Will improving wastewater treatment impact shorebirds? Effects of sewage discharges on estuarine invertebrates and birds

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Abstract

Human communities often discharge wastewaters into estuaries, influencing their organic and pollutant loading, benthic community and trophic structure. The implementation of the Water Framework Directive has encouraged the treatment of wastewater discharges across European estuaries, but the implications for invertebrate and waterbird communities are poorly understood. We explore the effects of untreated sewage discharges on the distribution and abundance of foraging black-tailed godwits Limosa limosa and their main benthic prey (bivalves and polychaetes) on the Tejo estuary in Portugal, a major European Special Protection Area with ongoing wastewater improvements. Patches of mudflat in close proximity to sewage streams (< 30 m) can support polychaete densities and biomass that are an order of magnitude higher than more distant sites (> 70 m), and godwits foraging in these areas can attain the highest intake rates recorded for the estuary. However, high intake rates can also be attained on bivalve prey, and bivalve biomass and density increase slightly with distance from sewage streams. As the organic input from sewage outfalls influences invertebrate abundance and godwit foraging rates over relatively small areas, the ongoing implementation of a sewage treatment network on the Tejo estuary seems likely to have only a limited impact on the wintering godwit population. The localized effect of untreated sewage discharges on benthic communities suggests that the implications for predatory birds are relatively minor where alternative prey are available, but may be more severe in locations with more depauperate, polychaete-dominated invertebrate communities.

Introduction

Estuaries are highly productive systems offering an abundance of resources to many species. The benthic invertebrate populations of estuaries, in particular, support a wide range of predatory fish and bird species (Van de Kam et al., 2004). However, the area surrounding estuaries also frequently provides favourable conditions for urban developments and consequently anthropogenic pressure at these sites tends to be very high. Human coastal communities frequently discharge wastewaters into estuaries, producing direct effects such as pollution that can affect several levels of the estuarine ecosystem (Diaz & Rosenberg, 1995; Van de Kam et al., 2004).

Wastewater including sewage discharge into estuaries can produce focal points of chemical pollution and organic matter that will influence the benthic community (Pearson & Rosenberg, 1978). Several studies have shown that particular elements of the benthic community, especially common and opportunistic species, increase in abundance and biomass in response to increased organic loading (Weston, 1990;

Beukema, 1991; Cardell, Sardà & Romero, 1999; Savage, Elmgren & Larsson, 2002). However, excessive nutrient enrichment can lead to anoxia, and consequently, to declines in biomass and diversity in the benthic community (Beukema, 1991; Ysebaert et al., 1998; Savage et al., 2002). Species richness among benthic communities therefore tends to increase in relation to both temporal and spatial distance from organic loading sources (Savage et al., 2002; Smith & Shackley, 2006; Wear & Tanner, 2007). For pollution-tolerant and opportunistic macrozoobenthos, such as the ragworm Hediste diversicolor (Mucha & Costa, 1999), the supply of organic matter can, however, provide a potential food source (Reise, 1985; Olivier et al., 1995), and thus the rates of growth and recruitment can be high around sewage outfalls (Ait Alla et al., 2006). Reductions in organic loading due to either closure or treatment of raw sewage consequently tend to result in a decrease in the density and biomass of the polychaetes (Ait Alla et al., 2006; Smith & Shackley, 2006).

Untreated sewage outfalls provide direct and indirect food resources to the estuarine bird community (Green, Hill

& Clark, 1993). Several gull species have been observed foraging directly on untreated sewage (Raven & Coulson, 2001), wildfowl can feed on items present in the sewage or on the benthic organisms, capitalizing on the high organic loading (Pounder, 1976; Campbell, 1984), and waders are likely to forage mostly on the abundant macrozoobenthos in nutrient-enriched areas (Van Impe, 1985; Burton & Armitage, 2005; Burton, Fuller & Eaton, 2005). Establishing the link between changes in the macrozoobenthic species due to organic loading and its effects on the estuarine bird community is not straightforward (Van de Kam et al., 2004). Nevertheless, several studies report a reduction in numbers or changes in behaviour or in site use of bird species following the reduction of organic loading in estuaries (Pounder, 1976; Campbell, 1984; Green et al., 1993; Raven & Coulson, 2001; Burton et al., 2005).

