**Appendix S1**

**Ecosphere**

**Evidence-based conservation in a changing world: lessons from waterbird individual-based models**

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| Case study title: | Bahia de Cadiz, Spain |
| Location: | 36.439, -6.182 |
| Birds: | Grey plover, *Pluvialis squatarola*Kentish Plover, *Charadrius alexandrinus*Ringed plover, *Charadrius hiaticula*Oystercatcher, *Haematopus ostralegus*Bar-tailed godwit, *Limosa lapponica*Black-tailed godwit, *Limosa limosa*Little Stint, *Calidris minuta*Redshank, *Tringa totanus*Sanderling, *Calidris alba* |
| Modelling: | Not MORPH |
| Abstract: | The overall aim of this project was to provide for policy-makers and their scientific advisors a suite of field-tested predictive population models with which they can devise local and Europe-wide management plans for maintaining the biodiversity of migratory (wintering/on passage) coastal birds (waders and wildfowl) that feed on inter-tidal and, often, supra-tidal (supplementary) habitats. The original project objective was to achieve this by adapting, simplifying and parameterising two existing individual-based population models so that they could be applied rapidly to a variety of species whenever policy decisions were required and at any geographic scale. Both predicted the body condition and mortality rate over the non-breeding season of classes of individuals within the population. Both models assumed that, when responding to management-induced changes in their feeding environment, individual birds chose the options that maximize their intake rate. Both were individual-based, in the sense that they tracked the location, foraging decisions and ultimate fate of each individual within the population, and predicted population level responses to environmental change (e.g. mortality rate) from the behaviour and fates of individuals (e.g. the proportion of individuals which die). One model, the single-site wader model, was a single-site (e.g. estuary) model for the non-breeding season which had been developed, parameterized and extensively (and successfully) tested for one common European wader species. The other, the multi-site goose model, was a multi-site, Europe-wide model which had been parameterized and tested, in a preliminary fashion, for one common wildfowl species. The aim of the project was to build, test and define the utility of the models for a much wider range of species in order to rapidly provide, at whatever geographic scale required, bird population predictions for a range of policy options. The original objective of adapting two existing models was extended during the project, and instead a completely new model was developed capable of making predictions for both waders and geese, at either the single or multi-site scale. The new model can be applied to a much wider range of systems and issues than could either of the initial models. The new model is based on the same principles as the existing models and is also individual-based. It builds on the strengths of the existing models, and adds improvements where the previous models were limited.Three key scientific advances were made during the project. • *Development of a general individual-based modelling framework*. The development of the new individual-based model has been one of the major scientific advances made during the project. The new model has the following advantages over the initial models. (i) It is much more flexible than the original models and so can be applied to a wider range of environmental issues. (ii) Using a single model for both geese and waders highlighted the similarities between these systems, rather than differences. (iii) The new model has been developed in a more general way than the previous models and so it not simply restricted to waders and geese, increasing the potential application of the model in the future. • *Development of a general equation to predict the feeding rate of waders*. The project showed that the a simple equation could be used to predict the feeding rate of wading birds feeding on a range of prey species. Feeding rate is one of the most important parameters in the model. All that needs to be known is the mass of the wading bird species, and the mass and abundance of the prey. This breakthrough meant that wader models could be developed much more quickly and for a wider range of species than would have been possible if feeding rate needed to be measured for each new wader and prey species. * *Rapid application of models to real-world issues*. If individual-based models are to be valuable tools for advising policy, they must be developed within a relatively short time span (e.g. a few years) and produce realistic predictions. Three site-specific multi-species wader models (Bahia de Cadiz, Spain, Baie de Somme, France and Exe Estuary, England) and a multi-site brent goose model (throughout western Europe) were successfully parameterised using data collected or collated during the four years of the project. The models successfully predicted much of the observed behaviour (e.g. amount of time spent feeding, rate of consuming food) and ecology (e.g. distribution between habitats) of the birds in the real systems. They were also used to answer a wide range of key site or system specific policy issues (e.g. hunting, disturbance, habitat loss of saltpans, fish farms, intertidal vegetation and sandflats). The successful parameterisation, testing and application of the wader and goose models is one of the key scientific advances made during the project, because it shows the potential of the approach to address European coastal issues.

The site and system-specific wader and goose models predicted the effect of a wide range of environmental issues (e.g. disturbance from people, hunting, habitat loss, sedimentation, encroachment of saltmarsh vegetation onto mudflats) on the survival and body condition of birds. These specific predictions are detailed in the report. In addition, the following more general policy recommendations can be derived from the results of the project.* *Monitor bird food reserves as well as bird numbers*. Estuary managers are often required to monitor the quality of a site for important bird species or to assess how potential changes to a site may influence site quality. The conservation importance of an estuary is often measured in terms of bird numbers using the estuary, but monitoring numbers is not necessarily a reliable way of assessing changes in site quality. In particular, this is because the numbers of birds using a site depend not only on the conditions at the site, but also the conditions at other sites both within the non-breeding and breeding seasons. Changes in the food supply can be used in combination with bird numbers to determine whether any decline in bird numbers is likely to reflect a problem on the site itself. Decreasing bird numbers in combination with a decrease in the amount of food would indicate that the problem was within the site, whereas decreasing bird numbers without a decrease in the food supply would indicate either that the problem was not limited food within the site, or that the decrease in bird numbers was due to factors outside of the site. A policy derived from these predictions would be to establish a monitoring programme to record the abundance of food on sites at the start of winter as well as continuing the usual procedure of monitoring bird numbers.
* *Monitor the use of marginal habitats and feeding times*. The models developed during this project all predicted that birds fed in the most profitable and safest places and times when feeding conditions were good and survival rates high, behaviour which mimicked that of real birds. In contrast, birds were predicted to feed more in marginal habitats or at more risky times when feeding conditions were poorer, again behaviour which mimicked that of real birds. A possible policy would be to establish a monitoring programme to detect such changes in the behaviour of bird populations as an early warning that survival rates are likely to be falling. This approach would pick up possible detrimental changes on a site before increases in mortality rate could be detected through traditional approaches based on bird ringing programmes, increasing the chance that management can be implemented to improve conditions before bird survival declines greatly.
* *Maintain a network of sites*. The multi-site models predicted that birds emigrated from a site when the feeding conditions declined on the site. The consequences for the population depended on whether emigrating birds were able to find and survive on an alternative site. Birds could not survive if they did not have the energy reserves to successfully fly between the two sites (i.e. alternative sites must be relatively close together). A simple policy derived from this prediction is that wherever possible a network of high-quality sites should be maintained. This maximises the chance that emigrating birds are able to find and survive on an alternative site, if conditions deteriorate on their initial site.
* *Include terrestrial habitats in conservation areas*. Birds were predicted to use terrestrial habitats when feeding conditions declined on their intertidal habitats, a pattern also observed in real birds. For example, brent geese in northern Europe fed on grass when intertidal *Zostera* and algae biomass declined during winter. Waders consumed more earthworms from terrestrial fields when intertidal food was depleted in late winter. These terrestrial habitats are often critical to the survival of waders and geese, even though they are often considered as marginal habitats. These habitats are often excluded from the designation of Special Protection Areas, but this means that vital habitat is not being protected and as a result may be lost to building developments, or suffer high disturbance levels. A simple policy derived from these predictions is that wherever possible conservation areas should include the terrestrial habitats around estuaries as well as the intertidal habitats of the estuary itself. This would ensure that the full range of habitats required by birds are protected.

The model developed in this contract provides a means for predicting the effects of environmental issues on the survival and body condition of wading birds and wildfowl. As such, it is a tool which can be used by decision-makers concerned with the management of the coastal zone throughout Europe, whether they represent governments, fisheries organisations or nature conservation bodies. The model also provides the basis for further research into the interaction between coastal birds and their environment, and could be expanded in a number of directions, including application to the breeding season and to species other than waders and geese. |
| Funders: | European Commission. Project number: EVK2-2000-00612 |
| Papers or reports: | Stillman, R.A., Caldow, R.W.G., le V. dit Durell, S.E.A., West, A.D., McGrorty, S., Goss-Custard, J.D., Pérez-Hurtado, A., Castro, M., Estrella, S., Masero, J.A., Rodríguez-Pascual, F.H., Triplet, P., Loquet, N., Desprez, M., Fritz, H., Clausen, P., Ebbinge, B., Norris, K. and Mattison, E., 2005. Coastal bird diversity. Maintaining migratory coastal bird diversity: management through individual-based predictive population modelling, Centre for Ecology and Hydrology, Winfrith Newburgh, Dorset.http://nora.nerc.ac.uk/id/eprint/9513/1/Coast\_Bird\_Diversity\_Final\_Report.pdf |

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| Case study title: | Baie de Seine, France |
| Location: | 49.457, 0.146 |
| Birds: | Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Dunlin, *Calidris alpina* |
| Modelling: | Not MORPH |
| Abstract: | Reproduced with permission from ElservierA behaviour-based model was used to explore the effect of an extension of the port at Le Havre (Port 2000), and the effect of proposed mitigation measures, on the mortality and body condition of the three main shorebird species that overwinter in the estuary of the river Seine, France. In the model, a 20% reduction in the area of mudflats on the north side of the estuary had little effect on curlew Numenius arquata mortality and body condition but significantly increased mortality and decreased body condition in dunlin Calidris alpina and oystercatchers Haematopus ostralegus. Disturbance of feeding birds both day and night had a significant effect on the mortality and body condition of all three shorebird species, as did disturbance of roosting birds. Disturbance of feeding birds in the daytime only had a significant effect on dunlin mortality and body condition, but not that of curlew and oystercatchers. In the model, the creation of a buffer zone to reduce disturbance of feeding birds restored shorebird mortality and body condition to pre-disturbance levels. A new mudflat area was also effective in mitigating the effect of habitat loss on all three shorebirds and in mitigating the effect of roost disturbance on dunlin and curlew. However, a new mudflat area was not effective in mitigating the effect of roost disturbance on oystercatcher mortality and body condition. The effectiveness of the mitigating mudflat depended as much on its size as its quality. We believe that this is the first time that anyone has been able to forecast the efficacy of proposed mitigation measures. |
| Funders: | No information provided. |
| Papers or reports: | dit Durell, S.E.A.L.V., Stillman, R.A., Triplet, P., Aulert, C., dit Biot, D.O., Bouchet, A., Duhamel, S., Mayot, S. and Goss-Custard, J.D., 2005. Modelling the efficacy of proposed mitigation areas for shorebirds: a case study on the Seine estuary, France. Biological Conservation, 123(1): 67-77. |

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| Case study title: | Baie de Somme (A) |
| Location: | 50.201, 1.651 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MORPH |
| Abstract: | In a number of extensive coastal areas in northwest Europe, large numbers of long-lived migrant birds eat shellfish that are also commercially harvested. Competition between birds and people for this resource often leads to conflicts between commercial and conservation interests. One policy to prevent shellfishing from harming birds is to ensure that enough food remains after harvesting to meet most or all of their energy demands. Using simulations with behaviour-based models of five areas, we show here that even leaving enough shellfish to meet 100% of the birds’ demands may fail to ensure that birds survive in good condition. Up to almost eight times this amount is needed to protect them from being harmed by the shellfishery, even when the birds can consume other kinds of non-harvested prey. |
| Funders: | No information provided. |
| Papers or reports: | Goss-Custard, J.D., Stillman, R.A., West, A.D., Caldow, R.W.G., Triplet, P., le V dit Durell, S.E.A. and McGrorty, S., 2004. When enough is not enough: shorebirds and shellfishing. Proceedings. Biological sciences, 271(1536): 233-237. |

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| Case study title: | Baie de Somme (B) |
| Location: | 50.201, 1.651 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MORPH |
| Abstract: | Reproduced with permission from ElservierIntertidal areas support during the non-breeding season many wading birds Charadrii thatmay often take flight in response to the presence of people or of birds of prey on their intertidal feeding and roosting grounds. Disturbance can cause birds to spend energy flying away and to lose feeding time while relocating to different feeding areas, where the increased bird densities may intensify competition from interference and, if of sufficient duration, from prey depletion. Until now, there has been no method for establishing how frequently birds can be put to flight before their fitness is reduced. We show how individual-based behavioural models can establish critical thresholds for the frequency with which wading birds can be disturbed before they die of starvation. It uses oystercatchers Haematopus ostralegus in the baie de Somme, France where birds were put to flight by disturbance up to 1.73 times/daylight hour. Modelling shows that the birds can be disturbed up to 1.0–1.5 times/h before their fitness is reduced in winters with good feeding conditions(abundant cockles Cerastoderma edule and mild weather) but only up to 0.2–0.5 times/h when feeding conditions are poor (scarce cockles and severe winter weather). Individual based behavioural models enable critical disturbance thresholds to be established for the first time. |
| Funders: | No information provided. |
| Papers or reports: | Goss-Custard, J.D., Triplet, P., Sueur, F. and West, A.D., 2006. Critical thresholds of disturbance by people and raptors in foraging wading birds. Biological Conservation, 127(1): 88-97. |

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| Case study title: | Baie de Somme (C) |
| Location: | 50.201, 1.651 |
| Birds: | Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Dunlin, *Calidris alpina* |
| Modelling: | MORPH |
| Abstract: | Reproduced with permissionConservation managers need to be able to assess and prioritize issues that may affect their target habitats and species. In the Baie de Somme, France, conservation issues affecting overwintering shorebirds include hunting pressure, cockle fishing, recreational disturbance, Spartina encroachment, and changing sediment levels. We used an individual-based model to predict the effect of these issues on the survival of three shorebird species: dunlin Calidrisalpina, oystercatcher Haematopus ostralegus and curlew Numenius arquata. In the model, removing hunting from the mudflats in the eastern part of the estuary had the greatest positive effect on shorebird survival. Oystercatcher survival decreased markedly when stocks of large cockles were reduced to ,250 m-2 or numbers of fishermen per day were doubled. Short-term disturbance events, such a swalkers, had more effect on shorebird survival than long term events, such as fishermen. Dunlin, as a protected species, were able to feed outside the Re´serve Naturelle andwere unaffected by disturbance within the Re´serve. Oystercatcher survival decreased when the number of disturbance events within the Re´serve exceeded one h-1, and curlew survival when disturbance events exceeded six h-1.Spartina encroachment caused dunlin survival to decline steadily as feeding habitat was lost. Dunlin were also the species most affected by changes in sediment levels, likely to occur through either sedimentation or sea level rise. |
| Funders: | European Commission. Project number: EVK2-2000-00612 (extracted from Stillman et al 2005 report) |
| Papers or reports: | dit Durell, S.E.A.L.V., Stillman, R.A., Triplet, P., Desprez, M., Fagot, C., Loquet, N., Sueur, F. and Goss-Custard, J.D., 2008. Using an individual-based model to inform estuary management in the Baie de Somme, France. Oryx, 42(2): 265-277. |

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| Case study title: | Bangor Flats |
| Location: | 53.234, -4.107 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MORPH |
| Abstract: | In a number of extensive coastal areas in northwest Europe, large numbers of long-lived migrant birds eat shellfish that are also commercially harvested. Competition between birds and people for this resource often leads to conflicts between commercial and conservation interests. One policy to prevent shellfishing from harming birds is to ensure that enough food remains after harvesting to meet most or all of their energy demands. Using simulations with behaviour-based models of five areas, we show here that even leaving enough shellfish to meet 100% of the birds' demands may fail to ensure that birds survive in good condition. Up to almost eight times this amount is needed to protect them from being harmed by the shellfishery, even when the birds can consume other kinds of non-harvested prey. |
| Funders: | No information provided. |
| Papers or reports: | Goss-Custard, J.D., Stillman, R.A., West, A.D., Caldow, R.W.G., Triplet, P., le V dit Durell, S.E.A. and McGrorty, S., 2004. When enough is not enough: shorebirds and shellfishing. Proceedings of the Royal Society B: Biological Sciences, 271(1536): 233-237. |

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| Case study title: | Bridgwater Bay, UK |
| Location: | 51.224, -3.015 |
| Birds: | Shelduck, *Tadorna tadorna*Grey plover, *Pluvialis squatarola*Ringed plover, *Charadrius hiaticula*Oystercatcher, *Haematopus ostralegus*Pied oystercatcher, *Haematopus longirostri*Curlew, *Numenius arquata*Black-tailed godwit, *Limosa limosa*Dunlin, *Calidris alpine*Knot, *Calidris canutus*Redshank, *Tringa totanus*Turnstone, *Arenaria interpres* |
| Modelling: | MORPH |
| Abstract: | Reproduced with permission from ElservierLocal alteration of species abundance in natural communities due to anthropogenic impacts may have secondary, cascading effects on species at higher trophic levels. Such effects are typically hard to single out due to their ubiquitous nature and, therefore, may render impact assessment exercises difficult to undertake. Here we describe how we used empirical knowledge together with modelling tools to predict the indirect trophic effects of a future warm-water outflow on populations of shorebirds and wildfowl. Of the main potential benthic prey used by the birds in this instance, the clam Macoma balthica was the only species suspected to be adversely affected by a future increase of temperature. Various scenarios of decreases in prey energy content, simulating various degrees of temperature increase, were tested using an individual-based model, MORPH, in order to assess the effects on birds. The survival and body condition of eight of the 10 bird species modelled, dunlin, ringed plover, turnstone, redshank, grey plover, blacktailed godwit, oystercatcher and shelduck were shown to be notinfluenced even by the most conservative prey reduction scenarios. Most ofthese species are known to feed primarily on polychaete worms. For the few bivalve-feeding species, the larger size-classes of polychaete worms were predicted to be a sufficient alternative food. Only knot was predicted to have a lower survival under the two worst case scenario of decreased M. balthica energy content. We believe that this is the first time such predicted cascade effects from a future warm-water outflow have been shown. |
| Funders: | EDF NNB Genco |
| Papers or reports: | Garcia, C., Stillman, R.A., Forster, R.M., Silva, T. and Bremner, J., 2016. Nuclear power and coastal birds: Predicting the ecological consequences of warm-water outflows. Ecological Modelling, 342: 60-81. |

