, shifting clear-water lakes to a turbid state, thereby having potential effects on other birds for which water transparency is important (Dessborn *et al.* 2016). Clearly to assess the potential impacts of changes to water treatment on bird communities, it is important to bear in mind the influence the birds themselves may have on the water quality, and thus the potential for unforeseen feedback effects.

Table 3.2 Principal studies investigating the effects of nutrient loading of freshwater systems on bird communities. These are studies in which nutrient loading is the focus, or at least features prominently in the discussion. The location of each study is given, together with details of the scale at which responses were observed. Most studies either report effects at a local (i.e. within-site) scale or across a whole waterbody study site (or large section thereof).

Refs	Guild	Habitat	Site	Variable	Scale	Results	Pathway	Quality of evidence
Marsden & Bellamy (2000)	Diving ducks	Canal	Manchester ship canal	Sewage discharge	Local (point source)	**Tufted duck** and **Pochard** concentrate around outfalls	Distribution of food resources	Analysis of duck abundance in relation to prey abundance and organic carbon
Fox and Salmon (1988)	Diving ducks	Freshwater lake	Duddingston Loch	Closure of sewage outfalls	Whole waterbody	Disappearance of **Pochard**	Decreased food resources (assumed)	Correlative but pochard known to feed at sewage outfalls and corresponds with declines of other ducks in the area.
Nilsson & Nilsson (1978)	Open waterbirds	Shallow lake	11 lakes in Sweden	Nutrient gradient	Whole waterbody	Density and species richness positively associated with P and N concentrations respectively. **Black-throated Diver** negatively related to chlorophyll A and P concentrations, but no relationship with transparency	Increased productivity leading to increased food resources, but reduced transparency	Associations between bird abundance and nutrient concentrations, based on one year
MacDonald 2006	Gulls, shorebirds	Freshwater	Review	Nutrient loading		Predicted increase, except some specialist shorebirds (e.g. **Shelduck**)	Increased food availability, except where macroalgal mats persist	Predicted based on review of effects on vegetation, food resources and therefore birds
MacDonald 2006	Dabbling waterfowl,	Freshwater	Review	Nutrient loading		Predicted decrease	Decreased food resources and reduced	Predicted based on review of effects on

Refs	Guild	Habitat	Site	Variable	Scale	Results	Pathway	Quality of evidence
	diving ducks, bitterns and rails						water transparency, loss of habitat	vegetation, food resources and therefore birds
MacDonald 2006	Piscivores		Review			**Red-throated Diver** and **Black-throated Diver** predicted to decrease, other diving piscivores to increase. **Bittern** and **Water Rail** predicted to decrease	Reduced water transparency but increased prey resources	Predicted based on review of effects on vegetation, food resources and therefore birds
Andersson & Nilsson (1999)	Waterbirds		Lake Ringsjon, Sweden	Eutrophication and recovery	Whole waterbody	Most species followed pattern of high abundance before eutrophication, a period of low abundance and then recovery after programme to restore water quality	Changes in food resources	Long term monitoring, postulated link between trends and eutrophication, no formal testing
Harper (1992)	Waterbirds		Hickling Broad	Eutrophication	Whole waterbody	Decline in **Mute Swan, Pochard** and **Tufted Duck**	Loss of submerged aquatic flora	
Allen *et al.* (2004), Maclean *et al.* (2006)	Diving ducks		Lough Neagh	Eutrophication	Whole waterbody	**Pochard, Tufted Duck** and **Goldeneye** declined, **Scaup** remained stable	Loss of eutrophication-sensitive chironomid larvae. Possible redistribution of birds to other sites	Analysis of long-term bird abundance data. Links with eutrophication are postulated, likely to be other factors involved
Hargeby *et al.* (1994)	Waterbirds		Lake Krankesjon, Sweden	Recovery from eutrophication	Whole waterbody	**Coot, Mute Swan** and **dabbling ducks** increased	Increased food resources	
Noordhuis (2002)	Herbivorous waterbirds	Lake	Lake Veluwemmer Netherlands	Recovery from eutrophication (including sewage treatment)	Whole waterbody	Birds returned to the lake, long-necked waterfowl and diving ducks increased more strongly than short-necked, non-diving	Increased food resources as *Chara* spp recolonised	