Throughout Europe, the implementation of the Water Framework Directive (EC, 2000) has increased efforts to improve wastewater treatment, including reducing nutrient inputs into watercourses and estuaries. The Tejo estuary in west Portugal is one of the most important wetlands in Europe, harbouring in excess of 150 000 waterbirds during winter, and serving as a major stop-over location for several species migrating along the East Atlantic Flyway (Leitão et al., 1998). Areas of the Tejo estuary have been designated as a Nature Reserve since 1976 under national legislation, and as a Special Protection Area since 1988 under the European Union Birds Directive 79/409/EEC. However, the estuary is in the vicinity of the most populated area in Portugal, with c. 2.5 million people (CCDRLVT, 2009) likely to have an impact on this estuary (Gaudêncio & Cabral, 2007). The vast majority of tidal flats are located on the southern and eastern banks of the Tejo estuary and, as recently as 2006, an area-wide development of Sewage Treatment Works (STW) for the residual waters of the southern and east banks of the Tejo estuary was initiated. This involves the construction of a wastewater collection grid, the installation of five new STWs and the improvement of another four of the current seven STWs around the estuary. All 12 STWs on the Tejo are predicted to be fully functional by the end of 2010 (SIMARSUL, 2009). Before the installation of this system of STWs, the vast majority of sewage was discharged raw and directly into the estuarine sediments, producing focal points of organic matter loading that are likely to have resulted in the middle sectors of estuary (where most urban development and sewage outfalls are located) having around twice the total organic matter present in the sediments than either upstream and downstream (Gaudêncio & Cabral, 2007). Although seven of the proposed 12 STWs are in operation on the Tejo, deficiencies in the collection grid for wastewaters mean that many outfalls are still discharging untreated sewage directly into the estuary. The levels of total organic matter found in the sediments of the Tejo estuary (c. 3–6%; Gaudêncio & Cabral, 2007) are likely to create focal areas of reduced diversity in the benthic community, but also to be advantageous to opportunistic species such as the ragworm. The improvement of the water treatment system will reduce the quantities of untreated sewage and

thus the organic loading currently being discharged into the estuarine sediments. This is likely to have important implications for the benthic community and, as a consequence, for the birds that prey on these species. However, the extent to which these changes may affect the bird community is currently unknown.

In this study, we explore the effect of the untreated sewage (hereafter termed sewage) currently being discharged into the Tejo estuary on the density and biomass of the two main benthic prey species of a migratory shorebird, the black-tailed godwit Limosa limosa currently classified as near threatened (IUCN, 2009). Several estuaries in western Europe support internationally important populations of black-tailed godwits (Gunnarsson et al., 2005; Delany et al., 2009), and the Tejo estuary is particularly important because it supports black-tailed godwits from breeding populations in both Iceland and mainland Europe (Alves et al., 2010). Black-tailed godwits (hereafter termed godwits) forage mainly on the bivalve Scrobicularia plana and the polychaete H. diversicolor (Moreira, 1994; Gill, Sutherland & Norris, 2001). As these two invertebrate species comprise a substantial proportion of the invertebrate community on intertidal mudflats in western Europe, and of the diet of many shorebird species (Goss-Custard et al., 2006), godwits are an ideal species in which to identify the potential consequences of changes in prey abundance and distribution following changes in nutrient inputs to mudflats. Here, we assess whether the biomass and size distribution of S. plana and H. diversicolor vary in relation to distance from sewage streams and whether this influences the distribution and foraging rates of godwits. We conclude by discussing the implications of future improvements in water treatment on the Tejo estuary and elsewhere for benthic invertebrates and shorebirds.