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| Case study title: | Burry Inlet, UK |
| Location: | 51.656, -4.193 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MOPRH |
| Abstract: | West et al. 2003:The Burry inlet, South Wales, supports a licensed cockle Cerastoderma edule fishery and occasional mussel Mytilus edulis fishery. It is also an important overwintering ground for oystercatchers Haematopus ostralegus. In recent years mussels have settled over parts of some cockle beds, preventing cockle fishery there and leading to a request by shellfishers to remove this ’mussel crumble’. Conservation managers, however, were concerned that the mussel crumble might be providing a high-quality food source for the oystercatchers, making its removal detrimental to the birds. A behaviour-based model of oystercatcher feeding on cockles and mussels was parameterised for the inlet and its predictions tested against the distribution of birds across the shellfish beds and the amount of time they spent feeding. The model was then used to explore whether the birds were currently food-limited and what would be the effects on their mortality rate and body condition if the mussel crumble were to be removed, thereby re-exposing underlying cockle beds. The model predicted successfully the proportion of birds feeding on the different types of food and the number of hours birds spent feeding on neap tides. It was predicted that, at current bird population sizes, there would have to be a 50% reduction in shellfish stocks and the areas of shellfish beds from 2000–01 levels to cause noticeable extra emigration or mortality. A given area of mussel bed was predicted to be able to support more birds than the same area of cockle bed, but the greater area of the cockle beds meant that they were more important than mussels in determining the number of birds supported by the inlet. The simulated removal of mussel crumble to expose underlying cockles had no effect on predicted bird mortality and body condition at 2000–01 shellfish stock levels. However, there were circumstances under which the mussel crumble was predicted to increase the inlet’s capacity to support birds, particularly when the area of existing cockle and mussel beds was substantially reduced.Stillman et al. (2001) © 2001 British Ecological Society: 1. Human interests often conflict with those of wildlife. In the coastal zone humans often exploit shellfish populations that would otherwise provide food for populations of shorebirds (Charadrii). There has been considerable debate on the consequences of shellfishing for the survival of shorebirds, and conversely the effects of shorebird predation on the shellfish stocks remaining for human exploitation. Until now, it has been difficult to determine the impact of current shellfishery practices on birds or to investigate how possible alternative policies would affect their survival and numbers.2. One long‐running contentious issue has been how to manage mussel Mytilus edulis and cockle Cerastoderma edule shellfisheries in a way that has least effect on a co‐dependent shorebird, the oystercatcher Haematopus ostralegus, which also consumes these shellfish. This study used a behaviour‐based model to explore the effects that the present‐day management regimes of a mussel (Exe estuary, UK) and a cockle (Burry inlet, UK) fishery have on the survival and numbers of overwintering oystercatchers. It also explored how alternative regimes might affect the birds.3. The model includes depletion and disturbance as two possibly detrimental effects of shellfishing and some of the longer‐term effects on shellfish stocks. Importantly, model birds respond to shellfishing in the same ways as real birds. They increase the time spent feeding at low tide and feed in fields and upshore areas at other times. When shellfishing removes the larger prey, birds eat more smaller prey.4. The results suggest that, currently, neither shellfishery causes oystercatcher mortality to be higher than it would otherwise be in the absence of shellfishing; at present intensities, shellfishing does not significantly affect the birds. However, they also show that changes in management practices, such as increasing fishing effort, reducing the minimum size of shellfish collected or increasing the daily quota, can greatly affect oystercatcher mortality and population size, and that the detrimental effect of shellfishing can be greatly increased by periods of cold weather or when prey are unusually scarce. By providing quantitative predictions of bird survival and numbers of a range of alternative shellfishery management regimes, the model can guide management policy in these and other estuaries. |
| Funders: | Countryside Council for Wales, Commission of the European Communities, Directorate-General for Fisheries and the Natural Environment Research Council |
| Papers or reports: | West, A.D., Goss-Custard, J.D., McGrorty, S., Stillman, R.A., le V. dit Durell, S.E.A., Stewart, B., Walker, P., Palmer, D.W. and Coates, P.J., 2003. The Burry shellfishery and oystercatchersusing a behaviour-based model to advise on shellfishery management policy. Marine Ecology Progress Series, 248: 279-292.Stillman, R.A., Goss-Custard, J.D., West, A.D., Durell, S.E.A.L.V.D., McGrorty, S., Caldow, R.W.G., Norris, K.J., Johnstone, I.G., Ens, B.J., Van Der Meer, J. and Triplet, P., 2001. Predicting shorebird mortality and population size under different regimes of shellfishery management. Journal of Applied Ecology, 38(4): 857-868. |

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| Case study title: | Burry Inlet / Three Rivers |
| Location: | 51.656, -4.193 |
| Birds: | Oystercatcher, *Haematopus ostralegus*Knot, *Calidris canutus* |
| Modelling: | MORPH |
| Abstract: | Stillman et al. (2008) © CNC/NRW 2009The Burry Inlet Special Protection Area (SPA) supports nationally and internationally important populations of wildfowl and waders which feed on the mudflats and sandflats over the winter period. Oystercatcher feed predominantly on cockles, and knot feed on a range of prey including cockle spat. CCW have commissioned a series of studies to determine the food requirements of oystercatcher and knot, to develop conservation objectives, monitoring targets and to assess the implications of cockle and mussel fishing scenarios on the bird populations. These studies were initiated with the Centre for Ecology and Hydrology (Dorset) and have now been taken on by Bournemouth University. They use an individual behaviour-based model to predict the food requirements of a bird population. The model requires information on bird foraging behaviour together with site-specific data on bird numbers, and the size and distribution of cockle and mussel stocks. Other reports therefore describe surveys of the cockles and mussel in the Burry Inlet (e.g. Moore, 2009) and the distribution and numbers of wading birds (e.g. Banks et al., 2007). The analyses of these combined projects are the subject of the present report. In the model simulations here it is shown that birds move between the Burry Inlet and the nearby Three Rivers Estuary. This shows that the conservation objectives and management of these two sites should not be considered in isolation. The present project also shows that, for the Burry Inlet and Three Rivers Estuary, oystercatchers need twice as much food available than they actually consume in order to maintain high survival rates. This needs to be accounted for in management decisions concerning cockle and mussel fisheries. Although generally not the case during 2004 to 2007, cockle or mussel fishing are capable of decreasing knot and oystercatcher survival rates and the common strategy of harvesting a fixed proportion of the shellfish stock could adversely effect potential fishing yield in years of high stock size and adversely effect birds in years of low stock size. This finding warrants further consideration in the future management of the site. The present study also shows that in 2007 the Burry Inlet could no longer support the population size of oystercatcher for which it was designated and was therefore in an unfavourable conservation condition. Against a back-drop of declining cockle stocks and cockle mass mortalities, the future conservation prospects of the site do not appear to be favourable either. The management of the estuary therefore needs to be addressed and possibly also that of the wider catchment.Stillman et al. (2010) Reproduced with permission from Elservier:We use an individual-based model to assess the conservation objectives for knot Calidris canutus L. and oystercatcher Haematopus ostralegus L. on the Burry Inlet Special Protection Area (SPA), UK. Population monitoring has identified a decline in oystercatcher numbers, but cannot determine whether this is due to a decline in site quality. Long term data on cockle stocks show that the biomass of the large-sized cockles consumed by oystercatcher declined after 2004, whereas a similar decline was not observed in the smaller cockles consumed by knot. The model postdicts that during the winters of 2005/2006 to 2008/2009 the site was unable to support the number of oystercatcher present at the time it was designated (i.e. the SPA population). Large cockle biomass remained low during 2009/2010, but increases in mussel biomass meant that the model postdicted that the site could support the SPA population of oystercatcher. Knot food supplies remained high during most years, except 008/2009 during which the model postdicted that the SPA population could not be supported. The model postdicted that the stock reserved for oystercatchers after shellfishing needed to be 2–4 times the amount consumed by the birds in order to support the bird population. We recommend that where necessary, the conservation objectives of waterbirds should be assessed using a combination of thorough population size and behaviour monitoring to identify sites with population declines, and individual-based modelling on these sites to determine whether reduction in site quality may contribute to the site-specific population decline |
| Funders: | Countryside Council for Wales |
| Papers or reports: | Stillman, R.A., 2008. Predicting the effect of shellfish stocks on the oystercatcher and knot populations of the Burry Inlet and Three Rivers. Countryside Council for Wales Marine Monitoring Report No. 65, Bournemouth University for the Countryside Council for Wales.Stillman, R.A., Moore, J.J., Woolmer, A.P., Murphy, M.D., Walkere, P., Vanstaen, K.R., Palmer, D. and Sanderson, W.G., 2010. Assessing waterbird conservation objectives: An example for the Burry Inlet, UK. Biological Conservation, 143(11): 2617-2630.The 2010 paper supersedes the 2008 report. |

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| Case study title: | Camargue |
| Location: | 43.377037, 4.653244 |
| Birds: | Greater flamingo, *Phoenicopterus roseus* |
| Modelling: | MORPH |
| Abstract: | Overall thesis abstract (MORPH is in chapter 5 but has no English abstract):Understanding and predicting the consequences of land-use changes on species are essential to decrease the negative effects on biodiversity. Salt harvesting in commercial saltpans shaped anthropogenic habitats harboring a typical biodiversity. This is particularly true for the emblematic Greater flamingo (Phoenicopterus roseus) in the Mediterranean basin, saltpans offering foraging and nesting sites to this species. Nevertheless, the saltpans industry currently undergoes profound changes. In the Camargue (southern France), the saltpans of Salin-de-Giraud, which hold the unique French breeding site of the Greater flamingo, recently ceased their activity over half of the surface. The remaining part could be used for other industrial activities. Here, we aim at understanding and predicting the impacts of these changes on the breeding flamingo population, using an individual-based mechanistic model. This model needs three key parameters, the determination of which structured this work: i) the flamingo’ efficiency to ingest food in function of the type and the density of prey, ii) flamingo energy requirements, iii) others environmental factors than food resources explaining flamingos’ distribution in the saltpans. Our results show i) the importance of prey in the water column (e.g. Artemia spp.), easier to filter for flamingos comparing to prey in the sediment, ii) a flamingo preference for simple shaped ponds (i.e. circular) with low and medium salinity (<150 g.l-1), iii) a higher sensitivity of males to a decrease of food resources due to their higher energy requirements comparing to females. This study allowed implementing an individual-based mechanistic model providing a decision-making tool to discuss the future management of the saltpans of Salin-de-Giraud. Our study argues in favour of further use and development of this type of predictive tool to anticipate the effects of land-use changes on biodiversity. We also open up perspectives about the methods available to anticipate these impacts. |
| Funders: | MAVA Foundation, Single Inter-ministerial Fund |
| Papers or reports: | Deville, A.-S., 2013. Besoins énergétiques et distribution spatiale du Flamant rose (Phoenicopterus roseus) dans les salins de Camargue, conséquences de la reconversion du site pour la conservation de l’espèce (Energetic needs and spatial distribution of the Greater Flamingo (Phoenicopterus roseus), salt pans reconversion consequences for the conservation of the species). PhD thesis, Universite Montpellier II. |

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| Case study title: | Cardiff Bay, UK |
| Location: | 51.453, -3.169 |
| Birds: | Redshank, *Tringa totanus* |
| Modelling: | Not MORPH |
| Abstract: | © 2006 by the Ecological Society:In behavior-based individual-based models (IBMs), demographic functions are emergent properties of the model and are not built into the model structure itself, as is the case with the more widely used demography-based IBMs. Our behavior-based IBM represents the physiology and behavioral decision making of individual animals and, from that, predicts how many survive the winter nonbreeding season, an important component of fitness.This paper provides the first test of such a model by predicting the change in winter mortality of a charadriid shorebird following removal of intertidal feeding habitat, the main effect of which was to increase bird density. After adjusting one calibration parameter to the level required to replicate the observed mortality rate before habitat loss, the model predicted that mortality would increase by 3.65%, which compares well with the observed increase of 3.17%. The implication that mortality was density-dependent was confirmed by predicting mortality over a range of bird densities. Further simulations showed that the density dependence was due to an increase in both interference and depletion competition as bird density increased. Other simulations suggested that an additional area of mudflat, equivalent to only 10% of the area that had been lost, would be needed by way of mitigation to return mortality to its original level. Being situated at a high shore level with the flow of water in and out impeded by inlet pipes, the mitigating mudflat would be accessible to birds when all mudflats in the estuary were covered at high tide, thus providing the birds with extra feeding time and not just a small replacement mudflat. Apart from providing the first, and confidence-raising, test of a behavior-based IBM, the results suggest (1) that the chosen calibration procedure was effective; (2) that where no new fieldwork is required, and despite being parameter rich, a behavior-based IBM can be parameterized quickly (few weeks), and thus cheaply, because so many of the parameter values can be obtained from the literature and are embedded in the model; and (3) that behavior- based IBMs can be used to explore system behavior (e.g., the role of depletion competition and interference competition in density-dependent mortality). |
| Funders: | No information provided. |
| Papers or reports: | Goss-Custard, J.D., Burton, N.H.K., Clark, N.A., Ferns, P.N., McGrorty, S., Reading, C.J., Rehfisch, M.M., Stillman, R.A., Townend, I., West, A.D. and Worrall, D.H., 2006. Test of a Behavior-Based Individual-Based Model: Response of Shorebird Mortality to Habitat Loss. Ecological Applications, 16(6): 2215-2222. |
| Case study title: | Colne Estuary |
| Location: | 51.804, 1.016 |
| Birds: | Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Bar-tailed godwit, *Limosa lapponica*Black-tailed gotwit, *Limosa limosa*Redshank, *Tringa tetanus* |
| Modelling: | MORPH |
| Abstract: | 1. A combined empirical and modelling approach was used to investigate the value of a Pacific oyster reef to feeding shorebirds and to observe and predict the impact of reef clearance on bird populations in the Colne Estuary, a protected area in south‐eastEngland. Macro‐invertebrate biomass and numbers of feeding birds were measured on a Pacific oyster reef, an adjacent uncolonized mudflat, and an area of mudflat that had been cleared of oysters 6 months previously. These data were used to parameterize anindividual‐basedmodel (MORPH) to predict the impact of clearance of the reef on winter bird survival. Feeding success and intake rates of Eurasian oystercatcher, Eurasian curlew, and Eurasian common redshank were also recorded during the course of a winter.2. Themacro‐invertebrate diversity and biomass within both the oyster reef and the cleared area were significantly greater than the adjacent uncolonized mudflat. The density and biomass of large invertebrate prey in the mudflat were low, yet the Pacific oyster reef had much higher densities and biomass of large prey, especially annelids and shore crabs. 3. The winter assemblage of feeding birds differed significantly between each of the areas. The mean total number of feeding birds was significantly greater on the uncolonized mudflat; however, mean peak counts, feeding success rate and prey intake rate of Eurasian oystercatcher were greater on the reef. Significantly greaterintake rates and feeding success rates were also observed on the reef for Eurasian curlew, a species of conservation concern.4. Field data and model predictions show that Pacific oyster reefs can provide valuable supplementary feeding areas for some shorebirds, yet other species avoided the reef. However, as estuaries vary in available feeding resources, it is important that the value of reefs and their management is determined regionally. |
| Funders: | Natural England |
| Papers or reports: | Herbert, R.J.H., Davies, C.J., Bowgen, K.M., Hatton, J. and Stillman, R.A., 2018. The importance of nonnative Pacific oyster reefs as supplementary feeding areas for coastal birds on estuary mudflats. Aquatic Conservation: Marine and Freshwater Ecosystems, 28(6): 1294-1307. |

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| Case study title: | Dee Estuary |
| Location: | 53.292, -3.157 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MORPH |
| Abstract: | West and McGrorty 2003: © CNC/NRW 20031. This study of oystercatcher and cockle populations on the Dee Estuary, Traeth Lafan and the Burry Inlet had two main objectives. The first was to assess the power of existing surveys to detect changes in the cockle population at each site and to recommend possible improvements. The second objective was to determine how each site was used by the population of oystercatchers that roosted there.2. Cockle densities at all three sites were highly variable, indicating that cockle Distributions are aggregated. The amount of variation differed between sites and between years within a site. The amount of variance measured at a particular site in any given year was not related to the size of the surveyor the mean cockle density measured.3. Between 200 and 400 0.1 m2 samples appeared to provide a reasonable balance between accuracy and efficient use of time and resources. This level of sampling would allowing on average the detection of a 25-40% decrease or a 30-65% increase in cockle density, depending on the site. Increasing sample numbers above 400 provided a relatively small return in terms of improved accuracy for the extra effort involved.4. A survey scheme is presented which aims to provide a balance between the information needed for fisheries and conservation management purposes. Methods for surveying other common sources of food for oystercatchers are also described.5. WetlandBird Survey (WeBS) low-tide counts show a substantial proportion of the Oystercatcher population feeding outside the areas covered by fisheries cockle stock surveys on all three sites. On the Burry Inlet, these birds are known to be feeding both on cockle patches occurring outside the fisheries survey area and on other sources of food, particularly mussel beds.6. WeBS high-tide counts at each site show substantialvariation,50% or more at every site, in the numbers of oystercatchers roosting at each site from month to month over winter. The total numbers across all sites as a whole also varied considerably.7. Comparison of high and low-tide WeBS counts showed no significant difference between the numbers of oystercatchers roosting on the Dee and feeding there at low tide. More birds appear to feed on Traeth Lafan than the numbers roosting there. On the Burry Inlet, counts show increased bird numbers at low tide during early winter and decreased Numbers at low tide in later months.8. The energy requirements of oystercatchers, combined with physiological constraints on their intake, mean that birds roosting on the Dee could not fly further than the Ribble to feed at low tide. In mid winter when temperatures are lower, they would only profitably be able to fly as far as the Mersey or Alt estuaries.9. High- and low-tide counts on the Dee and surrounding estuaries show that most Oystercatchers that roost on the Alt probably feed in the Mersey. A small proportion of the Dee population may also feed in the Mersey.10. Finally, the implications of this study's findings for modelling the oystercatcher Population of the Dee estuary are discussed.Stillman et al. 2013:In UK estuaries conflicts have routinely occurred between economic and conservation interests regarding shellfish such as cockles *Cerastoderma edule* and mussels *Mytilus edulis*. The harvest of these species is economically important, but shellfish also constitute the main overwinter food supply of the oystercatcher *Haematopus ostralegus*. In this report we use a simplified spreadsheet model to predict the overwinter food requirements of oystercatchers in the Dee Estuary and compare the predictions of this model with those of an individual-based model which has been used to advise the setting of Total Allowable Catch in the Dee Estuary over recent years.The models are based on the energy requirements of the birds and the energy value of their shellfish food. The spreadsheet model predicts the amount of shellfish required to maintain high survival rates within the oystercatcher population. The individual-based model predicts how the survival rate within the oystercatcher population is related to the amount of shellfish food and the amount removed by shellfishing. Although more complicated, the individual-based model represents the system in a more realistic way and can simulate specific shellfishing scenarios.The models produced relatively similar predictions, especially when it was assumed that birds fed on upshore and terrestrial food in addition to cockles. As the biomass of cockles has declined since 2008, the models predicted that the amount required by the birds became close to the total available in 2012. The cockle biomass during 2013 was lower than that during 2012 and the spreadsheet model predicted that the birds required virtually all of the cockle stocks available. |
| Funders: | Countryside Council for Wales, Natural Resources Wales |
| Papers or reports: | West, A.D. and McGrorty, S., 2003. Marine monitoring project: Modelling osytercatchers and their food on the Dee Estuary, Traeth Lafan and Burry Inlet Spa to inform target setting and site management, Centre of Ecology and Hydrology, Dorchester, Dorset.Stillman, R.A. and Wood, K.A., 2013. Predicting oystercatcher food requirements on the Dee Estuary. A report to Natural Resources Wales, Bournemouth University, Poole, Dorset. |
| Case study title: | Doñana, Spain |
| Location: | 36.904929, -6.38513 |
| Birds: | Glossy ibis, *Plegadis falcinellus* |
| Modelling: | MORPH |
| Abstract: | Reproduced with permission from ElservierArtificial wetlands provide alternative habitats for waterbirds. The Doñana rice fields (SW Spain) are extensively used as a foraging site by the glossy ibis (Plegadis falcinellus). The aim of this study was to develop an individual-based model to predict the possible effects of glossy ibis’ population growth, reductions in the rice cultivated area, and changes on the phenology of the management processes of the paddies on the mortality rate of the glossy ibis population. We test the hypothesis that the glossy ibis breeding population of Doñana can obtain its energy requirements during the non-breeding season by feeding on rice fields alone. Our results show that the glossy ibis population growth is not currently limited by rice field availability. However, a reduction of 80% would cause mortality rate increases above the observed mortality (5.9% per year), with values around 10% per year for populations between 50,000 and 100,000 birds. A reduction of 90% of the rice field area would cause mortality rate increase above the observed value for populations greater than 20,000 birds, reaching 60% per year with a population of 100,000 birds. Cultivated area in Doñana suffers temporary reduction on its area during drought periods. Taking into account the fact that the glossy ibis population for 2011 may exceed 22,900 birds, large scale changes in the area of rice fields due to habitat transformations and/or drought periods may have important effects on the viability of the glossy ibis population in Doñana. |
| Funders: | Regional Government of Andalusia (Junta de Andalucía) via the project Las aves acuáticas de Doñana y el cultivo del arroz: la interacción entre la agricultura y la conservación de las zonas húmedas and by the Spanish Ministry of Science and Innovation via project CGL2006-02247/BOS. Gregorio M. Toral was funded by an I3P-CSIC grant for the formation of researchers. |
| Papers or reports: | Toral, G.M., Stillman, R.A., Santoro, S. and Figuerola, J., 2012. The importance of rice fields for glossy ibis (Plegadis falcinellus): Management recommendations derived from an individual-based model. Biological Conservation, 148(1): 19-27. |