Refs	Guild	Habitat	Site	Variable	Scale	Results	Pathway	Quality of evidence
						waterfowl		
Crozier and Gawlik (2002)	All birds (includes non-waterbirds)		Everglades, Florida	Nutrient gradient	Local (areas of varying nutrient enrichment).	Higher total abundance at nutrient enriched sites, and changes in species composition along nutrient gradient. At enriched sites, **herons** and **rails** were at higher abundance**, Pied-billed Grebe** at lower abundance, and **Kildeer and Black-necked Stilt** were absent	Increased food resources, changes to vegetation	Associations between birds and nutrient status, links with food and habitat postulated. Some models did not converge, and interacted with water depth and rainfall

4. DISCUSSION

4.1 Summary

Nutrient loading of aquatic systems from anthropogenic sources can have varying impacts on the waterbirds they support, making consequences of programmes to reduce such loading difficult to determine. Generally, discharge of sewage effluent or run-off from agricultural sources enriches the nutrient content of the system and thereby leads to increases in the food resources of birds, both directly and indirectly. This is evident from the numerous studies presented here showing birds aggregating around points of sewage discharge, or increasing in abundance as eutrophication progresses. It might be expected, therefore, that efforts to improve water quality, by treating sewage, reducing effluent volume, or mitigating for leakage of agricultural nutrients, will negatively impact waterbirds. Whilst this is likely to be the case in some situations, and has been implicated in localised declines of several populations, effects will be site- and species-specific.

In general, birds are likely to benefit from nutrient enrichment. However, when waters are loaded to such an extent that changes in habitat occur, such as changes to vegetation and water transparency, the subsequent shifts in prey composition will, at the least, alter the waterbird community and may lead to population declines. Reversing these shifts through water quality improvements may therefore benefit birds, as will improvements to the water quality of hypereutrophic systems as oxygen levels increase allowing vegetation and invertebrates to recolonize. Similarly, if nutrient loading allowed the formation of extensive algal mats on mudflats, measures that cause these mats to recede may have positive effects on waders that were formerly excluded from algae-covered areas. It is important to bear in mind, however, the temporary reduction in food that is likely immediately after mat disappearance.

Lastly, impacts of improvements to water quality are likely to be different in coastal and freshwater systems. Coastal waters subject to tidal influences and therefore regular flushing will be less sensitive to nutrient loading than freshwater sites, and the trophic state of isolated lakes in particular may be affected by relatively minor changes in nutrient inputs, with largely negative effects on biodiversity. Waterbirds within these lake systems may therefore show more positive effects of improvements to water quality than their tidal system counterparts. Similarly, birds of rocky shore environments may be the least affected by changes to nutrient discharge.

Many of the studies reported have investigated associations between nutrient inputs and waterbirds at a local, within-site scale. Associations may be particularly apparent at the sources of inputs, and even where changes in these inputs do have an impact on waterbird numbers, it might not be possible to see this at the level of a whole site (i.e. waterbody or protected site) because other factors operating at this level may mask them (Burton *et al.* 2003a). While evidence of the impacts on waterbirds of changes to nutrient inputs is thus likely to be most apparent at a finer, within-site scale, the studies of Møller & Laursen (2015) and Møller *et al.* (2015) suggest that populations at site or even national levels may have been impacted by changes in human (agricultural or waste water treatment) practices that have impacted water quality across wider scales.

4.2 Species at Risk from Improvements to Water Quality

Identifying species for which improvements to water quality may have negative consequences is therefore not clear-cut, but depends on many factors. Generally, species that are less flexible in their foraging strategy would be expected to be more vulnerable to any reductions in food resources resulting from reduced nutrient inputs. Table 4.1 summarises species that may be affected by improvements to water quality, either negatively or positively, assuming improvements are made to moderately loaded waters.