Methods

Prey abundance and biomass

The abundance and biomass of invertebrates were sampled monthly at six locations on the Tejo estuary between October 2006 and March 2007 (Fig. 1). These sites are all regularly used by foraging godwits (Moreira, 1993) and vary in distance (between 70 and 243 m) from the closest sewage outfall. The sewage outfall forms streams that meander across the mudflats (Fig. 1), and the six locations varied in distance from the closest sewage stream by between 16 and 86 m. At each sampling location, six to 12 random points were selected and a sediment core 9 cm in diameter and 15 cm in depth (the maximum probing depth of a godwit) was extracted from each point. More cores were extracted from sites for which we had no prior knowledge of invertebrate densities, in order to ensure that adequate estimates were achieved in all sites. The sediment was sieved in situ through a 1 mm mesh and all macrozoobenthos collected were transported to the laboratory for identification and measurement. Given that godwits foraging on estuarine mudflats prey almost exclusively on bivalves (mostly S. plana) and polychaetes (mostly H. diversicolor) (Moreira,
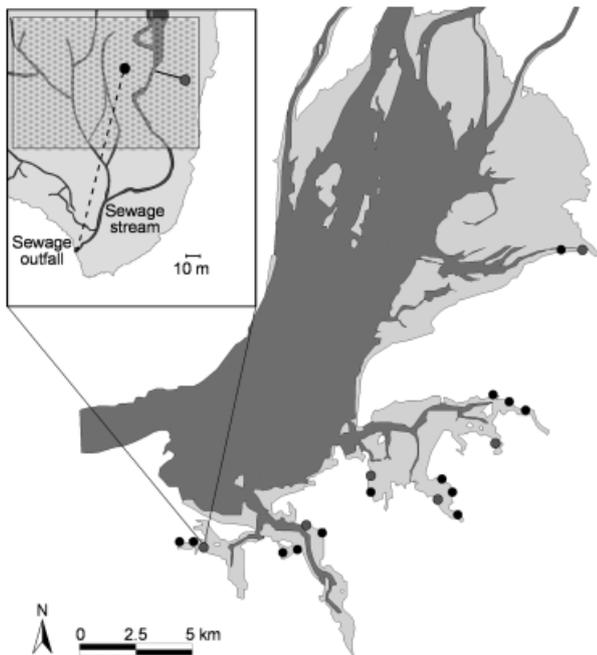
Figure 1 The estuarine mudflats at high (light grey) and low water (dark grey) of the Tejo estuary, and the location of sites used for measurements of black-tailed godwit Limosa limosa foraging behaviour (all circles) and prey sampling (grey circles). The inset illustrates the measurements of distances from prey sampling points (grey) to the nearest sewage stream (solid line), and the distance from most frequently used patch (black) within the godwit foraging area (stippled) to the nearest sewage outfall (dashed line).

1994; Gill et al., 2001), the analysis was thus restricted to these two prey items, which were classified into the following size categories: small (3–5.5 mm bivalves; 3–9.9 mm polychaetes); medium (5.6–9.5 mm bivalves; 10–19.9 mm polychaetes); large (9.6–14.5 mm bivalves; 20–49.9 mm polychaetes); very large (14.6–20 mm bivalves; >50 mm polychaetes). The mean body length of consumed H. diversicolor for each size class was reconstructed from the distribution of mandible lengths (following Moreira, 1994) attained from godwit faeces collected at two roosting sites on the Tejo: small ($n = 8$), medium ($n = 27$), large ($n = 105$) and very large ($n = 7$). No measurable S. plana fragments (i.e. the cardinal tooth) were found in the faeces and thus the mean lengths of individuals within each size class were calculated from the bivalves collected during prey sampling and for which body length was measured: small ($n = 466$), medium ($n = 217$), large ($n = 68$) and very large ($n = 60$). Prey biomass was then calculated using published formulae relating body length to ash-free dry mass established for these species in the Tejo estuary (Moreira, 1994).

Black-tailed godwit foraging behaviour

During the winters of 2006–2007 and 2007–2008, a total of 19 sites, distributed across all areas where godwits are known to forage along the south-east bank of the Tejo estuary (Moreira, 1993), were surveyed every fortnight between October and March for flocks of foraging godwits (Fig. 1). These sites included the six sites used for prey sampling and were all located within 800 m of a sewage outfall. On each site, foraging flocks were counted and focal individuals were randomly selected and observed for the time taken to complete ten paces while foraging. Within this time, each successful peck or probe, the identity of the prey (bivalve or polychaete) and its size class were recorded. The foraging techniques used to capture bivalves and polychaetes differ, and the great majority of foraging bouts consist of one prey type only; thus, prey types can be easily distinguished. All observations were carried out by JAA using a $\times 20$–60 telescope. The size category of each ingested prey item was estimated visually as one of four categories (small, medium, large or very large, corresponding to the size ranges for each prey type described above), and the number of each prey type and size class was multiplied by the average ash-free dry mass of prey in that size class to provide an estimate of the mean biomass intake rate for each site and prey type. Intake rates were pooled for each prey type separately (mean number of observations per site of godwits foraging on polychaetes = 197, range = 30–824, and on bivalves = 178, range = 31–637). The location of the foraging patch used during intake rate measurements was mapped using fixed landmarks and the most frequently used patch at each site was selected as the point from which the distance to the nearest sewage outfall was measured (Fig. 1).