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| Case study title: | Exe Estuary (A) |
| Location: | 50.667414, -3.463671 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MORPH |
| Abstract: | Stillman et al. (2000) © 2000 British Ecological Society:1. In order to assess the future impact of a proposed development or evaluate the cost effectiveness of proposed mitigating measures, ecologists must be able to provide accurate predictions under new environmental conditions. The difficulty with predicting to new circumstances is that often there is no way of knowing whether the empirical relationships upon which models are based will hold under the new conditions, and so predictions are of uncertain accuracy.2. We present a model, based on the optimality approach of behavioural ecology, that is designed to overcome this problem. The model's central assumption is that each individual within a population always behaves in order to maximize its fitness. The model follows the optimal decisions of each individual within a population and predicts population mortality rate from the survival consequences of these decisions. Such behaviour‐based models should provide a reliable means of predicting to new circumstances because, even if conditions change greatly, the basis of predictions – fitness maximization – will not.3. The model was parameterized and tested for a shorebird, the oystercatcher Haematopus ostralegus. Development aimed to minimize the difference between predicted and observed overwinter starvation rates of juveniles, immatures and adults during the model calibration years of 1976–80. The model was tested by comparing its predicted starvation rates with the observed rates for another sample of years during 1980–91, when the oystercatcher population was larger than in the model calibration years. It predicted the observed density‐dependent increase in mortality rate in these years, outside the conditions for which it was parameterized.4. The predicted overwinter mortality rate was based on generally realistic behaviour of oystercatchers within the model population. The two submodels that predicted the interference‐free intake rates and the numbers and densities of birds on the different mussel Mytilus edulis beds at low water did so with good precision. The model also predicted reasonably well (i) the stage of the winter at which the birds starved; (ii) the relative mass of birds using different feeding methods; (iii) the number of minutes birds spent feeding on mussels at low water during both the night and day; and (iv) the dates at which birds supplemented their low tide intake of mussels by also feeding on supplementary prey in fields while mussel beds were unavailable over the high water period.5. A sensitivity analysis showed that the model's predictive ability depended on virtually all of its parameters. However, the importance of different parameters varied considerably. In particular, variation in gross energetic parameters had a greater influence on predictions than variations in behavioural parameters. In accord with this, much of the model's predictive power was retained when a detailed foraging submodel was replaced with a simple functional response relating intake rate to mussel biomass. The behavioural parameters were not irrelevant, however, as these were the basis of predictions.6. Although we applied the model to oystercatchers, the general principle on which it is based applies widely. We list the key parameters that need to be measured in order to apply the model to other systems, estimate the time scales involved and describe the types of environmental changes that can be modelled. For example, in the case of estuaries, the model can be used to predict the impact of habitat loss, changes in the intensity or method of shellfishing, or changes in the frequency of human disturbance.7. We conclude that behaviour‐based models provide a good basis for predicting how demographic parameters, and thus population size, would be affected by novel environments. The key reason for this is that, by being based on optimal decision rules, animals in these models are likely to respond to environmental changes in the same way as real ones would.Stillman et al. (2001) © 2001 British Ecological Society:1. Human interests often conflict with those of wildlife. In the coastal zone humans often exploit shellfish populations that would otherwise provide food for populations of shorebirds (Charadrii). There has been considerable debate on the consequences of shellfishing for the survival of shorebirds, and conversely the effects of shorebird predation on the shellfish stocks remaining for human exploitation. Until now, it has been difficult to determine the impact of current shellfishery practices on birds or to investigate how possible alternative policies would affect their survival and numbers.2. One long‐running contentious issue has been how to manage mussel Mytilus edulis and cockle Cerastoderma edule shellfisheries in a way that has least effect on a co‐dependent shorebird, the oystercatcher Haematopus ostralegus, which also consumes these shellfish. This study used a behaviour‐based model to explore the effects that the present‐day management regimes of a mussel (Exe estuary, UK) and a cockle (Burry inlet, UK) fishery have on the survival and numbers of overwintering oystercatchers. It also explored how alternative regimes might affect the birds.3. The model includes depletion and disturbance as two possibly detrimental effects of shellfishing and some of the longer‐term effects on shellfish stocks. Importantly, model birds respond to shellfishing in the same ways as real birds. They increase the time spent feeding at low tide and feed in fields and upshore areas at other times. When shellfishing removes the larger prey, birds eat more smaller prey.4. The results suggest that, currently, neither shellfishery causes oystercatcher mortality to be higher than it would otherwise be in the absence of shellfishing; at present intensities, shellfishing does not significantly affect the birds. However, they also show that changes in management practices, such as increasing fishing effort, reducing the minimum size of shellfish collected or increasing the daily quota, can greatly affect oystercatcher mortality and population size, and that the detrimental effect of shellfishing can be greatly increased by periods of cold weather or when prey are unusually scarce. By providing quantitative predictions of bird survival and numbers of a range of alternative shellfishery management regimes, the model can guide management policy in these and other estuaries. |
| Funders: | Commission of the European Communities, Directorate-General for Fisheries and the Natural Environment Research Council |
| Papers or reports: | Stillman, R.A., Goss-Custard, J.D., West, A.D., Durell, S.E.A.L.V.D., Caldow, R.W.G., McGrorty, S. and Clarke, R.T., 2000. Predicting mortality in novel environments: tests and sensitivity of a behaviour-based model. Journal of Applied Ecology, 37(4): 564-588.Stillman, R.A., Goss-Custard, J.D., West, A.D., Durell, S.E.A.L.V.D., McGrorty, S., Caldow, R.W.G., Norris, K.J., Johnstone, I.G., Ens, B.J., Van Der Meer, J. and Triplet, P., 2001. Predicting shorebird mortality and population size under different regimes of shellfishery management. Journal of Applied Ecology, 38(4): 857-868. |

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| Case study title: | Exe Estuary (B) |
| Location: | 50.667414, -3.463671 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MORPH |
| Abstract: | In a number of extensive coastal areas in northwest Europe, large numbers of long-lived migrant birds eat shellfish that are also commercially harvested. Competition between birds and people for this resource often leads to conflicts between commercial and conservation interests. One policy to prevent shellfishing from harming birds is to ensure that enough food remains after harvesting to meet most or all of their energy demands. Using simulations with behaviour-based models of five areas, we show here that even leaving enough shellfish to meet 100% of the birds’ demands may fail to ensure that birds survive in good condition. Up to almost eight times this amount is needed to protect them from being harmed by the shellfishery, even when the birds can consume other kinds of non-harvested prey. |
| Funders: | No information provided. |
| Papers or reports: | Goss-Custard, J.D., Stillman, R.A., West, A.D., Caldow, R.W.G., Triplet, P., le V dit Durell, S.E.A. and McGrorty, S., 2004. When enough is not enough: shorebirds and shellfishing. Proceedings of the Royal Society B: Biological Sciences, 271(1536): 233-237. |

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| Case study title: | Exe Estuary (C) |
| Location: | 50.667414, -3.463671 |
| Birds: | Brent geese, *Branta bernicla* |
| Modelling: | Not MORPH |
| Abstract: | This is the final report for the joint English Nature and Centre for Ecology and Hydrology (CEH) project entitled “Estuary Special Protection Areas – Establishing Baseline Targets for Shorebirds”. The aim of this project was to use individual-based models, comprised of fitness-maximising individuals, to predict how changes in the mortality rate and body condition of wader and wildfowl populations are related to the amount of food and human disturbance within a site. Individual-based models predict population level responses, such as mortality rate, from the combined behavioural responses of the individual animals within a population. An important aspect of the models developed in the project is that the behavioural decisions of model animals are derived from fitness-maximising decision rules (for example, animals attempt to maximise their chances of surviving starvation by feeding in locations in which prey are most abundant, or can be consumed most rapidly). As real animals are thought to use similar decision rules, model animals should behave in similar ways to real animals.Models were applied to four Special Protection Areas (SPAs), the Humber estuary, the Wash, Poole harbour and the Exe estuary, to predict the food abundances required to maintain low shorebird and wildfowl mortality rates and high body conditions. The major site-specific predictions were as follows.* *Humber estuary shorebirds*. Nine shorebird species were modelled; dunlin, ringed plover, knot, redshank, grey plover, black-tailed godwit, bar-tailed godwit, oystercatcher and curlew. The model predicted that the presence of fields around the estuary provided supplementary feeding areas which increased the survival rates of curlew. With the exception of curlew, shorebird survival rates fell below 90% when autumn, estuary-wide food biomass density was below about 4 g AFDM m-2. Curlew survival rates fell when food biomass density decreased below 8 g AFDM m-2. Prey biomass densities for all species except curlew were above the threshold prey density below which survival rates were predicted to decline. Shorebird survival was most strongly influenced by the biomass densities of annelid worms, and the bivalve molluscs *Cerastoderma edule* and *Macoma balthica*. It was unaffected by the biomass densities of *Corophium* and *Hydrobia*.
* *Wash shorebirds*. Eight shorebird species were modelled; dunlin, knot, redshank, grey plover, black-tailed godwit, bar-tailed godwit, oystercatcher and curlew. Shorebird survival rates fell below 100%, i.e. birds began to starve, when autumn, estuary-wide food biomass density was below about 5g AFDM m-2 and fell below 90% at 4g AFDM m-2. Prey biomass densities for all species were above the threshold prey density below which survival rates were predicted to decline. Shorebird survival was most strongly influenced by the biomass densities of *Arenicola* and other annelid worms, and the bivalve molluscs *Cerastoderma edule* and *Macoma balthica*. It was unaffected by the biomass densities of *Corophium* and *Hydrobia*. The survival of most species in the model remained high at fewer than 20 disturbances per hour, but bar-tailed godwit and curlew were affected at disturbance rates as low as two per hour.
* *Poole harbour shorebirds*. Five shorebird species were modelled; dunlin, redshank, black-tailed godwit, oystercatcher and curlew. The model predicted that dunlin, redshank, black-tailed godwit and oystercatcher survival would start to decline when prey biomass densities dropped below 3 g AFDM m-2. Prey biomass densities for dunlin, redshank and oystercatchers were well above this, indicating that these three species would be less vulnerable to declines in their food supply. However, black-tailed godwit prey biomass densities were very close to this level. Curlew survival was not predicted to decline until prey biomass densities dropped below 2 g AFDM m-2, probably because curlew fed extensively in surrounding fields on terrestrial prey. However, mean prey biomass densities measured for curlew were close to this value, and the 95% confidence limits below it. Shorebird survival was most strongly influenced by the biomass densities of *Arenicola* and other annelid worms, earthworms and the bivalve molluscs *Cerastoderma edule* and *Macoma balthica*. It was unaffected by the biomass densities of *Corophium* and *Hydrobia*.
* *Exe estuary shorebirds*. Six shorebird species were modelled; dunlin, grey plover, black-tailed godwit, bar-tailed godwit, oystercatcher and curlew. Two models were developed. The simplified model (A) was comparable to those developed for the Humber estuary, Wash and Poole harbour. The more detailed model (B) incorporated more aspects of the behaviour and ecology of the shorebirds. In Model A, the response of shorebird survival to reductions in prey biomass densities were very similar to those obtained for the Humber, the Wash and Poole Harbour. In Model B, however, shorebird survival started to decrease at higher prey biomass densities and the decline in survival with prey biomass was much more gradual. We believe that this is likely to be the more realistic scenario and that threshold prey biomass densities for shorebird survival should not be regarded as around 3-4 g AFDM m-2 as suggested in previous models, but as around 8-10 g AFDM m-2. All prey biomass densities on the Exe were as high, or higher, than those measured on other estuaries in this Report. Using Model A, no shorebird species appeared to be vulnerable to declines in their prey biomass densities. With Model B, however, curlew and bar-tailed godwit survival started to decline with prey biomass densities below the 95% confidence interval. It is likely, therefore, that curlew and bar-tailed godwit are the species most likely to be vulnerable to declines in their food supply in the Exe estuary.
* *Exe estuary brent geese*. The time at which Brent geese switch from feeding on *Zostera* to feeding on pastures is affected by the abundance of *Zostera*. A reduction in *Zostera* abundance will bring forward the switch date and an increase will delay it. Accordingly, the number of goose days that *Zostera* supports before the switch is complete will be reduced if *Zostera* abundance declines and will increase if it rises. This general pattern is little affected either by the assumed efficiency with which geese exploit the *Zostera* or by the percentage of time lost to disturbance on the *Zostera* beds during daylight (subject to the proviso that access at night is undisturbed). Moreover, the birds end of winter body condition and over-winter survival is unaffected by any changes to the abundance or availability of *Zostera*. Rather, the well-being of the Brent goose population on the Exe is much more dependent upon the availability of grass pastures on which they feed for the bulk of their winter stay on the estuary.

The following general recommendations (in *italics*) can be derived from the site and system-specific predictions detailed above.* *Monitor bird food resources as well as bird numbers*. The conservation importance of an estuary is often measured in terms of bird numbers using the estuary, but monitoring numbers is not necessarily a reliable way of assessing changes in site quality. In particular, this is because the numbers of birds using a site depend not only on the conditions at the site, but also the conditions at other sites both within the non-breeding and breeding seasons. The models developed in this project predict site quality as the survival rate of birds on a site rather than simply the numbers of birds on the site. When food is abundant, survival rates are high, but survival decreases when food abundance declines below a threshold value. From this is it possible to derive critical amounts of food required to maintain high body mass and survival. *A recommendation derived from these predictions would be to establish a monitoring programme to record the abundance of food on sites at the start of winter as well as continuing the usual procedure of monitoring bird numbers.* If resources are limited, surveys should be restricted to Annelid worms, earthworms and bivalves (the key species predicted to affect shorebird survival in this study). Provided that bird densities are comparable to those on the Humber estuary, Wash, Poole harbour and Exe estuary, an initial food supply in excess of 8-10 g afdm m-2, would be predicted to maintain high shorebird survival.
* *Monitor the use of marginal habitats and feeding times*. The models developed during this project all predicted that birds fed in the most profitable and safest places and times when feeding conditions were good and survival rates high, behaviour which mimicked that of real birds. In contrast, birds were predicted to feed more in marginal habitats or at more risky times when feeding conditions were poorer, again behaviour which mimicked that of real birds. *A recommendation would be to establish a monitoring programme to detect such changes in the behaviour of bird populations as an early warning that survival rates are likely to be falling*. This approach would pick up possible detrimental changes on a site before increases in mortality rate could be detected through traditional approaches based on bird ringing programmes, increasing the chance that management can be implemented to improve conditions before bird survival declines greatly.
* *Include terrestrial habitats in conservation areas*. The models predicted that terrestrial habitats were often critical for the survival of waders and geese, even though these habitats are often considered as marginal habitats. These habitats are often excluded from the designation of Special Protection Areas, but this means that vital habitat is not being protected and as a result may be lost to building developments, suffer high disturbance levels or simply be subject to changes in the way in which it is managed. *A simple recommendation derived from these predictions is that wherever possible conservation areas should include the terrestrial habitats around estuaries as well as the intertidal habitats of the estuary itself.* This would ensure that the full range of habitats required by birds is protected.
* *Further understand the response to disturbance*. The disturbance experiments conducted during the study show considerable flexibility in the response to disturbance. Birds were more tolerant of human presence in parts of the Wash in which they more frequently encountered humans. Oystercatchers and brent goose feeding on recreational grassland in Poole harbour, in which they frequently encountered people and dogs, were very tolerant, usually only walking away from people rather than flying. The response to disturbance can be viewed as a trade-off between avoiding the perceived threat of the disturbance and the cost of moving. Increased tolerance of human presence (i.e. a reduced response to disturbance) will occur either if birds perceive the disturbance of less of a threat and / or if the detrimental effects of avoiding the disturbance are greater. In conservation terms the second situation is what needs to be avoided. It is less serious if birds can simply adapt to increased disturbance by learning that the disturbance source is less of a threat. Unfortunately, it is difficult or impossible to separate these two alternatives using the data collected in many disturbance studies. *A recommendation is that future disturbance studies should aim to determine why birds respond to disturbance sources in the way they do, rather than simply measuring the response to disturbance alone.*

This project used individual-based models to predict how site quality depends on the food density and levels of disturbance in the site. The survival rates of most shorebirds and brent goose were predicted to be high with the current biomass densities of food and current rates of disturbance. Target food biomass can be determined as biomass per bird in situations in which a resource is mainly consumed by one species, such as oystercatchers consuming large bivalves. However, this is not possible in multi-species situations and so the more simple measure of food biomass at the start of winter was used in the multi-species models developed during this project. Provided that bird densities are comparable to those on the Humber estuary, Wash, Poole harbour and Exe estuary, an initial food supply in excess of 8-10 g afdm m-2, is predicted to maintain high shorebird survival. |
| Funders: | English Nature |
| Papers or reports: | Stillman, R.A., West, A.D., le V dit Durell, S.E.A., Caldow, W.R.G., McGrorty, S., Yates, M.G., Garbutt, R.A., Yates, T.J., Rispin, W.E. and Frost, N.J., 2005. Estuary Special Protection Areas - Establishing baseline targets for shorebirds, Centre for Ecology and Hydrology, Dorchester, Dorset. Chapter 10. |

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| Case study title: | Exe Estuary (D) |
| Location: | 50.667414, -3.463671 |
| Birds: | Grey plover, *Pluvialis squatarola*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Bar-tailed godwit, *Limosa lapponica*Black-tailed godwit, *Limosa limosa*Dunlin, *Calidris alpina* |
| Modelling: | MORPH |
| Abstract: | Stillman et al. (2005a): No abstract, but a very long summary, so not provided here.Stillman et al. (2005b): No abstract, but a very long summary, so not provided here.Durell et al. (2007):We used an individual-based model to assess site quality and to predict the effect of local (i.e. disturbance from a cycle path) and global (i.e. climate change) environmental change on the survival of six species of overwintering shorebirds on the Exe estuary, U.K. We also compare site quality on the Exe estuary with three other estuary Special Protection Areas (SPAs) and compare our predictions for the effects of climate change with predictions made for another southern U.K. estuary, Poole Harbour. Prey biomass densities in the Exeestuary were high for all six shorebirds, being as high as or higher than those found on other estuary SPAs. Simulations of increased levels of disturbance from a proposed cycle path along the side of the estuary predicted that disturbance of upper mudflat areas was unlikely to affect shorebird survival but that increased disturbanceof nearby fields would reduce curlew survival. Shorebirds on the Exe estuary were far less seriously affected than those in Poole Harbour by reductions in mean daily temperatures, loss of terrestrial habitats and simulated sea-level rise. We conclude that the Exe estuary is a high quality estuary and that the shorebird populations modelled were less susceptible to climate change than those in Poole Harbour. |
| Funders: | European Commission, English Nature |
| Papers or reports: | Stillman et al. (2005a, Chapter 9):Stillman, R.A., West, A.D., le V dit Durell, S.E.A., Caldow, W.R.G., McGrorty, S., Yates, M.G., Garbutt, R.A., Yates, T.J., Rispin, W.E. and Frost, N.J., 2005. Estuary Special Protection Areas - Establishing baseline targets for shorebirds, Centre for Ecology and Hydrology, Dorchester, Dorset.Stillman et al. (2005b):Stillman, R.A., Caldow, R.W.G., le V. dit Durell, S.E.A., West, A.D., McGrorty, S., Goss-Custard, J.D., Pérez-Hurtado, A., Castro, M., Estrella, S., Masero, J.A., Rodríguez-Pascual, F.H., Triplet, P., Loquet, N., Desprez, M., Fritz, H., Clausen, P., Ebbinge, B., Norris, K. and Mattison, E., 2005. Coastal bird diversity. Maintaining migratory coastal bird diversity: management through individual-based predictive population modelling. Centre for Ecology and Hydrology, Winfrith Newburgh, Dorset.Durell et al. (2007):Durell, S.E.A.L.V.d., Stillman, R.A., McGrorty, S., West, A.D. and Price, D.J., 2007. Predicting the effect of local and global environmental change on shorebirds: a case study on the Exe estuary, U.K. Wader Study Group Bulletin, 112: 24-36. |

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| Case study title: | Exe Estuary (E) |
| Location: | 50.667414, -3.463671 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | MORPH |
| Abstract: | http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/The purpose of this project was to assess the mussel (*Mytilus edulis*) food requirements of oystercatcher (*Haematopus ostralegus*) in the Exe Estuary, which has been designated a Special Protection Area for overwintering waterbirds, including oystercatcher. The overwintering oystercatcher population of the Exe Estuary has been well-studied, and the birds are known to feed predominantly upon mussels in intertidal areas. There have been recent declines in the population size of oystercatcher in the Exe Estuary, mirroring wider declines throughout Europe, the reasons for which are unknown.The study comprised:* The collection of new data on the area of mussel beds, the density and size distribution of mussels on these beds, and the numbers and behaviour of oystercatcher on these beds;
* The collation of existing data on the food supply of oystercatchers in the Exe Estuary;
* The development of models to predict the food requirements of oystercatcher;
* Running simulations of the models to predict whether there is / could be any effect on oystercatcher survival of the current / potential future ways of managing the mussel fishery on the Exe Estuary.