Table 4.1 Wintering waterbird interest features of freshwater and coastal sites classified as Special Protection Areas (SPAs) in England under the EC Directive on the conservation of wild birds (79/409/EEC) that may be affected by improvements to water quality.

Guild	Example species from literature	Causal factors
Dabbling waterbirds	Brent Goose, Wigeon, Teal, Pintail, Gadwall, Coot, Bewick's Swan, Mute Swan	Loss of invertebrate food following nutrient reduction, however accompanying improvements to aquatic flora may also benefit this group.
Generalist wetland waders	Black-tailed Godwit, Avocet, Curlew, Lapwing.	Loss of invertebrate food following nutrient reduction. Except where nutrient loading caused extensive algal mat formation; removal of these likely to benefit this group.
Intertidal invertebrate feeders	Shelduck, Turnstone, Purple Sandpiper, Grey Plover, Redshank, Dunlin, Ringed Plover, Bar-tailed Godwit	Loss of invertebrate food following nutrient reduction. Except where nutrient loading caused extensive algal mat formation; removal of these likely to benefit this group. Purple sandpiper and Turnstone on rocky coasts may be less affected by changes than other species in sheltered estuaries.
Intertidal bivalve specialists	Oystercatcher, Knot	Loss of invertebrate food following nutrient reduction
Diving benthivores	Tufted Duck, Pochard, Scaup, Goldeneye	Improved transparency of waters may benefit this group, as will recovery of eutrophication-sensitive prey. Reduced abundance of fish competitors with decreased eutrophication may benefit some species. This group may also be negatively affected by the loss of food resources as a result of nutrient reduction.
Diving benthivores (marine)	Eider, Common Scoter, Velvet Scoter	These species expected to be less at risk from water quality improvements than other benthivorous duck species which may be more reliant on artificial food sources
Diving piscivores	Red-throated Diver, Goosander, Red-breasted Merganser, Great-crested Grebe, Cormorant.	Improved transparency may benefit this group, but declines in fish resource may follow nutrient reduction thereby causing decreases in piscivores.
Non-diving piscivores	Bittern	Improved transparency of waters, restoration of weakened reedbed habitat and positive impacts on main prey species, Rudd, may benefit this group.

4.3 Recommendations

As noted above, although there is evidence of impacts between changes in water quality and waterbird numbers at a local within-site scale, evidence for impacts at a site-level may be harder to discern, due to the number of other factors that might affect populations at this scale. Nevertheless, recent research has linked temporal changes in waterbird populations to changes in fertiliser use at national and European scales (Møller *et al.* 2015, Møller & Laursen 2015).

To build on this research, it is recommended that the spatial and temporal variation in non-breeding waterbird numbers (both freshwater and coastal), derived from Wetland Bird Survey (WeBS: https://www.bto.org/volunteer-surveys/webs) data, should be explored in relation to spatial and temporal patterns in broad-scale metrics relating to fertilizer usage and water quality.

Data on fertilizer usage and water quality are available as official statistics from the Department for Environment, Food and Rural Affairs (Defra). For example, fertilizer usage in Great Britain has been recorded through annual surveys from sample farms from 1992 to 2016 (https://www.gov.uk/government/collections/fertiliser-usage), while the ENV-16 Harmonised Monitoring Scheme provided data from 1980 to 2013 across the UK on river water quality and thus nutrient and heavy metal loads entering the marine environment (https://www.gov.uk/government/statistical-data-sets/env-16-harmonised-monitoring-scheme-datasets).

It is recommended that analyses should consider all non-breeding waterbird features of freshwater or coastal SPAs in England as detailed in this review and be undertaken at both regional and site-levels, as appropriate for available environmental datasets. Analyses should also aim to consider other factors, such as midwinter temperatures, previous work having demonstrated shifts in the distributions of non-breeding waterbirds in response to warming winters (Austin & Rehfisch 2005, Maclean *et al.* 2008, Lehikoinen *et al.* 2013).

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