Distances to sewage outfall and sewage streams

The location of each prey sampling site and the location of all sewage outfall sites along the south and east sections of the estuary were recorded using GPS (model eTrex, Garmin Ltd., Southampton, UK). These locations were imported into Google Earth (version 4.3) and the linear distance from each prey sampling site to the nearest sewage outfall or stream was measured using the software ruler tool (Fig. 1). As sewage discharges into streams that meander across the mudflats, the distance between each prey sampling location and the closest point of the sewage stream was measured in order to capture the direct effect of sewage on the macrozoobenthos for each site (Fig. 1). Sewage flow within streams is independent of tidal action and thus distance to sewage stream is likely to directly influence the local macrozoobenthos. However, as foraging godwit flocks typically move across the entire mudflat, usually following the tide edge (Dias et al., 2006), the distance between the outfall discharge point and the most frequently used foraging patch within each mudflat area was also measured (Fig. 1). Sewage outfall is likely to be spread across mudflats by the action of the tide, and foraging areas can encompass and be influenced by multiple sewage streams; hence, the distance between the most frequently used foraging patch and the nearest sewage outfall was used in order to capture the effects of the sewage loading over the entire foraging area.

Sediment penetrability

To assess whether sediment type varied in relation to distance from sewage stream, sediment penetrability was measured on nine sites ranging in distance between 16 and 86 m, by recording the maximum depth (in cm) of a 20 cm length metal rod dropped from a height of 90 cm within a PVC cylinder (Jones, Reynolds & Raffaelli, 2006). At each site, 30–33 depth measurements were recorded at random points.

Results

Effects of sewage on macrozoobenthic prey

Across six sites ranging from 16 to 86 m from the nearest sewage stream, the abundance and biomass of polychaetes declined by an order of magnitude (Fig. 2). In contrast, bivalve density and biomass did not vary significantly with distance from the sewage stream (Fig. 2). The biomass of polychaetes in all size classes declined significantly with distance from the nearest sewage stream (Fig. 3a), while the biomass of all bivalve size classes increased with distance from the nearest sewage stream, although this pattern was only statistically significant for very large bivalves (Fig. 3b).

No seasonal changes in the density of either polychaetes or bivalves was evident at any of the sites, regardless of distance from the nearest sewage stream (Fig. 4, polychaetes: overall variation between months: $F_{1,137} = 0.006$, $P = 0.94$; month × distance from nearest outfall: $F_{1,137} =$

0.012, $P = 0.92$; bivalves: overall variation between months: $F_{1,137} = 0.13$, $P = 0.72$; month × distance from nearest outfall: $F_{1,137} = 0.81$, $P = 0.37$). Despite the foraging activities of the very large numbers of predatory birds on the Tejo during winter, polychaete densities on sites within 30 m of sewage streams were between 700 and 3000 ind m^{-2} in all months but were only between 30 and 600 ind m^{-2} at sites further from sewage streams (Fig. 4). In contrast, bivalve densities were typically 50–200 ind m^{-2} within 30 m of sewage streams but densities in excess of 500 ind m^{-2} were regularly recorded at sites further than 80 m from sewage streams (Fig. 4). Sediment penetrability did not vary in relation to distance from the nearest sewage stream ($F_{1,7} = 0.56$, $r^2 = 0.075$, $P = 0.48$).