The current mussel fishery on the Exe provides a feeding resource for oystercatcher on intertidal lays that are exposed on spring tides. Two potential management options that could be effective at improving the feeding conditions of oystercatcher would be to increase the number and area of intertidal mussel lays, and / or to place mussel discards at a relatively high shore level close to the oystercatcher roost.This project documented a number of changes that have occurred to the Exe Estuary mussel and oystercatcher populations including:* The number and size of mussel beds have decreased since traditional methods of maintaining mussel beds in the estuary have ceased.
* The density of mussels within the size range consumed by the birds has generally decreased, but the density of the larger mussels within this size range, which are more profitable to oystercatcher, has generally increased.
* Oystercatcher lose a higher proportion of mussels to attacks by carrion crows and herring gulls than they have in the past.
* The number of oystercatcher wintering in the estuary has declined, but the number of birds feeding on the mussel beds has been relatively stable.

The models developed in the project predict that the present day mussel population is sufficient to support the number of oystercatcher that were observed to feed on mussels.The presence of mussel lays provides extra food for oystercatcher when these lays are exposed on spring tides. The present area, or increases in the area of mussel lays could increase the survival rate of oystercatcher if the number of birds feeding on mussels was over 2000. Below this threshold, starvation was predicted to affect 0 % of the population and so additional food resources cannot further reduce the starvation. The effect over 2000 birds is relatively small because the lays are only exposed for a short time, and so oystercatcher will obtain the majority of their food from mussel beds that are higher on the shore, and hence exposed for longer. Simulations were not run in which lays were positioned higher on the shore because this would not be commercially viable from a fishery perspective; the growth rate of mussels declines as they are positioned further up the shore because they are inundated with water for less time and so have less time to feed. Factors that would affect the beneficial effect of discards include the size of the discards, the size of the discard bed and the date from which discards are replenished. Our simulations predicted that larger discards spread at lower density over a larger bed increased oystercatcher survival by the greatest amount. This happened because interference competition excluded some birds from smaller patches, and oystercatcher can maintain high intake rate down to low mussel densities. It is unlikely that the size of discards could be increased, but the simulations suggest that the greatest benefit to oystercatchers could be achieved by spreading discards over a larger area. Our simulations predicted that making discards available from January increased oystercatcher survival by the same amount as making them available from September. This was because the feeding conditions of birds deteriorate through winter as, for example, the ash-free dry mass of prey declines, interference competition intensifies and day length shortens. The intake rate of birds feeding on discards was not measured during the study, but we recommend that this is done to between understand the potential benefit of discards. We recommend that the best place for the discard bed would be along the top of the shore on an area of gravel (and hence of relatively low food value to the birds), to the south of Cockwood. This is south of an area where discards have been laid and exploited by oystercatcher in the past, but would experience lower levels of disturbance from human activity. |
| Funders: | Natural EnglandIPENS programme (LIFE11NAT/UK/000384IPENS) which is financially supported by LIFE, a financial instrument of the European Community. |
| Papers or reports: | Stillman, R.A., Goss-Custard, J.D. and Wood, K.A., 2014. Predicting the mussel food requirements of oystercatchers in the Exe Estuary, Bournemouth University / Natural England, Bournemouth / Exeter.http://publications.naturalengland.org.uk/publication/5406546051727360 |

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| Case study title: | Exe Estuary (F) |
| Location: | 50.667414, -3.463671 |
| Birds: | Grey plover, *Pluvialis squatarola*Oystercatcher, *Haematopus ostralegus*Black-tailed godwit, *Limosa limosa*Dunlin, *Calidris alpine*Curlew, *Numenius arquata*Bar-tailed godwit, *Limosa lapponica*Common redshank, *Tringa totanus*Turnstone, *Arenaria interpres* |
| Modelling: | MORPH |
| Abstract: | With the pressures that today’s ecosystems are being placed under, from both environmental change and anthropogenic developments, the speed at which management decisions need to be made has increased. Coastal development means that estuaries are particularly affected and their characteristic species, like wading birds (Charadrii), are now experiencing worldwide declines. In such situations there is a need for predictive ecology to understand in advance how species might react to future changes.This thesis looks into how we can use individual-based models (IBM) to make accurate predictions of how wading birds are affected by environmental change. Starting with previously validated models I show the importance of measuring size of invertebrates though an IBM investigation into regime shifts and wading birds responses. The models show that by altering their diet preferences, birds adapt to regime shifts in their prey but that this maintenance of population size masks the true changes in the system and limits the use of waders as direct bio-indicators of ecosystem health. Using the current literature, an analysis on empirical responses of wader populations to environmental change revealed the lack of comparability between studies and the scarcity of studies on small scale events.Data from literature and fieldwork was used to develop a comparable suite of individual-based models for five UK estuaries with up to eleven wading bird species. These models were validated using current BTO Wetland Bird Surveys data to increase confidence in final results. Using these new models, investigations of population thresholds and environmental change were carried out. Increases to current populations revealed that several estuaries are no longer able to support the number of birds around the time of Special Protection Area designation. This, alongside higher populations currently seen since the years of designation, indicates the need for re-assessment of SPA species numbers. When looking at the impacts of two types of environmental change, habitat loss and sea-level rise, certain species declined predictably across sites whilst the individual make up of each estuary had particular impacts on some waders more than others. The work of this thesis further indicates the great potential of using individual-based models to predict the effects of a wide range of environmental changes. With the new models and a quicker and systematic way of developing IBMs for additional areas, wecan aid the conservation and management of estuarine systems for wading birds. |
| Funders: | Bournemouth University and HR Wallingford |
| Papers or reports: | Bowgen, K.M., 2016. Predicting the effect of environmental change on wading birds: insights from individual-based models. PhD thesis, Bournemouth University in collaboration with HR Wallingford. |

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| Case study title: | Exe Estuary (G) |
| Location: | 50.667414, -3.463671 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | MORPH |
| Abstract: | Oystercatchers Haematopus ostralegus arriving on their wintering grounds at the end of summer require 6 to 8 times more mussel Mytilus edulis biomass to be available on their feeding grounds than they will consume over the winter if the birds’ normal high survival rate until spring is to be maintained. In other words, their ecological requirement (ER) is considerably larger than their physiological requirement (PR). The ecological multiplier (EM) is the ratio of ER:PR and has been applied to a number of shellfisheries to calculate the total allowable catch (TAC). The high value of the EM, however, has meant that mussel fisheries have suffered from much-reduced harvests and thus economic difficulties. This paper proposes 2 methods by which the TAC could be increased with no predicted impact on the birds. In the ‘roll-over’ approach, the surplus biomass remaining at the end of a given month is harvested during the next. In the ‘delayed start’ approach, the EM is not set at the beginning of autumn but at the beginning of the winter, which is when birds begin to starve. The 2 approaches can be applied together and would enable many more mussels to be harvested than is currently allowed without reducing oystercatcher survival. In the test case presented here, the TAC over the winter could be increased from 5% to between 35 and 45% of the standing crop of mussels present in September when the birds arrive. |
| Funders: | No information provided |
| Papers or reports: | Goss-Custard, J.D., Bowgen, K.M. and Stillman, R.A., 2019. Increasing the harvest for mussels Mytilus edulis without harming oystercatchers Haematopus ostralegus. Marine Ecology Progress Series, 612: 101-110. |

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| Case study title: | Fehmarnbelt, Germany |
| Location: | 54.517832, 11.237025 |
| Birds: | Eider, *Somateria mollissima* |
| Modelling: | MORPH |
| Abstract: | Unable to contact report authors. Please see below for weblinks to abstract. |
| Funders: | DHI / BioConsult SH Consortium in association with University of Copenhagen and BIOLA. European Union Trans-European Transport Network |
| Papers or reports: | FEBI, 2013a. Fehmarnbelt Fixed Link EIA. Bird Investigations in Fehmarnbelt – Baseline. Volume II. Waterbirds in Fehmarnbelt. Report No. E3TR0011, DHI, Hørsholm, Denmark. https://vvmdocumentation.femern.com/26.%20E3TR0011%20Vol%20II789b.pdf?filename=files/BR/26.%20E3TR0011%20Vol%20II.pdfFEBI, 2013b. Fehmarnbelt Fixed Link Bird Services (FEBI). Fauna and Flora - Birds – Impact Assessment. Birds of the Fehmarnbelt Area. E3TR0015, DHI, Hørsholm, Denmark. https://vvmdocumentation.femern.com/25.%20E3TR0015%20Vol%20I8099.pdf?filename=files/BR/25.%20E3TR0015%20Vol%20I.pdf |

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| Case study title: | Humber Estuary (A) |
| Location: | 53.719897, -0.278445 |
| Birds: | Grey plover, *Pluvialis squatarola*Ringed plover, *Charadrius hiaticula*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Bar-tailed godwit, *Limosa lapponica*Black-tailed gotwit, *Limosa limosa*Dunlin, *Calidris alpine*Knot, *Calidris canutus*Redshank, *Tringa totanus* |
| Modelling: | Not MORPH |
| Abstract: | The conservation importance of estuaries is often measured by bird numbers, but monitoring numbers is not necessarily a reliable way of assessing changes in site quality. We used an individual-based model, comprised of fitness-maximising individuals, to assess the quality of the Humber estuary, UK, for 9 shorebirds; dunlin Calidris alpina, common ringed plover Charadrius hiaticula, red knot Calidris canutus, common redshank Tringa totanus, grey plover Pluvialis squatarola, blacktailed godwit Limosa limosa, bar-tailed godwit L. lapponica, Eurasian oystercatcher Haematopus ostralegus and Eurasian curlew Numenius arquata. We measured site quality as predicted overwinter survival. The model accurately predicted the observed shorebird distribution (if non-starving birds were assumed to feed on any prey or patch on which intake rate equalled or exceeded their requirements), and the diets of most species. Predicted survival rates were highest in dunlin and common ringed plovers, the smallest species, and in Eurasian oystercatchers, which consumed larger prey than the other species. Shorebird survival was most strongly influenced by the biomass densities of annelid worms, and the bivalve molluscs Cerastoderma edule and Macoma balthica. A 2 to 8 % reduction in intertidal area (the magnitude expected through sea level rise and industrial developments) decreased predicted survival rates of all species except the dunlin, common ringed plover, red knot and Eurasian oystercatcher. This paper shows how an individual-based model can assess present-day site quality and predict how site quality may change in the future. The model was developed using existing data from intertidal invertebrate and bird monitoring schemes plus new intertidal invertebrate data collected over 2 winters. We believe that individual-based models are useful tools for assessing estuarine site quality. |
| Funders: | ABP Marine Environmental Research and English Nature |
| Papers or reports: | Stillman, R.A., West, A.D., Goss-Custard, J.D., McGrorty, S., Frost, N.J., Morrisey, D.J., Kenny, A.J. and Drewitt, A.L., 2005. Predicting site quality for shorebird communities: a case study on the Humber estuary, UK. Marine Ecology Progress Series, 305: 203-217. |

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| Case study title: | Humber Estuary (B) |
| Location: | 53.719897, -0.278445 |
| Birds: | Grey plover *Pluvialis squatarola*Ringed plover *Charadrius hiaticula*Oystercatcher *Haematopus ostralegus*Curlew *Numenius arquata*Bar-tailed godwit *Limosa lapponica* Black-tailed godwit *Limosa limosa* Dunlin *Calidris alpina*Knot *Calidris canutus*Redshank *Tringa totanus*  |
| Modelling: | MORPH |
| Abstract: | With the pressures that today’s ecosystems are being placed under, from both environmental change and anthropogenic developments, the speed at which management decisions need to be made has increased. Coastal development means that estuaries are particularly affected and their characteristic species, like wading birds(Charadrii), are now experiencing worldwide declines. In such situations there is a need for predictive ecology to understand in advance how species might react to future changes.This thesis looks into how we can use individual-based models (IBM) to make accurate predictions of how wading birds are affected by environmental change. Starting with previously validated models I show the importance of measuring size of invertebrates though an IBM investigation into regime shifts and wading birds responses. The models show that by altering their diet preferences, birds adapt to regime shifts in their prey but that this maintenance of population size masks the true changes in the system and limits the use of waders as direct bio-indicators of ecosystem health. Using the current literature, an analysis on empirical responses of wader populations to environmental change revealed the lack of comparability between studies and the scarcity of studies on small scale events.Data from literature and fieldwork was used to develop a comparable suite of individual-based models for five UK estuaries with up to eleven wading bird species. These models were validated using current BTO Wetland Bird Surveys data to increase confidence in final results. Using these new models, investigations of population thresholds and environmental change were carried out. Increases to current populations revealed that several estuaries are no longer able to support the number of birds around the time of Special Protection Area designation. This, alongside higher populations currently seen since the years of designation, indicates the need for re-assessment of SPA species numbers. When looking at the impacts of two types of environmental change, habitat loss and sea-level rise, certain species declined predictably across sites whilst the individual make up of each estuary had particular impacts on some waders more than others. The work of this thesis further indicates the great potential of using individual-based models to predict the effects of a wide range of environmental changes. With the new models and a quicker and systematic way of developing IBMs for additional areas, wecan aid the conservation and management of estuarine systems for wading birds. |
| Funders: | Bournemouth University and HR Wallingford |
| Papers or reports: | Bowgen, K.M., 2016. Predicting the effect of environmental change on wading birds: insights from individual-based models. PhD thesis, Bournemouth University in collaboration with HR Wallingford. |

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| Case study title: | Humboldt Bay |
| Location: | 40.752182, -124.215369 |
| Birds: | Black brant *Branta bernicula nigricans* |
| Modelling: | MORPH |
| Abstract: | Changes in climate, food abundance and disturbance from humans threaten the ability of species to successfully use stopover sites and migrate between non-breeding and breeding areas. To devise successful conservation strategies for migratory species we need to be able to predict how such changes will affect both individuals and populations. Such predictions should ideally be process-based, focusing on the mechanisms through which changes alter individual physiological state and behavior. In this study we use a process-based model to evaluate how Black Brant (Branta bernicla nigricans) foraging on common eelgrass (Zostera marina) at a stopover site (Humboldt Bay, USA), may be affected by changes in sea level, food abundance and disturbance. The model is individual-based, with empirically based parameters, and incorporates the immigration of birds into the site, tidal changes in availability of eelgrass, seasonal and depth-related changes in eelgrass biomass, foraging behavior and energetics of the birds, and their mass-dependent decisions to emigrate. The model is validated by comparing predictions to observations across a range of system properties including the time birds spent foraging, probability of birds emigrating, mean stopover duration, peak bird numbers, rates of mass gain and distribution of birds within the site: all 11predictions were within 35%of the observed value, and 8 within 20%. The model predicted that the eelgrass within the site could potentially support up to five times as many birds as currently use the site. Future predictions indicated that the rate of mass gain and mean stopover duration were relatively insensitive to sea level rise over the next 100 years, primarily because eelgrass habitat could redistribute shoreward into intertidal mudflats within the site to compensate for higher sea levels. In contrast, the rate of mass gain and mean stopover duration were sensitive to changes in total eelgrass biomass and the percentage of time for which birds were disturbed. We discuss the consequences of these predictions for Black Brant conservation. A wide range of migratory species responses are expected in response to environmental change. Process-based models are potential tools to predict such responses and understand the mechanisms which underpin them. |
| Funders: | Ducks Unlimited, Inc., funded this study (Project US-RS-14-2). |
| Papers or reports: | Stillman, R.A., Wood, K.A., Gilkerson, W., Elkinton, E., Black, J.M., Ward, D.H. and Petrie, M., 2015. Predicting effects of environmental change on a migratory herbivore. Ecosphere, 6(7). |

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| Case study title: | Izembek, USA |
| Location: | 55.289, -162.678 |
| Birds: | Blank brant, *Branta bernicula nigricans* |
| Modelling: | MORPH |
| Abstract: | Climate change is driving worldwide shifts in the distribution of biodiversity, and fundamental changes to global avian migrations. Some arctic-nesting species may shorten their migration distance as warmer temperatures allow them to winter closer to their high-latitude breeding grounds. However, such decisions are not without risks, since this intensifies pressure on resources when they are used for greater periods of time. In this study, we used an individual-based model to predict how future changes in food abundance, winter ice coverage, and human disturbance could impact an Arctic / sub-Arctic breeding goose species, black brant (Branta bernicla nigricans, Lawrence 1846), and their primary food source, common eelgrass (Zostera marina L.), at the Izembek Lagoon complex in southwest Alaska. Brant use the site during fall and spring migrations, and increasingly, for the duration of winter. The model was validated by comparing predictions to empirical observations of proportion of geese surviving, proportion of geese emigrating, mean duration of stay, mean rate of mass gain / loss, percentage of time spent feeding, number of bird days, peak population numbers, and distribution across the complex. The model predicted that reductions > 50% of the current decadal (2007–2015) mean of eelgrass biomass, which have been observed in some years, or increases in the number of brant, could lead to a reduction in the proportion of birds that successfully migrate to their breeding grounds from the site. The model also predicted that access to eelgrass in lagoons other than Izembek was critical for overwinter survival and spring migration of brant, if overall eelgrass biomass was 50% of the decadal mean biomass. Geese were typically predicted to be more vulnerable to environmental change during winter and spring, when eelgrass biomass is lower, and thermoregulatory costs for the geese are higher than in fall. We discuss the consequences of these predictions for goose population trends in the face of natural and human drivers of change. |
| Funders: | Izembek National Wildlife Refuge, US Geological Survey, US Fish and Wildlife Service |
| Papers or reports: | Stillman, R.A., Rivers, E.M., Gilkerson, W., Wood, K.A., Golicher, J.D., Nolet, B.A., Clausen, P., Wilson, H.M. and Ward, D.H., 2021 Predicting impacts of food competition, climate and disturbance on a long-distance migratory herbivore. Ecosphere. |