Effects of sewage outfalls on intake rates

For godwits foraging on polychaetes, prey intake rates were significantly higher at sites that are closer to sewage outfalls (Fig. 5a). For godwits foraging on bivalves, there was no apparent change in prey intake rates with distance to sewage outfall (Fig. 5b). Across all sites, prey intake rates for godwits foraging on bivalves are c 0.5 mg AFDM s^{-1} (range 0.2–0.7 mg AFDM s^{-1}), whereas intake rates on polychaetes
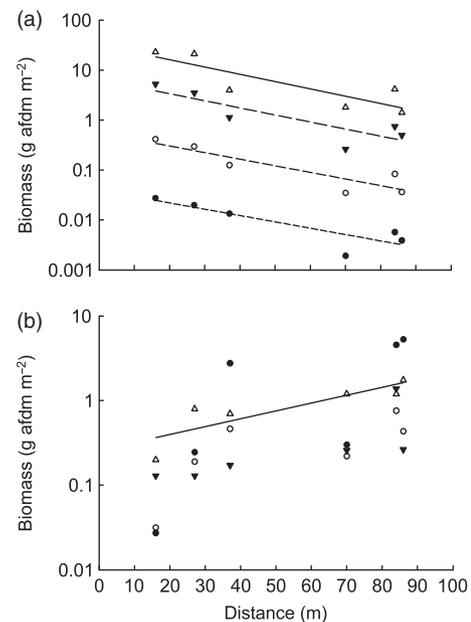
Figure 3 Changes in biomass of (a) polychaetes and (b) bivalves of each size class: small (filled circles), medium (open circles), large (filled triangles) and very large (open triangles), with distance from the nearest sewage stream. Lines indicate significant regressions: for polychaetes (short dashed line, $\log_{10}$ small biomass = $-0.013 \times$ distance-1.41, $r^2 = 0.75$, $P = 0.025$; medium dashed line, $\log_{10}$ medium biomass = $-0.013 \times$ distance-0.26, $r^2 = 0.80$, $P = 0.016$; long dashed line, $\log_{10}$ large biomass = $-0.014 \times$ distance $+ 0.81$, $r^2 = 0.74$, $P = 0.027$; solid line, $\log_{10}$ very large biomass = $-0.015 \times$ distance $+ 1.49$, $r^2 = 0.73$, $P = 0.031$) and bivalves ($\log_{10}$ very large biomass = $0.009 \times$ distance-0.59, $r^2 = 0.73$, $P = 0.030$).
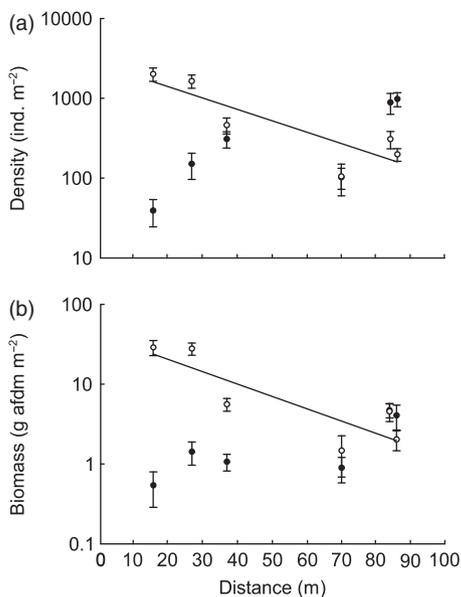
Figure 2 Changes in the mean (± SE) (a) density and (b) biomass of polychaetes (open circles) and bivalves (filled circles) with distance from the nearest sewage stream. Solid lines indicate significant relationships ($\log_{10}$ polychaete density = $-0.014 \times$ distance $+ 3.43$, $r^2 = 0.74$, $P = 0.029$; and $\log_{10}$ polychaete biomass = $-0.016 \times$ distance $+ 1.58$, $r^2 = 0.73$, $P = 0.030$).
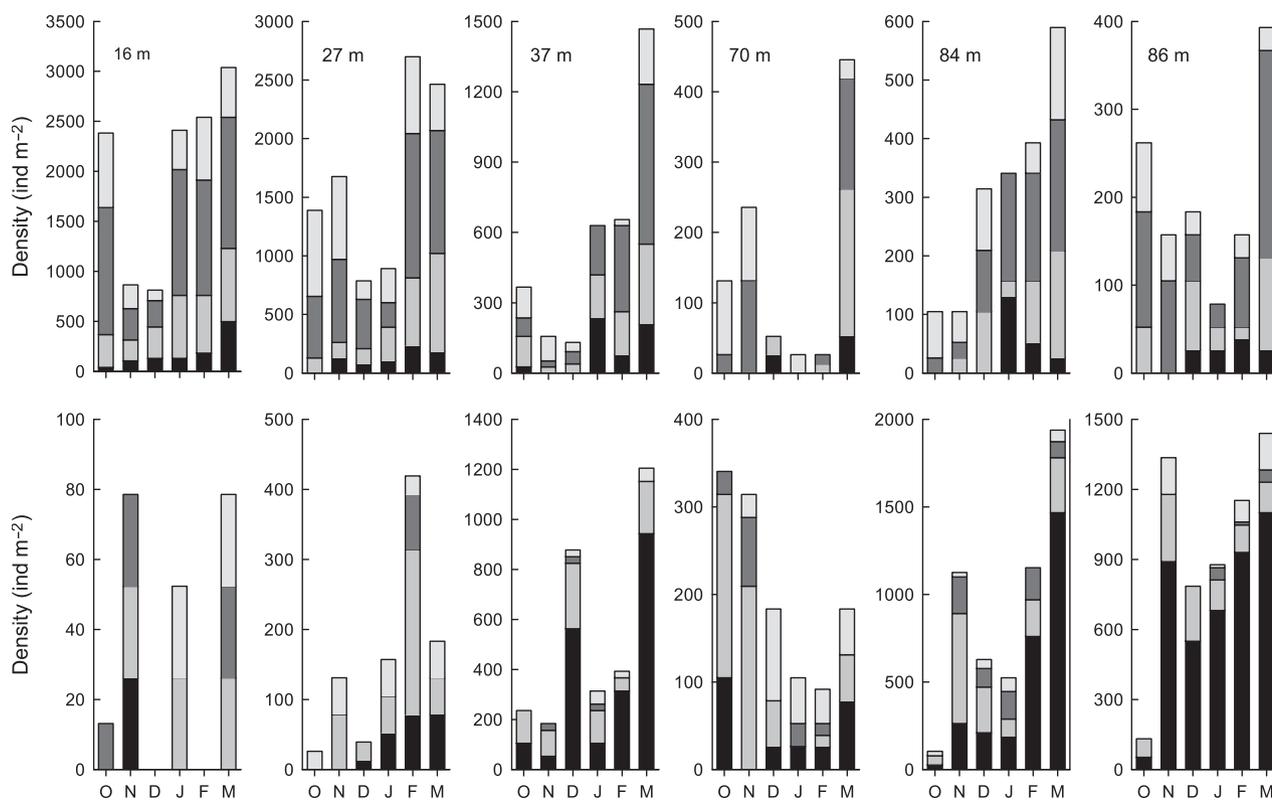
Figure 4 Monthly variation in densities of polychaetes (top row) and bivalves (bottom row) of small (black), medium (grey), large (dark grey) and very large (light grey) size classes from October 2006 to March 2007 at six sites on the Tejo estuary. The distance of each site from the nearest sewage stream is indicated in the upper graphs. Note the different scales on each panel.