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| Case study title: | Lauderdale, Tasmania, Australia |
| Location: | -42.912673, 147.481715 |
| Birds: | Pied oystercatcher *Haematopus longirostri* |
| Modelling: | MORPH |
| Abstract: | Reproduced with permission.The Walker Corporation Pty Ltd has proposed the development of a marina village at Lauderdale in southern Tasmania (i.e. the Project). The proposed development site includes a large area of tidal flats (70 ha) that is used by a wide range of migratory waders and a significant proportion of the world population of Pied Oystercatchers. Lauderdale forms part of a complex of lagoons and bays situated within the Derwent/Pitt Water region that collectively support approximately 8% of the estimated global population of 110,000 Pied Oystercatchers. Averages of 2.6% and 2.4% of the global population of Pied Oystercatchers occur at Lauderdale in summer and winter respectively (Aquenal 2008b), satisfying Criterion 6 of the Ramsar Convention of 1% of the global population being present at a site. Within the Derwent/Pitt Water region, the South Arm Neck site in Ralphs Bay also exceeded this 1% criterion. The effect of loss of bird habitat (foraging, roosting and breeding) has been identified as an issue that needs to be addressed as part of the Integrated Impact Statement (IIS) for the Project.The current study assessed one aspect of habitat loss by using a behaviour-based model to determine the likely impact of the proposed development on food resources available to Pied Oysterctachers. This report details the modelling studies and background analyses needed to parameterise the model. A total of seven sites located in south eastern Tasmania were included in the model, and were selected on the basis of supporting large numbers of Pied Oystercatchers and having potential links to the proposed development site. Two of the sites, Orielton Lagoon and Barilla Bay, fall within the existing Pitt Water/Orielton Lagoon Ramsar site. The seven sites included a total of 34 ‘patches’ identified for the model and had a total area of 616 ha. Field data required as input to the model were collected during spring, summer and winter seasons to correspond with important life stages of wader species and hence variation in food availability. Data collected related to bird numbers, invertebrate prey species, and bird foraging activity, while information on sandflat exposure, energy demands by the birds and the energy content of their food were also input to the model. Surveys by Harrison (2008) provided foraging data input to the model, and identified 20 prey species consumed by Pied Oystercatchers during full surveys. Polychaete worms and two species of bivalve (Katelysia scalarina and Anapella cycladea) accounted for approximately 90% of prey consumed in numeric terms. Inclusion of additional less common benthic infauna bivalves, as well as the gastropod Salinator fragilis and epibenthic bivalves Crassostrea gigas and Mytilus galloprovincialis, meant than data input to the model accounted for 98% of food items. The largest single numerical contributor to the diet was polychaete worms, which accounted for more than 40% of prey during each season. The benthic invertebrate survey (Aquenal 2008a) provided the densities and sizes of the invertebrate prey available and targeted the species identified as important components of the Pied Oystercatcher diet from the above foraging studies. Energy intake by the birds was determined by calculating the relationship between the length of the organism and the ash-free dry mass (AFDM) for eight species (four bivalves, three polychaetes and one gastropod) for the seven sites and three seasons surveyed. These relationships were applied to the invertebrates observed to have been consumed by Pied Oystercatchers in the foraging surveys and were converted into the ‘common currency’ of AFDM. Analyses found that bivalves comprised on average 88% (range 70-95%) of the energy intake expressed as AFDM across all sites. Birds at Lauderdale had the highest intake rates (c. 6g AFDM per hour) and, in terms of biomass (expressed as AFDM) also consumed the highest proportion of bivalves. In terms of foraging, Lauderdale was therefore the highest quality site surveyed.In the absence of habitat loss (i.e. no development) the model predicted that there was a seasonal minimum of four times the amount of food needed to sustain the current number of birds at Lauderdale (mean across seasons of 189 and a maximum of 252 birds). This minimum occurred during the winter season when the quality of food was lowest. European Oystercatchers require between two to eight times the amount of food required to maintain low mortality rates, depending on the dominant prey types. At Lauderdale and surrounding sites, where birds feed largely on dispersed rather than aggregated bivalve species, the birds would suffer little intra-specific competition and we initially expected that the amount of food required in the environment would be closer to two, than eight times the amount the birds needed to consume. After removing the exact area that is covered by the proposed development, the model predicted no deaths or loss of condition of Pied Oystercatchers on the basis of reduced food availability. To ensure removal of any potential bias in the data, a sensitivity analysis was applied by increasing the number of birds to the seasonal maximum and not allowing birds to wade for food, however the same result was achieved. This scenario assumes that the development does not (a) impact on the sediments (and therefore food resources) to the south of the proposed development or (b) impact on the behaviour of the Pied Oystercatchers in the remaining area. These predictions do not take into account the presence of other waders but we expect the interaction between these species and Pied Oystercatcher to be relatively low for two reasons. First, there were relatively low numbers of other wader species present at the sites. Second, other wader species will not depend on bivalves to the same extent as the oystercatchers. As polychaetes only made up 11% of the Pied Oystercatcher diet (in terms of AFDM) overall, there was only a small amount of overlap in their diets.To allow for the scenario of the proposed development having an adverse impact on areas to the south of its ‘footprint’, additional model simulations were conducted whereby all of the habitat was removed from Lauderdale and birds were forced to move elsewhere. On the basis of food resources, birds were predicted to move to South Arm Neck and Pipeclay Lagoon and, due to the large amounts of food available at those sites, no increase in mortality, or loss of condition, were predicted. The conservative approach of increasing the numbers of birds in the model to their seasonal maximum in each site, and not allowing them to wade for food, also resulted in no increased mortality or decrease in body condition. The above default habitat loss simulations also assumed that the Pied Oystercatchers were the only source of prey mortality, whereas other factors may also be important. Additionally, the invertebrate survey may have overestimated the amount of food available to the birds. To account for these possibilities, a further sensitivity analysis was conducted by re-running the model, retaining the above assumptions about the seasonal maximum number of birds present and an absence of wading, but also assuming that only 50% of the observed food supply was actually available to the birds. Given the measured error (5th percentile of the total AFDM in the site) in the invertebrate survey varied seasonally between 31 and 43% of the total AFDM actually measured, and the fact that the preferred prey populations were relatively stable through the year (implying that mortality rates of these prey were relatively low), a 50% reduction of prey density was considered relatively extreme. The combined assumptions of this sensitivity analysis therefore provided a highly conservative assessment, with model output likely to reflect a worst case impact on the basis of reduction of food resource availability alone. For the partial habitat loss scenario (development area only), no increase in mortality or loss of condition were predicted with the 50% reduction in food. However when the other sectors to the south of the proposed development area at Lauderdale were made unsuitable, the model run predicted high mortality rates of 55% on average per year. In this scenario, it was therefore predicted that adjacent sites would not be able to support all birds displaced and mortality would occur.The model predicted that the current foraging resources at Lauderdale could support a potential maximum of up to 1,000 Pied Oystercatchers, with the area directly affected by the development's footprint supporting up to 200 individual Pied Oystercatchers. Making all of Lauderdale unavailable would therefore reduce capacity for 1,000 birds from the network of sites considered. It is unlikely that the development's impact would be limited to its immediate footprint and it is likely that birds would be forced to move to other sites. Given the current situation (i.e. current Pied Oystercatcher population level and food supplies), the most likely scenario is that there would be sufficient food available to these birds at other sites. If all the habitats at Lauderdale were made unsuitable by the proposed development then, again, the most likely scenario is that there would be sufficient food. It is only in the worst case scenario that mortality dramatically increases.Based on the current surveys, food does not therefore seem to be the factor limiting Pied Oystercatcher population numbers in south eastern Tasmania. The model indicates that sites such as Lauderdale, South Arm Neck and Pipeclay Lagoon are key sites for maintaining high survival for Pied Oystercatchers in the region. Data obtained by Birds Tasmania (see Aquenal 2008b) show no evidence of significant declines in the population. Based on 1983-2005 biannual wader count data, the Pied Oystercatcher population in the Derwent/Pitt Water region increased in the 1990s although there was a greater variability in numbers in the later years. Although there was an excess of food, if the oystercatcher population undergoes a similar increase in future then food, particularly that available in winter, may become a limiting factor. |
| Funders: | British Trust for Ornithology (originally from an organisation in Australia) |
| Papers or reports: | Atkinson, P.W. and Stillman, R.A., 2008. Carrying Capacity Modelling for the Pied Oystercatcher at Lauderdale and Surrounding Sites. Lauderdale Quay Proposal, British Trust for Ornithology, Norfolk. |

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| Case study title: | Lauwersmeer, Netherlands |
| Location: | 53.373304, 6.180918 |
| Birds: | Bewick’s swan *Cygnus columbianus bewickii* |
| Modelling: | MORPH |
| Abstract: | Predicting the environmental impact of a proposed development is notoriously difficult, especially when future conditions fall outside the current range of conditions. Individual-based approaches have been developed and applied to predict the impact of environmental changes on wintering and staging coastal bird populations. How many birds make use of staging sites is mostly determined by food availability and accessibility, which in the case of many waterbirds in turn is affected by water level. Many water systems are regulated and water levels are maintained at target levels, set by management authorities. We used an individual-based modelling framework (MORPH) to analyse how different target water levels affect the number of migratory Bewick’s swans Cygnus columbianus bewickii staging at a shallow freshwater lake (Lauwersmeer, the Netherlands) in autumn. As an emerging property of the model, we found strong non-linear responses of swan usage to changes in water level, with a sudden drop in peak numbers as well as bird-days with a 0.20 m rise above the current target water level. Such strong non-linear responses are probably common and should be taken into account in environmental impact assessments. |
| Funders: | This work was funded by the Netherlands Organisation for Scientific Research (http://www.nwo.nl), NWO grant 814.01.008 to BAN. |
| Papers or reports: | Nolet, B.A., Gyimesi, A., van Krimpen, R.R.D., de Boer, W.F. and Stillman, R.A., 2016. Predicting Effects of Water Regime Changes on Waterbirds: Insights from Staging Swans. Plos One, 11(2): e0147340. |

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| Case study title: | Liverpool Bay |
| Location: | 53.363342, -3.318254 |
| Birds: | Common scoter, *Melanitta nigra* |
| Modelling: | MORPH |
| Abstract: | The environmental impact assessments of most offshore windfarm proposals raise the potential effects on birds as an important issue. Offshore windfarms may affect birds in a number of different ways including mortality due to direct collisions of birds while in flight and mortality induced by habitat loss due to the avoidance by foraging birds of such conspicuous structures. Birds that may be affected by displacement from foraging areas within close proximity to windfarms are likely to be those such as common scoter and common eiders that feed on sedentary or slow-moving bottom-dwelling organisms such as bivalve molluscs and fish-eating birds such as grebes, terns, auks and divers. This present study used field observations and surveys combined with an individuals-based modelling approach to predict the change in over-winter mortality rates of common scoter that would result from the displacement of birds from potential feeding habitat through the avoidance of windfarms in Liverpool Bay. The model code is, however, not specific to Liverpool Bay and can be utilised for other areas provided that suitable data are collected. |
| Funders: | This project was supported by COWRIE funding under BEN-03-2002. The overflight data used in this study was funded jointly by the Countryside Council for Wales, English Nature, The Crown Estate, BHP and the developers of the offshore windfarms in Liverpool Bay.[Note: Collaborative Offshore Wind Research Into the Environment) is a Trust Fund that was established by the Crown Estate to identify, prioritise and fund environmental research. Funds are the interest accrued on deposits made to the Crown Estate by industry] |
| Papers or reports: | Kaiser, M.J., Elliott, A., Galanidi, M., Rees, E.I.S., Caldow, R., Stillman, R., Sutherland, W. and Showler, D., 2005. Predicting the displacement of common scoter Melanitta nigra from benthic feeding areas due to offshore windfarms, University of Wales, Bangor, Wales. |

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| Case study title: | Martin Mere |
| Location: | 53.621741, -2.868446 |
| Birds: | Pink footed goose, *Anser brachyrhynchus* |
| Modelling: | MORPH |
| Abstract: | None provided |
| Funders: | Natural England |
| Papers or reports: | Bournemouth University and Wildfowl and Wetlands Trust, 2018. Wildfowl functionally linked land. ECM\_48346. Individual based modelling approach, Wildfowl and Wetlands Trust, Slimbridge, Gloucestershire. |

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| Case study title: | Menai Straits |
| Location: | 53.238738, -4.116786 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MORPH |
| Abstract: | West and McGrorty (2003): © CNC/NRW 20031. This study of oystercatcher and cockle populations on the Dee Estuary, Traeth Lafan and the Burry Inlet had two main objectives. The first was to assess the power of existing surveys to detect changes in the cockle population at each site and to recommend possible improvements. The second objective was to determine how each site was used by the population of oystercatchers that roosted there.2. Cockle densities at all three sites were highly variable, indicating that cockle Distributions are aggregated. The amount of variation differed between sites and between years within a site. The amount of variance measured at a particular site in any given year was not related to the size of the surveyor the mean cockle density measured.3. Between 200 and 400 0.1 m2 samples appeared to provide a reasonable balance between accuracy and efficient use of time and resources. This level of sampling would allowing on average the detection of a 25-40% decrease or a 30-65% increase in cockle density, depending on the site. Increasing sample numbers above 400 provided a relatively small return in terms of improved accuracy for the extra effort involved.4. A survey scheme is presented which aims to provide a balance between the information needed for fisheries and conservation management purposes. Methods for surveying other common sources of food for oystercatchers are also described.5. WetlandBird Survey (WeBS) low-tide counts show a substantial proportion of the Oystercatcher population feeding outside the areas covered by fisheries cockle stock surveys on all three sites. On the Burry Inlet, these birds are known to be feeding both on cockle patches occurring outside the fisheries survey area and on other sources of food, particularly mussel beds.6. WeBS high-tide counts at each site show substantialvariation,50% or more at every site, in the numbers of oystercatchers roosting at each site from month to month over winter. The total numbers across all sites as a whole also varied considerably.7. Comparison of high and low-tide WeBS counts showed no significant difference between the numbers of oystercatchers roosting on the Dee and feeding there at low tide. More birds appear to feed on Traeth Lafan than the numbers roosting there. On the Burry Inlet, counts show increased bird numbers at low tide during early winter and decreased Numbers at low tide in later months.8. The energy requirements of oystercatchers, combined with physiological constraints on their intake, mean that birds roosting on the Dee could not fly further than the Ribble to feed at low tide. In mid winter when temperatures are lower, they would only profitably be able to fly as far as the Mersey or Alt estuaries.9. High- and low-tide counts on the Dee and surrounding estuaries show that most Oystercatchers that roost on the Alt probably feed in the Mersey. A small proportion of the Dee population may also feed in the Mersey.10. Finally, the implications of this study's findings for modelling the oystercatcher Population of the Dee estuary are discussed.Caldow et al. (2004) © 2004 by the Ecological Society of America:Bottom cultivation of mussels on intertidal flats is practiced throughout the world. This often generates conflicts between commercial interests and competing birds such as oystercatchers. At the Menai Strait, United Kingdom, the overwinter consumption of 242 tonnes (1 metric tonne = 1000 kg) of commercially harvestable mussels (>40 mm) by oystercatchers in 1999-2000 was worth ?133 000 ($226 000 U.S. dollars). This represents 19% of the value of the landings. We used a behavior-based simulation model to predict the extent to which such losses can be reduced by novel commercial management practices, and to explore the consequences for the oystercatcher population. Simulations of novel lay management practices indicated that the losses of commercially harvestable mussels to oystercatchers can be considerably reduced by altering the shore level and/or extent of the commercial lays. We propose a novel management strategy for the bottom cultivation of mussels in intertidal areas. Seed mussels (15-20 mm) should be laid relatively far upshore, where losses to oystercatchers will be minimal. As the mussels grow over the next 2-3 years, they should be moved progressively further downshore such that the largest mussels spend their last season prior to harvest in a relatively small area, lower on the shore than all mussels earlier in the cultivation cycle. Support for the effectiveness of this proposed management strategy can be found in the reports of commercial operators who have incorporated this management strategy in new management practices in the last few years. They report an increase in the ratio of the live mass of harvested to seeded mussels from the previous norm of 1:1 to 4:1. By accepting greater losses of mussels earlier in the cultivation cycle, rather than later, the feeding conditions for oystercatchers might even be improved under this system. With appropriate management, the interest of shellfish growers and competing shorebirds need not conflict. |
| Funders: | Environment Research Council LINK Aquaculture award ENVI1. Countryside Council for Wales |
| Papers or reports: | West, A.D. and McGrorty, S., 2003. Marine monitoring project: Modelling osytercatchers and their food on the Dee Estuary, Traeth Lafan and Burry Inlet Spa to inform target setting and site management, Centre of Ecology and Hydrology, Dorchester, Dorset.Caldow, R.W.G., Beadman, H.A., McGrorty, S., Stillman, R.A., Goss-Custard, J.D., le V. dit Durell, S.E.A., West, A.D., Kaiser, M.J., Mould, K. and Wilson, A., 2004. A Behavior-Based Modeling Approach to Reducing Shorebird-Shellfish Conflicts. Ecological Applications, 14(5): 1411-1427. |

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| Case study title: | Morecombe Bay |
| Location: | 54.083808, -2.8622 |
| Birds: | Oystercatcher *Haematopus ostralegus*Knot *Calidris canutus* |
| Modelling: | MORPH |
| Abstract: | The Morecambe Bay Special Protection Area (SPA) is one of the largest estuarine systems in the UK and supports nationally and internationally important populations of wildfowl and shorebirds. The flats usually contain abundant stocks of cockles *Cerastoderma edule* which, along with mussels *Mytilus edulis*, are the preferred prey of oystercatchers *Haematopus ostralegus* wintering in the bay. In recent years, the cockle population has declined to a fraction of what it used to be and there is concern about the potential effects of this decline on oystercatcher and knot *Calidris canutus* populations that overwinter in the bay.The aim of this project was to bring together existing information about shellfish populations and bird populations in the bay and use this information to parameterise an individual-based model of oystercatcher and knot populations in Morecambe Bay. The model would then be used to run simulations of various different scenarios to give some insight into the potential effects of the decline in cockle stocks and the extent to which bird populations rely on those stocks for their survival. The Morecambe Bay model was created in the knowledge that the shellfish data available, particularly with respect to mussels, was not comprehensive and up to date. Bearing that in mind, the predictions in this report should not be taken as an accurate representation of real-world conditions, but more an exploration of how the data that is available can be used to inform debate about shellfishing practices. They can also indicate where there is a need for further research.The model predicted that shellfish densities observed in the bay were sufficient to support the observed oystercatcher population in both 2005 and 2009, provided that supplementary food was included. Without supplementary food during 2009, large oystercatcher mortalities were predicted and this has not been observed on the ground. It therefore seems likely that oystercatchers currently require, and are exploiting, food supplies over and above the cockle, mussel and *Macoma* stocks recorded during the shellfishery surveys. At the cockle and mussel densities seen in 2005, no such supplementary food source was needed for oystercatchers in the model to survive the winter in good condition, so in years of high cockle abundance a knowledge of alternative sources of food for this species is less important.Knot mortalities were predicted to be 100% when the model contained cockles, mussels and the observed abundance of *Macoma*. This implies that the knot population is unlikely to be relying on prey from just the recorded shellfish beds. Given that the bay is a dynamic system and spat settlements are often ephemeral, this is perhaps to be expected. Doubling *Macoma* density tended to increase knot survival, indicating the quantity of additional food that the birds may be exploiting.Overall, the simulations show that the decline in cockle stocks between 2005 and 2009 is potentially large enough to affect the body condition and survival of oystercatchers in Morecambe Bay. The greatest unknown is the extent and availability of potential sources of food outside the established cockle beds. While the model predicted that oystercatchers would have no need of these alternative food supplies in a good cockle year, they are potentially very important in years when the cockle stocks are low. They also show that knot are likely to be exploiting food supplies outside the established cockle beds in both good and bad cockle years. Bearing this in mind, establishing a greater understanding of potential food supplies outside the cockle beds would provide a more accurate estimate of the importance of cockle stocks to the oystercatcher and knot populations of Morecambe Bay and increase confidence in the predictions of the model. |
| Funders: | Natural England |
| Papers or reports: | West, A. and Stillman, R., 2010. A single year study to determine the capacity of Morecambe Bay European marine site to support oystercatcher, using shellfish resource modelling techniques, Bournemouth University, Bournemouth. |

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| Case study title: | Poole Harbour (A) |
| Location: | 50.683827, -2.004393 |
| Birds: | Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Black-tailed godwit, *Limosa limosa*Dunlin, *Calidris alpine*Redshank, *Tringa tetanus*Sanderling, *Calidris alba* |
| Modelling: | MORPH |
| Abstract: | Stillman et al. 2005 (Contains public sector information licensed under the Open Government Licence v3.0): This is the final report for the joint English Nature and Centre for Ecology and Hydrology (CEH) project entitled “Estuary Special Protection Areas – Establishing Baseline Targets for Shorebirds”. The aim of this project was to use individual-based models, comprised of fitness-maximising individuals, to predict how changes in the mortality rate and body condition of wader and wildfowl populations are related to the amount of food and human disturbance within a site. Individual-based models predict population level responses, such as mortality rate, from the combined behavioural responses of the individual animals within a population. An important aspect of the models developed in the project is that the behavioural decisions of model animals are derived from fitness-maximising decision rules (for example, animals attempt to maximise their chances of surviving starvation by feeding in locations in which prey are most abundant, or can be consumed most rapidly). As real animals are thought to use similar decision rules, model animals should behave in similar ways to real animals.Models were applied to four Special Protection Areas (SPAs), the Humber estuary, the Wash, Poole harbour and the Exe estuary, to predict the food abundances required to maintain low shorebird and wildfowl mortality rates and high body conditions. The major site-specific predictions were as follows.* *Humber estuary shorebirds*. Nine shorebird species were modelled; dunlin, ringed plover, knot, redshank, grey plover, black-tailed godwit, bar-tailed godwit, oystercatcher and curlew. The model predicted that the presence of fields around the estuary provided supplementary feeding areas which increased the survival rates of curlew. With the exception of curlew, shorebird survival rates fell below 90% when autumn, estuary-wide food biomass density was below about 4 g AFDM m-2. Curlew survival rates fell when food biomass density decreased below 8 g AFDM m-2. Prey biomass densities for all species except curlew were above the threshold prey density below which survival rates were predicted to decline. Shorebird survival was most strongly influenced by the biomass densities of annelid worms, and the bivalve molluscs *Cerastoderma edule* and *Macoma balthica*. It was unaffected by the biomass densities of *Corophium* and *Hydrobia*.
* *Wash shorebirds*. Eight shorebird species were modelled; dunlin, knot, redshank, grey plover, black-tailed godwit, bar-tailed godwit, oystercatcher and curlew. Shorebird survival rates fell below 100%, i.e. birds began to starve, when autumn, estuary-wide food biomass density was below about 5g AFDM m-2 and fell below 90% at 4g AFDM m-2. Prey biomass densities for all species were above the threshold prey density below which survival rates were predicted to decline. Shorebird survival was most strongly influenced by the biomass densities of *Arenicola* and other annelid worms, and the bivalve molluscs *Cerastoderma edule* and *Macoma balthica*. It was unaffected by the biomass densities of *Corophium* and *Hydrobia*. The survival of most species in the model remained high at fewer than 20 disturbances per hour, but bar-tailed godwit and curlew were affected at disturbance rates as low as two per hour.
* *Poole harbour shorebirds*. Five shorebird species were modelled; dunlin, redshank, black-tailed godwit, oystercatcher and curlew. The model predicted that dunlin, redshank, black-tailed godwit and oystercatcher survival would start to decline when prey biomass densities dropped below 3 g AFDM m-2. Prey biomass densities for dunlin, redshank and oystercatchers were well above this, indicating that these three species would be less vulnerable to declines in their food supply. However, black-tailed godwit prey biomass densities were very close to this level. Curlew survival was not predicted to decline until prey biomass densities dropped below 2 g AFDM m-2, probably because curlew fed extensively in surrounding fields on terrestrial prey. However, mean prey biomass densities measured for curlew were close to this value, and the 95% confidence limits below it. Shorebird survival was most strongly influenced by the biomass densities of *Arenicola* and other annelid worms, earthworms and the bivalve molluscs *Cerastoderma edule* and *Macoma balthica*. It was unaffected by the biomass densities of *Corophium* and *Hydrobia*.
* *Exe estuary shorebirds*. Six shorebird species were modelled; dunlin, grey plover, black-tailed godwit, bar-tailed godwit, oystercatcher and curlew. Two models were developed. The simplified model (A) was comparable to those developed for the Humber estuary, Wash and Poole harbour. The more detailed model (B) incorporated more aspects of the behaviour and ecology of the shorebirds. In Model A, the response of shorebird survival to reductions in prey biomass densities were very similar to those obtained for the Humber, the Wash and Poole Harbour. In Model B, however, shorebird survival started to decrease at higher prey biomass densities and the decline in survival with prey biomass was much more gradual. We believe that this is likely to be the more realistic scenario and that threshold prey biomass densities for shorebird survival should not be regarded as around 3-4 g AFDM m-2 as suggested in previous models, but as around 8-10 g AFDM m-2. All prey biomass densities on the Exe were as high, or higher, than those measured on other estuaries in this Report. Using Model A, no shorebird species appeared to be vulnerable to declines in their prey biomass densities. With Model B, however, curlew and bar-tailed godwit survival started to decline with prey biomass densities below the 95% confidence interval. It is likely, therefore, that curlew and bar-tailed godwit are the species most likely to be vulnerable to declines in their food supply in the Exe estuary.
* *Exe estuary brent geese*. The time at which Brent geese switch from feeding on *Zostera* to feeding on pastures is affected by the abundance of *Zostera*. A reduction in *Zostera* abundance will bring forward the switch date and an increase will delay it. Accordingly, the number of goose days that *Zostera* supports before the switch is complete will be reduced if *Zostera* abundance declines and will increase if it rises. This general pattern is little affected either by the assumed efficiency with which geese exploit the *Zostera* or by the percentage of time lost to disturbance on the *Zostera* beds during daylight (subject to the proviso that access at night is undisturbed). Moreover, the birds end of winter body condition and over-winter survival is unaffected by any changes to the abundance or availability of *Zostera*. Rather, the well-being of the Brent goose population on the Exe is much more dependent upon the availability of grass pastures on which they feed for the bulk of their winter stay on the estuary.

The following general recommendations (in *italics*) can be derived from the site and system-specific predictions detailed above.* *Monitor bird food resources as well as bird numbers*. The conservation importance of an estuary is often measured in terms of bird numbers using the estuary, but monitoring numbers is not necessarily a reliable way of assessing changes in site quality. In particular, this is because the numbers of birds using a site depend not only on the conditions at the site, but also the conditions at other sites both within the non-breeding and breeding seasons. The models developed in this project predict site quality as the survival rate of birds on a site rather than simply the numbers of birds on the site. When food is abundant, survival rates are high, but survival decreases when food abundance declines below a threshold value. From this is it possible to derive critical amounts of food required to maintain high body mass and survival. *A recommendation derived from these predictions would be to establish a monitoring programme to record the abundance of food on sites at the start of winter as well as continuing the usual procedure of monitoring bird numbers.* If resources are limited, surveys should be restricted to Annelid worms, earthworms and bivalves (the key species predicted to affect shorebird survival in this study). Provided that bird densities are comparable to those on the Humber estuary, Wash, Poole harbour and Exe estuary, an initial food supply in excess of 8-10 g afdm m-2, would be predicted to maintain high shorebird survival.
* *Monitor the use of marginal habitats and feeding times*. The models developed during this project all predicted that birds fed in the most profitable and safest places and times when feeding conditions were good and survival rates high, behaviour which mimicked that of real birds. In contrast, birds were predicted to feed more in marginal habitats or at more risky times when feeding conditions were poorer, again behaviour which mimicked that of real birds. *A recommendation would be to establish a monitoring programme to detect such changes in the behaviour of bird populations as an early warning that survival rates are likely to be falling*. This approach would pick up possible detrimental changes on a site before increases in mortality rate could be detected through traditional approaches based on bird ringing programmes, increasing the chance that management can be implemented to improve conditions before bird survival declines greatly.
* *Include terrestrial habitats in conservation areas*. The models predicted that terrestrial habitats were often critical for the survival of waders and geese, even though these habitats are often considered as marginal habitats. These habitats are often excluded from the designation of Special Protection Areas, but this means that vital habitat is not being protected and as a result may be lost to building developments, suffer high disturbance levels or simply be subject to changes in the way in which it is managed. *A simple recommendation derived from these predictions is that wherever possible conservation areas should include the terrestrial habitats around estuaries as well as the intertidal habitats of the estuary itself.* This would ensure that the full range of habitats required by birds is protected.
* *Further understand the response to disturbance*. The disturbance experiments conducted during the study show considerable flexibility in the response to disturbance. Birds were more tolerant of human presence in parts of the Wash in which they more frequently encountered humans. Oystercatchers and brent goose feeding on recreational grassland in Poole harbour, in which they frequently encountered people and dogs, were very tolerant, usually only walking away from people rather than flying. The response to disturbance can be viewed as a trade-off between avoiding the perceived threat of the disturbance and the cost of moving. Increased tolerance of human presence (i.e. a reduced response to disturbance) will occur either if birds perceive the disturbance of less of a threat and / or if the detrimental effects of avoiding the disturbance are greater. In conservation terms the second situation is what needs to be avoided. It is less serious if birds can simply adapt to increased disturbance by learning that the disturbance source is less of a threat. Unfortunately, it is difficult or impossible to separate these two alternatives using the data collected in many disturbance studies. *A recommendation is that future disturbance studies should aim to determine why birds respond to disturbance sources in the way they do, rather than simply measuring the response to disturbance alone.*

This project used individual-based models to predict how site quality depends on the food density and levels of disturbance in the site. The survival rates of most shorebirds and brent goose were predicted to be high with the current biomass densities of food and current rates of disturbance. Target food biomass can be determined as biomass per bird in situations in which a resource is mainly consumed by one species, such as oystercatchers consuming large bivalves. However, this is not possible in multi-species situations and so the more simple measure of food biomass at the start of winter was used in the multi-species models developed during this project. Provided that bird densities are comparable to those on the Humber estuary, Wash, Poole harbour and Exe estuary, an initial food supply in excess of 8-10 g afdm m-2, is predicted to maintain high shorebird survival.Durell et al. 2006 Reproduced with permission from Elservier: An individuals-based model, MORPH, was used to assess the quality of Poole Harbour, UK,for five overwintering shorebirds: dunlin Calidris alpina, redshank Tringa totanus, black tailed godwit Limosa limosa, oystercatcher Haematopus ostralegus and curlew Numenius arquata. Site quality, and the effect of environmental change, was measured as predicted over winter survival. Dunlin had the highest prey biomass densities and were the least likely to be affected by reductions in their food supply, lower temperatures or loss of terrestrial habitats. Black-tailed godwits and curlew had the lowest prey biomass densities and were the most likely to be affected by reductions in their food supply, lower temperatures and loss of terrestrial habitats. All five shorebird species were seriously affected by simulated sea-level rise. Conservation issues identified for the Poole Harbour SPA were the relatively low densities of larger size classes of polychaete worms, the importance of maintaining and managing surrounding terrestrial habitats and the effect of sea-level rise on the length of time for which intertidal food supplies are available |
| Funders: | English Nature |
| Papers or reports: | Stillman, R.A., West, A.D., le V dit Durell, S.E.A., Caldow, W.R.G., McGrorty, S., Yates, M.G., Garbutt, R.A., Yates, T.J., Rispin, W.E. and Frost, N.J., 2005. Estuary Special Protection Areas - Establishing baseline targets for shorebirds, Centre for Ecology and Hydrology, Dorchester, Dorset.Durell, S.E.A.L.V.d., Stillman, R.A., Caldow, R.W.G., McGrorty, S., West, A.D. and Humphreys, J., 2006. Modelling the effect of environmental change on shorebirds: A case study on Poole Harbour, UK. Biological Conservation, 131(3): 459-473. |

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| Case study title: | Poole Harbour (B) |
| Location: | 50.683827, -2.004393 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Non MORPH |
| Abstract: | Introductions of non-native species are seen as major threats to ecosystem function and biodiversity. However, invasions of aquatic habitats by non-native species are known to benefit generalist consumers that exhibit dietary switches and prey upon the exotic species in addition to or in preference to native ones. There is, however, little knowledge concerning the population-level implications of such dietary changes. Here, we show that the introduction of the Manila clam Tapes philippinarum into European coastal waters has presented the Eurasian oystercatcher Haematopus ostralegus ostralegus with a new food resource and resulted in a previously unknown predator–prey interaction between these species. We demonstrate, with an individuals-based simulation model, that the presence of this non-native shellfish, even at the current low density, has reduced the predicted over-winter mortality of oystercatchers at one recently invaded site. Further increases in clam population density are predicted to have even more pronounced effects on the density dependence of oystercatcher over-winter mortality. These results suggest that if the Manila clam were to spread around European coastal waters, a process which is likely to be facilitated by global warming, this could have considerable benefits for many shellfish-eating shorebird populations. |
| Funders: | English Nature, ABP |
| Papers or reports: | Caldow, R.W.G., Stillman, R.A., Durell, S., West, A.D., McGrorty, S., Goss-Custard, J.D., Wood, P.J. and Humphreys, J., 2007. Benefits to shorebirds from invasion of a non-native shellfish. Proceedings of the Royal Society B-Biological Sciences, 274(1616): 1449-1455. |

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| Case study title: | Poole Harbour (C) |
| Location: | 50.683827, -2.004393 |
| Birds: | Avocet, *Recurvirostra avosetta* |
| Modelling: | MORPH |
| Abstract: | Coastal ecosystems are undergoing unprecedented rates of environmental change. Many of these changes are anthropogenically-driven and linked to long-term, climate-related phenomena. This thesis focusses on ecological change in soft sediment intertidal habitats. One of the largest harbours in Europe, Poole Harbour, is used as a case study. It contains a variety of important habitats including intertidal mudflat and non-tidal saline lagoon.The two main themes of the thesis are 1) assessing the physical and ecological factors that determine benthic invertebrate abundance, distribution and community structure, which is examined at the scale of the whole harbour, and at the scale of individual habitats: an intertidal mudflat and a saline lagoon; and 2) predicting the response of an overwintering shorebird population, the pied avocet (Recurvirostra avosetta), to future environmental changes, such as sea-level rise and habitat loss. This is achieved by development of an individual-based model (IBM) and consideration of the species’ unique foraging behaviour.This study contributes to the understanding of the factors structuring soft sediment benthic communities, including the use of data from fine-scale hydrodynamic models. It offers a unique comparison of the spatial and temporal variables driving community structure of a saline lagoon and an intertidal mudflat. It also provides insight into the foraging ecology of the pied avocet at a level of detail that has not previously been considered, including a comparison of foraging behaviour in a tidal and non-tidal habitat, the importance of social foraging, and the novel application of an IBM to this species. |
| Funders: | Bournemouth University. HR Wallingford. |
| Papers or reports: | Ross, K.E., 2013. Investigating the physical and ecological drivers of change in a coastal ecosystem: From indivdual-to population-scale impacts. PhD thesis, Bournemouth University. |

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| Case study title: | Poole Harbour (D) |
| Location: | 50.683827, -2.004393 |
| Birds: | Grey plover, *Pluvialis squatarola*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Bar-tailed godwit, *Limosa lapponica*Black-tailed godwit, *Limosa limosa*Dunlin, *Calidris alpine*Redshank, *Tringa tetanus* |
| Modelling: | MORPH |
| Abstract: | Bowgen et al. 2015 Reproduced with permission from Elservier:Regime shifts in benthic invertebrates within coastal ecosystems threaten the survival of wading birds (Charadrii). Predicting how invertebrate regime shifts will affect wading birds allows conservation management and mitigation measures to be implemented, including protection of terrestrial feeding areas. An individual-based model was used to investigate the impact of regime shifts on wading birds through their prey (marine worms and bivalves) in the estuarine system Poole Harbour, (UK). The model predicted the number of curlew (Numenius arquata), oystercatcher (Haematopus ostralegus), black-tailed godwit (Limosa limosa), redshank (Tringa totanus) and dunlin (Calidris alpina) supported in the Harbour during the non-breeding season (autumn and winter months). The most dramatic declines in bird numbers were for regime shifts that reduced the abundance of the largest invertebrates, particularly marine worms. The least adaptable bird species (those with the most restrictive diets) were unable to compensate by consuming other prey. Generally, as birds adapt to changes by switching to alternative prey species and size classes, changes in invertebrate size and species distribution do not necessarily affect the number of birds that the Harbour can support. Our predictions reveal a weakness in using birds as indicators of site health and invertebrate regime shifts. Differences in bird populations would not necessarily be detected by standard survey methods until extreme changes in invertebrate communities had occurred, potentially beyond the point at which these changes could be reversed. Therefore, population size of wading birds should not be used in isolation when assessing the conservation status of coastal sitesBowgen 2016:With the pressures that today’s ecosystems are being placed under, from both environmental change and anthropogenic developments, the speed at which management decisions need to be made has increased. Coastal development means that estuaries are particularly affected and their characteristic species, like wading birds (Charadrii), are now experiencing worldwide declines. In such situations there is a need for predictive ecology to understand in advance how species might react to future changes.This thesis looks into how we can use individual-based models (IBM) to make accurate predictions of how wading birds are affected by environmental change. Starting with previously validated models I show the importance of measuring size of invertebrates though an IBM investigation into regime shifts and wading birds responses. The models show that by altering their diet preferences, birds adapt to regime shifts in their prey but that this maintenance of population size masks the true changes in the system and limits the use of waders as direct bio-indicators of ecosystem health. Using the current literature, an analysis on empirical responses of wader populations to environmental change revealed the lack of comparability between studies and the scarcity of studies on small scale events.Data from literature and fieldwork was used to develop a comparable suite of individual-based models for five UK estuaries with up to eleven wading bird species. These models were validated using current BTO Wetland Bird Surveys data to increase confidence in final results. Using these new models, investigations of population thresholds and environmental change were carried out. Increases to current populations revealed that several estuaries are no longer able to support the number of birds around the time of Special Protection Area designation. This, alongside higher populations currently seen since the years of designation, indicates the need for re-assessment of SPA species numbers. When looking at the impacts of two types of environmental change, habitat loss and sea-level rise, certain species declined predictably across sites whilst the individual make up of each estuary had particular impacts on some waders more than others. The work of this thesis further indicates the great potential of using individual-based models to predict the effects of a wide range of environmental changes. With the new models and a quicker and systematic way of developing IBMs for additional areas, wecan aid the conservation and management of estuarine systems for wading birds. |
| Funders: | Bournemouth University and HR Wallingford |
| Papers or reports: | Bowgen, K.M., Stillman, R.A. and Herbert, R.J.H., 2015. Predicting the effect of invertebrate regime shifts on wading birds: Insights from Poole Harbour, UK. Biological Conservation, 186: 60-68.Bowgen, K.M., 2016. Predicting the effect of environmental change on wading birds: insights from individual-based models. PhD thesis, Bournemouth University in collaboration with HR Wallingford. |