range from c 1.6 mg AFDM s^{-1} within 100 m of a sewage outfall to 0.2 mg AFDM s^{-1} at 700 m from an outfall (Fig. 5).

The decline in prey intake rates of godwits foraging on polychaetes with distance to the nearest sewage outfall is primarily a consequence of declines in the proportion of very large polychaetes in the diet (Fig. 6a). Within 200 m of outfalls, very large polychaetes usually constitute c 80–90% of the biomass intake rate, whereas this typically declines to c 65% beyond 500 m from outfalls (Fig. 6a). The proportion of small, medium and large polychaetes in the godwit diet increases significantly with distance from sewage outfalls, but this is insufficient to maintain the biomass intake rates achieved close to the outfalls (Figs 5a and 6a). For godwits foraging on bivalves, the proportions of each size class do not vary with distance from the nearest sewage outfall, and the relative contribution of each size class to the biomass intake rate is more similar than for polychaetes (Fig 6b).

Across sites, the mean ($\pm$ SE) flock sizes ranged from 21 ± 3.6 to 139 ± 45.0, but there was no significant change in the mean flock size with distance from the nearest sewage outfall ($F_{1,17} = 0.611$, $r^2 = 0.04$, $P = 0.45$).

Discussion

On the Tejo estuary, areas of mudflat in the immediate vicinity (c 30 m) of a sewage stream support polychaete

densities and biomass that are an order of magnitude higher than more distant sites (> 70 m). This in turn allows godwits that forage on polychaetes in these locations to attain the highest intake rates. In contrast, there is little change in the density or biomass of bivalves with distance from sewage streams. However, godwit intake rates are only higher on polychaetes than on bivalves on mudflats that are within c 150 m of a sewage outfall (Fig. 5).