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| Case study title: | Poole Harbour (E) |
| Location: | 50.683827, -2.004393 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | MORPH |
| Abstract: | Intertidal harvesting of marine invertebrates has significant potential to come into conflict with the interests of nature conservation. This is particularly so for overwintering shorebirds that rely heavily on invertebrate prey to maintain body condition throughout the winter and to fuel migration towards breeding grounds. Harvesting activities in these areas therefore require careful management to achieve sustainability and to maintain healthy ecosystem functioning. This thesis investigates impacts of intertidal harvesting on benthic habitats and invertebrate communities as well as the potential impacts of harvesting on shorebird populations. Implications for management of inshore and intertidal fisheries are discussed. A meta-analysis investigated the response of key invertebrate prey groups to different gear types used in different intertidal habitats. Hand gathering most severely reduces prey abundance, which is likely to be due to the accuracy of harvesting with these gear types, while recovery trends vary between different combinations of gear and habitat and taxonomic groups. Results suggest that impacts may persist for longer in sandy habitats than in muddy habitats. In some cases fishermen may develop gears in response to local circumstance and the development of harvestable populations of new and introduced species. Extensive fieldwork was carried out to assess benthic impacts of ‘pump-scoop’ dredging in Poole Harbour, UK, a designated Special Protection Area under the European Union Birds Directive. The pump-scoop dredge is a novel gear typedeveloped by local fishermen following the introduction of the manila clam Ruditapes philippinarum in the 1980s. The use of this gear type elicits significant changes to macrobenthic community structure and a loss of fine sediments, while reductions in abundance of the target species of up to 95% occur in some areas throughout the open season. Although population dynamics of R. philippinarum vary across a gradient of fishing pressure, determining cause and effect is prevented by a lack of environmental data that could help isolate fishing impacts more confidently.Data on fishing effort is often lacking, particularly in inshore fisheries where Vessel Monitoring Systems (VMS) data are not collected. The analysis of aerial imagery collected by an unmanned aerial system (UAS) was used as an alternative measure of fishing effort in intertidal areas. Results indicate that the physical scarring of the sediment (quantified through image classification methods and calculation of a measure of image texture) is a reliable proxy for the distribution and intensity of fishing effort in intertidal areas. Remote sensing techniques offer an alternative source of data, useful to inform management of inshore fisheries, where no log book program or VMS data exists.A combination of fieldwork and individual-based modelling (IBM) was used to investigate the effect of shellfish dredging on shorebird populations in Poole Harbour. Field surveys showed no significant effect of dredging on shorebird feeding or intake rates, nor species distribution across the site, although continued monitoring is recommended. IBM results indicate that increased shellfish landings in Poole Harbour elicit a behavioural response in the Eurasian oystercatcher Haematopus ostralegus population, characterised by an increase in the time spent feeding and the amount of marine worms consumed. These shifts in behaviour and diet represent compensatory measures in response to a loss of preferred shellfish prey.The work presented in this thesis can directly contribute to ecosystem-based management of inshore fisheries. Results from the meta-analysis will assist managers in predicting the effects of harvesting on benthic ecosystems and provide useful evidence of recovery patterns, while survey data provide information on theimpacts of pump-scoop dredging in Poole Harbour, directly contributing to management. Other work provides demonstration of how tools such as remote sensing and IBMs can be applied to accurately quantify disturbance and predict the responses of shorebird populations to harvesting. The work presented will helpensure sustainable fishing, productive benthic habitats and healthy shorebird populations into the future. |
| Funders: | Bournemouth University, Natural England and the Southern Inshore Fisheries and Conservation Authority (SIFCA) |
| Papers or reports: | Clarke, L.J., 2018. Ecosystem impacts of intertidal invertebrate harvesting: from benthic habitats to bird predators. PhD thesis, Bournemouth University. |

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| Case study title: | Poole Harbour (F) |
| Location: | 50.683827, -2.004393 |
| Birds: | Grey plover, *Pluvialis squatarola*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Bar-tailed godwit, *Limosa lapponica*Black-tailed godwit, *Limosa limosa*Dunlin, *Calidris alpine*Redshank, *Tringa tetanus*Sanderling, *Calidris alba* |
| Modelling: | MORPH |
| Abstract: | Abstract available at: http://eprints.bournemouth.ac.uk/27019/1/Collop,%20Catherine%20Helen\_Ph.D.\_2016.pdf |
| Funders: | British Association for Shooting and Conservation. Bournemouth University. |
| Papers or reports: | Collop, C., 2016. Impact of human disturbance on coastal birds: Population consequences derived from behavioural responses. PhD thesis, Bournemouth University.  |

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| Case study title: | River Frome |
| Location: | 50.679609, -2.181684 |
| Birds: | Mute swan, *Cypnus olor* |
| Modelling: | MORPH |
| Abstract: | Effective wildlife management is needed for conservation, economic and human well-being objectives. However, traditional population control methods are frequently ineffective, unpopular with stakeholders, may affect non-target species, and can be both expensive and impractical to implement. New methods which address these issues and offer effective wildlife management are required. We used an individual-based model to predict the efficacy of a sacrificial feeding area in preventing grazing damage by mute swans (Cygnus olor) to adjacent river vegetation of high conservation and economic value. The accuracy of model predictions was assessed by a comparison with observed field data, whilst prediction robustness was evaluated using a sensitivity analysis. We used repeated simulations to evaluate how the efficacy of the sacrificial feeding area was regulated by (i) food quantity, (ii) food quality, and (iii) the functional response of the forager. Our model gave accurate predictions of aquatic plant biomass, carrying capacity, swan mortality, swan foraging effort, and river use. Our model predicted that increased sacrificial feeding area food quantity and quality would prevent the depletion of aquatic plant biomass by swans. When the functional response for vegetation in the sacrificial feeding area was increased, the food quantity and quality in the sacrificial feeding area required to protect adjacent aquatic plants were reduced. Our study demonstrates how the insights of behavioural ecology can be used to inform wildlife management. The principles that underpin our model predictions are likely to be valid across a range of different resource-consumer interactions, emphasising the generality of our approach to the evaluation of strategies for resolving wildlife management problems. |
| Funders: | Centre for Ecology & Hydrology, NERC |
| Papers or reports: | Wood, K.A., Stillman, R.A., Daunt, F. and O'Hare, M.T., 2014. Can Sacrificial Feeding Areas Protect Aquatic Plants from Herbivore Grazing? Using Behavioural Ecology to Inform Wildlife Management. Plos One, 9(7). |

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| Case study title: | Severn Estuary (A) |
| Location: | 51.585172, -2.660959 |
| Birds: | Grey plover, *Pluvialis squatarola*Golden plover, *Pluvialis apricaria*Lapwing, *Vanellus vanellus*Ringed plover, *Charadrius hiaticula*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Black-tailed, gotwit *Limosa limosa*Knot, *Calidris canutus*Redshank, *Tringa tetanus*Snipe, Gallinago gallinagoTurnstone, *Arenaria interpres*Dunlin, *Calidris alpina* |
| Modelling: | MORPH |
| Abstract: | Reproduced with permission under an Open Government Licence. https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/This annex reports on individual-based modelling studies of waterbirds carried out by Bournemouth University (BU) in order to inform the Waterbirds Topic paper. Reports on bird surveys and habitat association modelling, undertaken by the British Trust for Ornithology (BTO), are reported in separate annexes. To help inform the Waterbirds Topic paper, this annex presents the results of modelling work aiming to assess the primary effect of loss of intertidal habitat and changes to the nature of intertidal habitat within the Severn Estuary on the numbers of the non-breeding waterbird receptors. This project used the MORPH individual-based model, the latest in a series of such models developed for coastal birds. MORPH predicts how environmental change affects foraging animal populations. MORPH has been applied and tested for several systems, and has been shown to accurately predict the impact of environmental change. When parameterised for the Severn Estuary, MORPH followed the foraging decisions (i.e. patch and prey choice) of each individual bird, as they attempt to meet their daily energy requirements. The model predicted the distribution of birds between patches and the percentage of birds that survived to the end of winter.For compatibility with the Habitat Association modelling Waterbirds Annex, the key prediction was percentage change in supported population size resulting from a tidal power option. This wascalculated by initially predicting the population size of each species that could be supported in the baseline case (i.e. the population size at which survival equals 90%). The population size of each species that could be supported with each option was then predicted in the same way, from which the percentage change from baseline could be calculated.In the baseline simulations, for all species except curlew and oystercatcher, the maximum population size that could be supported was greater than the population size during 2008-2009. This implies that surplus food was available for these species, and that the duration of exposure was long enough to allow these species to meet their daily energy requirements throughout the winter. There was a general tendency for the larger bird species to be either be supported at current population sizes (Curlew and Oystercatcher), or to be very close to carrying capacity (Black-tailed Godwit). These species have higher energy requirements and require larger prey items (which are generally lacking on the Severn) to meet their daily requirements. The model was tested by comparing the observed and predicted mean overwinter distribution of each species across the estuary. Although the observed data were used to determine the initial distribution of the birds, model individuals moved to different feeding patches if they were unable to meet their daily energy requirements by feeding in their initial patch. In the baseline simulations, with theexception of Oystercatcher, Curlew and Black-tailed Godwit, the observed and predicted numbers of each species on each patch were virtually identical. This means that most model individuals of most species were able to obtain their overwinter energy requirements by feeding in the same locations as the real individuals. In the case of Oystercatcher, Curlew and Black-tailed Godwit, food resources were more limiting and so individuals were less able to meet their requirements by feeding in the same locations as the real individuals. Due to the uncertainties associated with the predictions for Oystercatcher and Curlew (low predicted survival and poor distribution predictions) the predictions for these species are not discussed in the main Waterbirds Topic paper.Model parameters were derived from the following sources: (i) The outputs of the Hydrology and Geomorphology (e.g. tidal exposure of patches), Marine Ecology (e.g. habitat type) and Waterbird(e.g. bird numbers) topics; (ii) A previous intertidal invertebrate survey of the Severn Estuary (numerical density of prey); (iii) Data collected on other sites (e.g. energy content of prey); (iv) General relationships thought to apply across sites (e.g. feeding rate of waterbirds). Even though all parameters were derived from measurements (either on the Severn, other sites, or across a range of species) the confidence that can be placed on these (as descriptions of the real system) will vary.Generally more confidence can be placed on parameters that are measured on the Severn itself as close as possible to the present day. The developed model is the best representation of the currentsystem achievable with the data currently available. Further Severn-estuary specific studies, particularly of prey abundance and biomass, will be required to increase confidence that the model more closely describes the current system.The following two sets of simulations were run, based on different assumptions of how tidal power options would effect invertebrate productivity. Predictions were made both for the short-term (i.e.ignoring long-term mud deposition or erosion) and the long-term (i.e. including long-term mud deposition or erosion).*Severn Estuary invertebrate simulations:* These simulations assumed that mudflats outside and within tidal power options (i.e. upstream of a barrage or within a lagoon) were occupied by the invertebrate species community recorded on the Severn.*Non-Severn Estuary invertebrate simulations:* These simulations assumed that mudflats within tidal power options (i.e. upstream of a barrage or within a lagoon) were occupied by the invertebrate species community recorded on other south-western UK estuaries (increasing prey biomass relative to the Severn Estuary invertebrate simulations). Mudflats outside of tidal power options were still assumed to be occupied by the invertebrate species community recorded on the Severn.For all species except curlew and oystercatcher, the maximum population size that could be supported was greater than the population size present during 2008-2009. This implies that surplusfood is available for these species, and that the duration of intertidal exposure was long enough to allow these species to meet their daily energy requirements throughout the winter.There was a general tendency for the larger bird species to be either be unsupported at current population sizes (curlew and oystercatcher), or to be very close to carrying capacity (black-tailedgodwit). These species have higher energy requirements and require larger prey items (which are generally lacking on the Severn) to meet their daily requirements.The B3 Cardiff-Western barrage had the largest negative effect on the bird populations. This barrage reduced mudflat area and reduced the duration of exposure of most patches. The total food resource for birds was therefore reduced as was the time birds had to feed. Relatively large amounts of long term erosion were predicted for the B3 Cardiff-Western barrage and this further reduced the population sizes of birds that were predicted to be supported. Assuming non-Severn Estuary invertebrate communities increased the number of birds supported by this option, but it was still predicted to have a more negative effect on bird populations than other options.The B4 Shoots and B5 Beachley barrages and the L2 Welsh Grounds lagoon had very similar negative effects on the size of bird populations supported. These options either had no effect ordecreased the area of mud within the patches they enclosed, and reduced the duration of exposure within the patches they enclosed. These options had a double negative effect on the birds as theyboth reduced the total amount of food available and reduced the time available for feeding. Relatively small amounts of erosion were predicted for these options and so short and long-term predictionswere similar. Assuming non-Severn Estuary invertebrate communities had little effect on the population sizes of birds predicted to be supported with these options.The L3 Bridgwater Bay lagoon decreased the mud area but increased the duration of exposure within the patch it enclosed. Despite this, when assuming Severn estuary invertebrate communities, this option had a slightly more negative effect than the B4, B5 and L2 options. This implies that the size of the bird population that can be supported is more sensitive to variation in mud area than it is to variation in the duration of exposure. Relatively small amounts of erosion were predicted for this option and so short and long-term predictions were similar. Assuming non-Severn Estuary invertebrate communities increased the population sizes of birds predicted to be support, and in these simulations the L3 Bridgwater Bay lagoon was predicted to support larger population sizes of birds than were predicted in the baseline simulations.Three species, Dunlin Calidris alpina, Curlew Numenius arquata and Redshank Tringa totanus, are named in the Special Protection Area (SPA) designation for the Severn Estuary. If the Severn Estuary is to remain in favourable condition from an SPA perspective, any tidal power options should still allow at least these population sizes of these species to be supported. The baseline simulations predicted that this was only the case for Redshank. For Dunlin and Curlew, the food supplies included in the baseline model were predicted not to be sufficient to support the population sizes of these species present at the time of SPA designation. Most tidal power options reduced the population size that could be supported. In these cases, the prediction was that the food supplies included in the model, in combination with the tidal power options were not sufficient to support the population sizes of Dunlin and Curlew. The food supplies were sufficient to support the SPA population size of Redshank in all cases. The L3 Bridgwater Bay lagoon in combination with non-Severn estuary invertebrates increased the population sizes of all of these species. In this case, the prediction was that the population sizes of Dunlin, Curlew and Redshank present at the time of SPA designation could be supported by the food supplies included in the model. |
| Funders: | Parsons Brinckerhoff Ltd, Black and Veatch Limited, Department for Energy and Climate Change |
| Papers or reports: | Bournemouth University, 2010. Severn tidal power - Sea topic paper. Waterbirds. Annex 3 – Waterbird Individual based modelling. Poole, Dorset, Bournemouth University. |

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| Case study title: | Severn Estuary (B) |
| Location: | 51.585172, -2.660959 |
| Birds: | Grey plover *Pluvialis squatarola*Ringed plover *Charadrius hiaticula*Oystercatcher *Haematopus ostralegus*Curlew *Numenius arquata*Black-tailed gotwit *Limosa limosa*Dunlin *Calidris alpina*Knot *Calidris canutus*Redshank *Tringa totanus*Turnstone *Arenaria interpres* |
| Modelling: | MORPH |
| Abstract: | With the pressures that today’s ecosystems are being placed under, from both environmental change and anthropogenic developments, the speed at which management decisions need to be made has increased. Coastal development means that estuaries are particularly affected and their characteristic species, like wading birds(Charadrii), are now experiencing worldwide declines. In such situations there is a need for predictive ecology to understand in advance how species might react to future changes.This thesis looks into how we can use individual-based models (IBM) to make accurate predictions of how wading birds are affected by environmental change. Starting with previously validated models I show the importance of measuring size of invertebrates though an IBM investigation into regime shifts and wading birds responses. The models show that by altering their diet preferences, birds adapt to regime shifts in their prey but that this maintenance of population size masks the true changes in the system and limits the use of waders as direct bio-indicators of ecosystem health. Using the current literature, an analysis on empirical responses of wader populations to environmental change revealed the lack of comparability between studies and the scarcity of studies on small scale events.Data from literature and fieldwork was used to develop a comparable suite of individual-based models for five UK estuaries with up to eleven wading bird species. These models were validated using current BTO Wetland Bird Surveys data to increase confidence in final results. Using these new models, investigations of population thresholds and environmental change were carried out. Increases to current populations revealed that several estuaries are no longer able to support the number of birds around the time of Special Protection Area designation. This, alongside higher populations currently seen since the years of designation, indicates the need for re-assessment of SPA species numbers. When looking at the impacts of two types of environmental change, habitat loss and sea-level rise, certain species declined predictably across sites whilst the individual make up of each estuary had particular impacts on some waders more than others. The work of this thesis further indicates the great potential of using individual-based models to predict the effects of a wide range of environmental changes. With the new models and a quicker and systematic way of developing IBMs for additional areas, wecan aid the conservation and management of estuarine systems for wading birds. |
| Funders: | Bournemouth University and HR Wallingford |
| Papers or reports: | Bowgen, K.M., 2016. Predicting the effect of environmental change on wading birds: insights from individual-based models. PhD thesis, Bournemouth University in collaboration with HR Wallingford. |

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| Case study title: | Solway Firth |
| Location: | 54.939633, -3.35944 |
| Birds: | Oystercatcher, *Haematopus ostralegus*Knot *Calidris canutus* |
| Modelling: | MORPH |
| Abstract: | Stillman (2008): This is a final report describing the predicted effect of shellfishing on the oystercatcher Haematopus ostralegus and knot Calidris canutus populations of the Solway Firth during the winter of 2007/08. These predictions have been derived from a model, MORPH, that has been used to predict the influence of shellfishing, and other forms of environmental change, on shorebirds on several UK and European sites (e.g. Caldow et al., 2004; Caldow et al., 2007; Durell et al., 2006; Durell et al., 2007; Stillman et al., 2000; Stillman et al., 2001; Stillman et al., 2003; Stillman et al., 2005b; West et al., 2003). This report collates the results presented in four preliminary reports produced during the course of the project (preliminary reports dated 30/09/2007, 14/10/2007, 19/10/2007 and 31/10/2007). The report describes the model used during the project, describes how the model was parameterised for the Solway Firth, and presents the predictions of the model.Stillman and Wood (2013):In this report we use a recently-­‐developed spreadsheet model to predict the overwinter food requirements of two shorebird species, oystercatcher (Haematopus ostralegus) and red knot (Calidris canutus), within the Solway Firth. The model is based on the energy requirements of the birds together with the energy value of their shellfish food. The model predicts the quantity of shellfish required to maintain high survival rates, and hence avoid significant mortality events within the oystercatcher and knot populations. Knot were assumed to consume 5-­‐14mm cockles (Cerastoderma edule L.), 5-­‐24mm mussels (Mytilus edulis L.) and 8-­‐16 mm tellin (Macoma balthica L.). Oystercatcher were assumed to consume >15mm cockles, 30-­‐60mm mussels and >12mm tellin. The biomasses of invertebrate prey were derived from intertidal surveys of the site. The population sizes of the bird species were derived from Wetland Bird Survey (WeBS) core counts. Predictions were for the winter of 2013-­‐2014. Shellfishing was assumed to exploit >28mm cockles. The food requirements of oystercatcher and knot were predicted for different combinations of food supply. All scenarios assumed that the birds could consume cockles, mussels and tellin. Alternative scenarios assumed that knot and oystercatcher could consume other food from upshore areas, or that oystercatcher could consume food from terrestrial habitats. Cockle and tellin biomasses were estimated within Solway Firth, and at Wigtown Bay, a site outside the area in which bird population sizes were estimated. Further scenarios therefore assumed that birds either could, or could not, consume food from Wigtown Bay. In each scenario the model initially predicted the amount of shellfish biomass not required by the birds. This was then converted into the biomass potentially available for fishing, accounting for the fact that the size range exploited by fishing did not overlap completely with that consumed by the birds. In the case of knot there was no overlap, and so the amount available to fishing was only calculated from the biomass of shellfish not required by oystercatcher. The model predicted that approximately 700 tonnes of >28mm cockles could potentially be exploited by shellfishing during the winter of 2013-­‐2014, after taking into 5 account the food requirements of the birds, excluding cockle and tellin biomass in Wigtown Bay, and assuming that oystercatcher consumed cockles, mussels, tellin and prey from upshore areas and terrestrial habitats. This was considered to be the most realistic scenario given that oystercatcher can potentially feed on terrestrial and upshore habitats, and given the distance between Wigtown and the area in which oystercatcher population size was estimated. The cockle, mussel and tellin surveys did not cover the entire extent of the Solway Firth, not recording cockles or tellin in English waters or mussels or the Scottish side, and so it is likely that a higher biomass of shellfish food is available to the birds in reality. However, without a more extensive survey it is not possible to quantify this. The spreadsheet model’s predictions for the winter of 2007-­‐2008 were also compared with those of a more complex individual-­‐based model that was developed for oystercatcher and knot in the Solway Firth based on shellfish biomass during 2005 to 2007. The individual-­‐based model predicted that knot survival was 100% in all simulations for the winter of 2007-­‐2008, consistent with the prediction of the spreadsheet model that 18038 tonnes of shellfish were not required by the birds during this winter. The spreadsheet model predicted that the oystercatcher population required all of the shellfish food available during the winter of 2007-­‐2008. Similarly, the individual-­‐based model predicted that oystercatcher were relatively sensitive to the amount of biomass removed by fishing during this winter. With a shellfishing Total Allowable Catch (TAC) set at 1000 tonnes there was a predicted reduction in survival and TACs set at 500, 750 and 1000 tonnes were predicted to reduce body mass. The spreadsheet model predicted that birds required all of the food during 2007-­‐2008 and hence that any TAC would reduce survival. This demonstrates that the spreadsheet model is capable of producing broadly similar predictions to the more complex individual model, although the latter is more sensitive when stock levels are more critical. |
| Funders: | Solway Shellfish Management Association. Scottish Natural Heritage. Marine Scotland. |
| Papers or reports: | Stillman, R., 2008. Predicted effect of shellfishing on the oystercatcher and knot populations of the Solway Firth, Bournemouth University, Poole, Dorset.Stillman, R.A. and Wood, K.A., 2013. Predicting food requirements of overwintering shorebird populations on the Solway Firth. A report to Scottish Natural Heritage and Marine Scotland, Bournemouth University, Poole, Dorset. |