The effect of proximity to sewage stream on polychaete density and biomass is very likely to occur as a consequence of high inputs of organic matter into these sites, providing a rich food supply for *H. diversicolor* (Reise, 1985; Olivier *et al.*, 1995). Invertebrate communities can also vary in relation to sediment type on estuaries (Gaston, 1987; Thrush, 1991), but the lack of any variation in sediment penetrability with distance from sewage outfalls suggests that this is not the driver of the variation in the abundance of polychaetes on the Tejo estuary. Bivalves could also benefit from an increase in the organic load in these locations (but see Matthews & Fairweather, 2008); however, the wastewaters currently being discharged into the Tejo estuary are likely to also contain chemical toxins from factory waste, which might influence bivalve abundance and biomass. High levels of lead in the Tejo estuary have recently led to *S. plana* being declared unfit for human consumption (DR, 2007). The polychaete *H. diversicolor* is generally more tolerant of pollution (Bartels-Hardege &
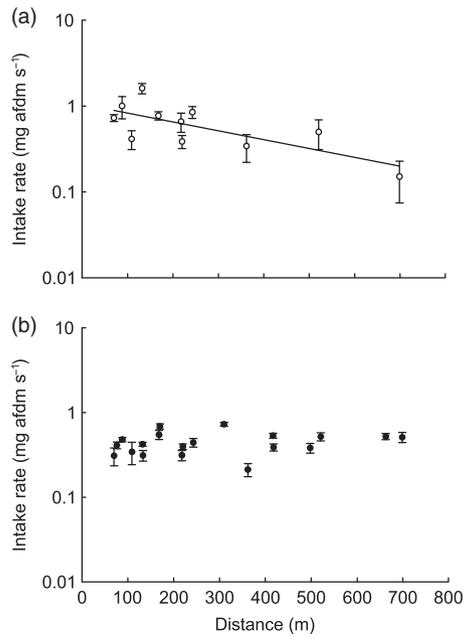
Figure 5 The change in the mean ($\pm$ se) rate of biomass intake of black-tailed godwits foraging *Limosa limosa* on (a) polychaetes ($\log_{10}$ intake rate = $-0.001 \times$ distance $- 0.085$, $r^2 = 0.39$, $P = 0.03$) and (b) bivalves with distance from the nearest sewage outfall on the Tejo estuary.
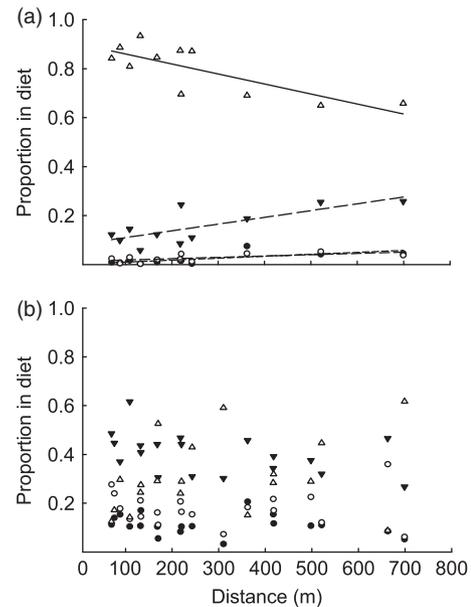

Figure 6 The change in the proportionate contribution of small (filled circles), medium (open circles), large (filled triangles) and very large (open triangles) prey size classes to the biomass intake rate of black-tailed godwits *Limosa limosa* foraging on (a) polychaetes and (b) bivalves with distance to the nearest sewage outfall. Lines indicate significant regressions for polychaetes (short dashed line, small = $7.92 \times 10^{-5} \times$ distance + 0.002, $r^2 = 0.48$, $P = 0.018$; medium dashed line, medium = $5.37 \times 10^{-5} \times$ distance + 0.01, $r^2 = 0.41$, $P = 0.033$; long dashed line, large = $0.001 \times$ distance + 0.08, $r^2 = 0.58$, $P = 0.007$; solid line, very large = $-0.001 \times$ distance + 0.90, $r^2 = 0.62$, $P = 0.004$).

Zeeck, 1990; Saiz-Salinas & Francés-Zubillaga, 1997*a,b*; Scraps, 2002) and is therefore more likely to be able to take advantage of these high organic loadings (Esselink, 1998).

The high prey intake rates achieved by godwits foraging on polychaetes in close proximity to sewage outfalls (Fig. 5a) are mostly driven by the increased abundance of polychaetes of the very large (> 50 mm) size class (Fig. 6a). Among bivalves and polychaetes of the very large size class, polychaetes exceeding 50 mm length have previously been shown to be the most profitable prey item for godwits (Alves, 2009). However, godwits are sexually size dimorphic (Gunnarsson *et al.*, 2006) and the longer-billed females have been found to forage on polychaetes (particularly of the large and very large size classes) more than the small-billed males (Alves, 2009); thus, the greater burrowing depths of large polychaetes may limit their accessibility to small-billed godwits. As polychaetes of < 50 mm body length are less profitable than bivalves of similar size classes (Alves, 2009), foraging on polychaetes is likely to be of most importance to the longer-billed females that can profit from consuming the large individuals. This may explain why flock sizes are not higher in close proximity to sewage streams; although prey abundances are higher at these sites, these resources may not be available to all individuals.

Conservation implications

The ongoing development of a network of improved sewage treatment on the Tejo estuary is likely to alter the distribution and abundance of polychaetes. In the Oued Souss

estuary, Morocco, both polychaete density and biomass were significantly reduced after wastewater discharge into the estuary was stopped (Ait Alla *et al.*, 2006). However, declines in polychaete abundance following wastewater treatment are unlikely to greatly influence the numbers of godwits on the Tejo estuary as (1) the current levels of organic loading only produce significant increases in polychaete abundance on sites within *c* 30 m of sewage streams and *c* 150 m from sewage outfalls, which comprise only a small proportion (*c* 8%), of the 34 000 ha of estuarine mudflats available in the Tejo estuary (there are *c*. 32 outfalls along the south-east shore); (2) estuary wide counts (encompassing low and high tides) of godwits across the Tejo suggest that the average proportion of godwits regularly foraging on areas within *c* 150 m of a sewage outfall is only *c*. 17% $\pm$ 0.02 se ($n = 26$ counts) and, within these flocks, only the longer-billed godwits may be capable of foraging on the profitable very large polychaetes; (3) the lack of any seasonal declines in the abundance of bivalves or polychaetes during winter (Fig. 4) suggests that sufficient resources are likely to be available elsewhere on the Tejo to accommodate godwits that can no longer exploit high polychaete densities adjacent to sewage streams.

Reducing the amount of untreated wastewater currently discharged into the Tejo estuary is therefore unlikely to

greatly affect the number of godwits supported on the estuary, and possibly of any other waterbirds foraging in these areas. Besides godwits, only black-headed gulls *Larus ridibundus* are common and frequently recorded foraging on areas in the close vicinity of sewage outfall. Moreover, reductions in inputs of chemical toxins to the estuary that led to the local extinction of oysters *Crassostrea angulata* (Dias & Marques, 1999), and are probably also the cause of the high levels of lead currently found in *S. plana* (DR, 2007), may very well benefit several invertebrate species. The improvement of wastewater treatment in the Tejo estuary is thus likely to be far more beneficial to the estuarine ecosystem than the current situation.

The location of the Tejo estuary in southern Europe makes it an extremely important stop-over and winter location for many waterbirds from across Europe (Delany *et al*., 2009), and may also contribute to the diversity of prey and lack of strong seasonal depletion in prey abundance on this estuary. In south Europe and North Africa, both *H. diversicolor* and *S. plana* are reported to have two recruitment periods per year and to grow throughout the winter months (Gillet, 1990, 1993; Silva, 1991; Sola, 1997; Ait Alla *et al*., 2006). In estuaries at more northerly latitudes where climatic conditions may constrain reproduction and growth, and invertebrate communities can be more dominated by polychaetes, the implications for predatory shorebirds of reducing organic loading through improved wastewater treatment may be more significant. However, the evidence presented here suggests that the benefits of reducing nutrient inputs into estuaries as part of the implementation of the EU Water Framework Directive will not necessarily incur high costs for the waterbirds for which many of these sites receive international protection.

Acknowledgements

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