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| Case study title: | Southampton Water (A) |
| Location: | 50.869653, -1.372339 |
| Birds: | Grey plover, *Pluvialis squatarola*Ringed plover, *Charadrius hiaticula*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Bar-tailed gotwit, *Limosa lapponica*Black-tailed gotwit, *Limosa limosa*Dunlin, *Calidris alpine*Redshank, *Tringa tetanus*Turnstone, *Arenaria interpres* |
| Modelling: | MORPH |
| Abstract: | Overall abstract for PhD thesis:European and UK legislation arising from The Convention on Biological Diversity 1993 aims to reduce biodiversity loss and to set guidelines for sustainable impacts of human activities. Withpredictions of increased biodiversity loss under climate change, it is paramount that present and future anthropogenic impacts on biodiversity are assessed, monitored and predicted. This thesisapplies techniques of assessment, monitoring and prediction to cases of potential losses of ornithological diversity within the Solent, UK, through overexploitation of resources, disturbance and habitat loss.An annual commercial harvest of the eggs of Black-headed Gulls was studied to assess impacts on their breeding success and distribution within the Solent. From in-situ measurements of breeding success indicators, including egg volume, hatching success and chick survival, we were able to show that harvesting of eggs reduced the breeding success of gulls, over and above effects of colony size and nest position within the colony. Ex-situ measurements on the yolk-toalbumen ratio and eggshell thickness showed that harvesting reduced these components, over and above effects of laying date. Harvested sites also had a higher proportion of abnormallyformed eggs, particularly taking the form of small yolkless eggs and unpigmented eggs. These impacts are all consistent with known effects of depletion of the female’s endogenous reserves.Data from long-term monitoring of seabirds breeding along the south coast of England indicated that egg harvesting and the associated disturbance may be directly and negatively influencing the breeding distribution of Black-headed Gulls and also the protected Mediterranean Gull that breeds in its colonies. Data suggests that egg harvesting has prevented the colonisation of Mediterranean Gulls on these sites, whereas un-harvested sites have seen rapid colonisation in the last 10 years. On this basis, both EU and UK legislation may be being violated, through infringement of the regulations surrounding the Mediterranean Gull as an Annex 1 (EC Birds Directive 1979) and Schedule 1 (Wildlife and Countryside Act 1981) species; and through the breeding habitat within the Solent being SACs and SPAs. Protected tern species that associate with Black-headed gull colonies start laying after the harvesting season, but are nevertheless susceptible to the collapse of harvested colonies.As well as its gull colonies, the Solent sustains important populations of wintering shorebirds that rely on the food resource supplied by estuaries and tidal flats. The quantity and composition of macrobenthic invertebrate prey in the Southampton Water SPA was sampled with a stratified-random design for ANOVA. The split-plot ANOVA revealed a higher level of heterogeneity within the estuary than could be resolved from the multiple regression techniques that are normally applied to grid-based designs. Bootstrap resampling indicated that the ANOVA design predicted invertebrate assemblages with adequate precision to produce an individual-based predictive model of site quality for shorebirds over-wintering on Southampton Water. This model accurately predicted the observed shorebird distribution, on the assumption that non-starving birds moved within restricted sections of the site, consuming any prey that yielded a threshold energy assimilation rate. Dunlin and curlew were the species predicted to be most sensitive to loss of prey biomass or overall habitat area, with losses of 5-10% provoking significant impacts on survival. When the area for the proposed development of a port terminal at Dibden Bay was modelled as habitat loss, the impacts on shorebird survival were eliminated by the proposed mitigation. However, our model did not account for the years of habitat removal and construction of the mitigation sites. Despite these limitations the model indicated the potential for evaluating ornithological losses within the Solent from a small loss of intertidal habitat.Chapter 5: European conservation law now requires environmental impact assessments of estuary sites of importance to over-wintering shorebirds. Reliable methodologies are consequently needed to monitor site quality and assess impacts of habitat loss. We developed an individual-based model of Southampton Water to evaluate site quality for eight shorebirds: dunlin Calidris alpina, ringed plover Charadrius hiaticula, ruddy turnstone Arenaria interpres, redshank Tringa totanus, grey plover Pluvialis squatarola, black-tailed godwit Limosa limosa, Eurasian oystercatcher Haematopus ostralegus and Eurasian curlew Numenius arquata. Over-winter survival was predicted both with and without 7% habitat loss for the proposed construction of a port terminal at Dibden Bay. The model accurately predicted the observed shorebird distribution if non starving birds were assumed to move within restricted sections of the site, consuming any prey which yielded a threshold energy assimilation rate. In contrast, the model predicted that too few patches were occupied if birds were assumed to consume only those prey that maximised energy assimilation rate. All species except turnstone and oystercatcher were reliant on the consumption of annelids to maintain high survival rates. Dunlin and curlew were predicted to be the species most likely to have reduced survival if either prey biomass or overall habitat area were reduced. In some simulations, the habitat loss caused by the Dibden Bay port terminal was predicted to decrease the survival rate of dunlin by 2.7%, turnstone by 0.9% and curlew by 1.7%, but did not effect the survival of any other species. The effect of habitat loss on these species was eliminated by the proposed mitigation of a tidal creek. The predicted success of the mitigation, however, did not account for the years required to construct the mitigation habitat, or any accumulative effects on the mortality of shorebirds which would be forced to feed from other sites within the estuary. |
| Funders: | English Nature, ABPmer, Beaulieu Estate |
| Papers or reports: | Wood, P.J. (2007). Human impacts on coastal bird populations in the Solent. PhD thesis, University of Southampton. |

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| Case study title: | Southampton Water (B) |
| Location: | 50.869653, -1.372339 |
| Birds: | Golden plover*, Pluvialis squatarola*Ringed plover, *Charadrius hiaticula*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Black-tailed gotwit, *Limosa limosa*Dunlin, *Calidris alpine*Redshank, *Tringa tetanus* |
| Modelling: | MORPH |
| Abstract: | The Solent coastline provides feeding grounds for internationally protected populations of overwintering waders and wildfowl, and is also extensively used for recreation. In response to concerns over the impact of recreational pressure on birds within protected areas in the Solent, the Solent Forum initiated the Solent Disturbance and Mitigation Project to determine visitor access patterns around the coast and how their activities may influence the birds. The project has been divided into two phases. Phase I collated and reviewed information on housing, human activities and birds around the Solent, and reviewed the potential impact of disturbance on birds. Phase II has involved a programme of major new data collection to (i) estimate visitor rates to the coast from current and future housing, (ii) measure the activities and distances moved by people on the shore and intertidal habitats, and (iii) measure the distances and time for which different bird species respond to different activities. The current report represents the culmination of Phase II, in which the primary data are used to predict whether disturbance may be reducing the survival of birds. Predictions are derived for wader species by developing detailed computer models of birds and disturbance within Southampton Water and Chichester Harbour. These models create a virtual environment within the computer incorporating the intertidal invertebrate food supply of the birds, the exposure and covering of this food through the tidal cycle, disturbance from human activities, and the energy requirements and behaviour of the birds as they avoid humans and search for food. The invertebrate food supply of birds in the models was derived from previous intertidal surveys, and the exposure of intertidal habitat predicted from a tidal model of the Solent. The models incorporate the costs that birds incur when avoiding human activities (e.g. increased density in non-disturbed areas, reduced time for feeding and increased energy demands when flying away), but also their abilities to compensate for these costs (e.g. by feeding for longer or avoiding more disturbed areas). The predictions indicate how disturbance may be effecting the survival of waders throughout the Solent. The following waders were included in the models: Dunlin Calidris alpina, Ringed Plover Charadrius hiaticula, Redshank Tringa totanus, Grey Plover Pluvialis squatarola, Black-tailed Godwit Limosa limosa, Bar-tailed Godwit Limosa lapponica (Chichester Harbour model only), Oystercatcher Haematopus ostralegus and Curlew Numenius arquata. A simpler approach was used to assess how disturbance may be effecting Brent Geese in the Solent. As with any models, the predictions of the models used in this project depend on the data with which they are parameterised and the assumptions they make about the real system. The current and future visitor rates used in the models were themselves predicted using statistical analyses of household survey and on-site visitor data. The responses of birds to disturbance were parameterised using on-site observations of the responses of birds to disturbance. Furthermore, models are a simplification of real systems, and it is important to recognise this when interpreting their predictions. The report considers how the model parameters and assumptions may influence predictions. These include: (i) the way in which the disturbance data were measured and assumptions made about how birds and people are distributed in space and time; (ii) the way in which the behaviour of birds to disturbance differs between sites; (iii) the effect of extreme weather on the birds; (iv) how rare or localised activities are incorporated into the models; and (v) how consumption of food by species other than waders is included. The project predicted changes in visitor numbers to the Solent coast. Local authorities in the Solent region provided projections of future housing developments in the region. These were combined with data on visitor rates to different parts of the coast and the distance travelled to visit the coast, to predict coastal visitor rates with current and future housing. Using current housing levels, 52 million household visits per year to the Solent coast were predicted (i.e. the shore from Hurst Castle to Chichester Harbour, including the north shore of the Isle of Wight). Using the housing data provided by local authorities, visitor numbers were predicted to rise by around 8 million household visits, to a total of 60 million, an overall increase of 15%. Within Chichester Harbour, the food supply surveyed was not predicted to be able to support the majority of wading birds modelled. This implied that either the invertebrate survey underestimated the intertidal food supply, or that other food was available either terrestrially, or from neighbouring intertidal sites such as Langstone Harbour. Similar invertebrate surveys have been used to parameterise 17 other similar models, and in all cases birds were predicted to have survival rates close to, or higher than those expected. Due to uncertainties with the Chichester Harbour invertebrate data, it was decided not to use the Chichester Harbour model to predict the effect of disturbance on the birds. However, it is important to note what the effect of low food abundance would be on the effect of disturbance on the birds. The impact of disturbance on survival and body condition will depend on the birds’ ability to compensate for lost feeding time and extra energy expenditure. Birds will be better able to compensate when more food is available, and so lower food abundance in a site will make it more likely that disturbance decreases survival and body condition. Within Southampton Water, in the absence of disturbance, all wader species modelled were predicted to have 100% survival and maintain their body masses at the target value throughout the course of winter. Disturbance from current housing was predicted to reduce the survival of Dunlin, Ringed Plover, Oystercatcher and Curlew. Increased visitor numbers as a result of future housing was predicted to further reduce the survival of Dunlin and Ringed Plover. Disturbance was predicted to have a relatively minor effect on the mean body mass of waders surviving to the end of winter, largely because the individuals with very low mass starved before the end of winter. The Southampton Water model provided evidence that current and future disturbance rates may reduce wader survival in this site. Hypothetical simulations were run to explore how intertidal habitat area, energy demands of the birds and the frequency of different activities may influence the survival of waders within Southampton Water. The survival rates of Dunlin, Ringed Plover, Oystercatcher and Curlew were predicted to be decreased by any reduction in intertidal habitat area (e.g. due to sea level rise) or increases in energy demands (e.g. due to disturbance at roosts or cold weather). Wader survival was predicted to increase if intertidal activities were moved to the shore. This meant that the disturbance from these activities was restricted to the top of the shore rather than the whole intertidal area, and so the proportion of intertidal habitat disturbed was reduced. Reductions in the number of dogs that were off leads were also predicted to increase the survival of some wader species. Removing bait digging from simulations did not increase wader survival. However, this happened because baitdigging was assumed to be a relatively infrequent activity. This does not mean that bait-digging could not adversely affect the birds if it occurs at a higher frequency, and the simulations did not incorporate the depletion of the invertebrate prey of the birds caused by bait digging, which would be an additional effect on the birds in addition to disturbance. Brent Geese were considered in the light of the Solent Waders and Brent Goose Strategy. Important issues are the size of individual sites, their spacing and the ease with which birds can move between the sites. A high proportion of each site needs to be further away from visitor access routes than the distances over which birds are disturbed to ensure that disturbance to the birds is minimised. This could be achieved through a network of larger sites or by preventing visitor access through, or close to, smaller sites. Both intertidal and terrestrial food resources are important to the birds, intertidal food typically being of higher food value but dying back and / or becoming depleted during the autumn / early winter. Previous models of Brent Geese have predicted that the loss of terrestrial habitat typically has the highest effect on survival, and so such habitat is predicted to be particularly important for the birds. Maintaining a suitable network of saltmarsh sites will be increasingly important as the total area of saltmarsh declines with sea level rise. The findings of the present project are in general support with the recommendations of the Solent Waders and Brent Goose Strategy. Predicted current visitor rates varied widely throughout the Solent, but were relatively high within Southampton Water. The highest percentage increases in visitor rates were on the Isle of Wight (50-75%). Wader survival was predicted to be decreased in Southampton Water when daily visitor rates to coastal sections were greater than 30 per ha of intertidal habitat. The potential impact of visitors on wader survival throughout the Solent was calculated by comparing visitor densities throughout the Solent (expressed relative to maximum intertidal habitat area) to the visitor densities predicted to decrease bird survival within Southampton Water. The intertidal food supply within Chichester Harbour was insufficient to support the model birds and so any disturbance (by reducing feeding area or time, or increasing energy demands) would have decreased predicted survival in this site. There is also doubt as to the food supply within the other harbours and so some caution is appropriate when applying the results from Southampton Water to these sites. Coastal sections with daily visitor rates over 30 per ha are identified. The predictions of the Southampton Water model suggest that birds within these sections may have reduced survival due to disturbance from visitors. Whether or not such visitor rates will reduce survival will depend on the food abundance in the coastal sections themselves as well as that in neighbouring sections. The area of overlap between an activity / development and the distribution of birds is often used as a measure of the impact of the activity on the birds, with 1% overlap often taken as the threshold for impact (note however that this 1% overlap does not necessarily mean that an activity will have an adverse effect on the survival or body condition of birds). Therefore, the percentage of intertidal habitat disturbed within each coastal section was calculated as an index of the potential impact of disturbance on the birds. Assuming the maximum intertidal area and only including intertidal visitors, over 50% of the area of many coastal sections was predicted to be disturbed, with an average of 42%. |
| Funders: | Solent Forum |
| Papers or reports: | Stillman, R.A., West, A.D., Clarke, R.T. and Liley, D., 2012. Solent Disturbance and Mitigation Project Phase II. Predicting the impact of human disturbance on overwintering birds in the Solent, Solent Forum, Bournemouth. |

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| Case study title: | Southampton Water (C) |
| Location: | 50.869653, -1.372339 |
| Birds: | Grey plover, *Pluvialis squatarola*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Black-tailed gotwit, *Limosa limosa*Dunlin, *Calidris alpine*Redshank, *Tringa tetanus*Turnstone, *Arenaria interpres* |
| Modelling: | MORPH |
| Abstract: | With the pressures that today’s ecosystems are being placed under, from both environmental change and anthropogenic developments, the speed at which management decisions need to be made has increased. Coastal development means that estuaries are particularly affected and their characteristic species, like wading birds(Charadrii), are now experiencing worldwide declines. In such situations there is a need for predictive ecology to understand in advance how species might react to future changes.This thesis looks into how we can use individual-based models (IBM) to make accurate predictions of how wading birds are affected by environmental change. Starting with previously validated models I show the importance of measuring size of invertebrates though an IBM investigation into regime shifts and wading birds responses. Themodels show that by altering their diet preferences, birds adapt to regime shifts in their prey but that this maintenance of population size masks the true changes in the system and limits the use of waders as direct bio-indicators of ecosystem health. Using the current literature, an analysis on empirical responses of wader populations toenvironmental change revealed the lack of comparability between studies and the scarcity of studies on small scale events.Data from literature and fieldwork was used to develop a comparable suite of individual-based models for five UK estuaries with up to eleven wading bird species. These models were validated using current BTO Wetland Bird Surveys data to increase confidence in final results. Using these new models, investigations of populationthresholds and environmental change were carried out. Increases to current populations revealed that several estuaries are no longer able to support the number of birds around the time of Special Protection Area designation. This, alongside higher populations currently seen since the years of designation, indicates the need for re-assessment of SPA species numbers. When looking at the impacts of two types of environmental change, habitat loss and sea-level rise, certain species declined predictably across sites whilst the individual make up of each estuary had particular impacts on some waders more than others. The work of this thesis further indicates the great potential of using individual-based models to predict the effects of a wide range of environmental changes. With the new models and a quicker and systematic way of developing IBMs for additional areas, wecan aid the conservation and management of estuarine systems for wading birds. |
| Funders: | Bournemouth University and HR Wallingford |
| Papers or reports: | Bowgen, K.M., 2016. Predicting the effect of environmental change on wading birds: insights from individual-based models. PhD thesis, Bournemouth University in collaboration with HR Wallingford. |

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| Case study title: | Strangford Lough |
| Location: | 54.557461, -5.625599 |
| Birds: | Pied oystercatcher, *Haematopus longirostri* |
| Modelling: | Non MORPH |
| Abstract: | 1. The objective of this project was to predict the potential impact of cockle harvesting on the oystercatcher population in Strangford Lough. Although there is currently no licensed commercial cockle fishery in Strangford Lough, some commercial cockle harvesting occurred following a crash in the cockle population of the Wash, Eastern England. Strangford Lough supports an overwintering population of between 5000 and 6000 oystercatchers, the majority of which feed on cockles and thus may be affected by commercial cockle harvesting. 2. The model used for this project was an individual behaviour-based model. The model incorporates the two aspects of shellfishing that are potentially detrimental to birds, depletion of their shellfish prey and disturbance. It follows individual birds and their behavioural responses to shellfishing, so it could be used to predict whether birds could compensate for the effects of shellfishing by feeding on alternative sources of food when cockle beds were not available. More importantly, it could predict the effects of different shellfishing regimes on bird body condition and mortality, crucial aspects of fitness in an overwintering population. 3. A number of important parameter values in the model were derived from extrapolated data, e.g. the abundance of cockles in the Lough. There were no available data on the quality of alternative feeding areas, such as upshore mudflats and terrestrial fields, which are often important to birds. The quality of these areas was assumed to be comparable to that in other sites. All of the model’s predictions therefore depend on the reliability of the cockle data and the assumption of the quality of alternative feeding areas, and thus must be treated as provisional. Predictions that are more accurate could be produced if a complete survey of the cockle beds and other feeding areas were to be conducted. 4. The model showed that the current estimated cockle stocks are sufficient to support the oystercatcher population of Strangford Lough, even under adverse circumstances such as a prolonged period of cold weather or a lack of alternative feeding areas. However, if the cockle beds declined in area, the birds would be more vulnerable and a large proportion might be in poor condition at the end of winter. 5. Harvesting of cockles by hand-gathering was predicted to have less effect on the birds than harvesting using a tractor-towed dredge. This was particularly true if the dredge killed cockles below its minimum fishable size. The model predicted one-third of current cockle stocks could be harvested by hand-gathering without any effect on oystercatcher mortality or body condition. 6. In comparison to allowing hand-gathering of cockles throughout the winter, restricting it to the second half of winter reduced its impact on the birds significantly. Conversely, restricting hand-gathering to the first half of winter substantially increased bird mortality at low shellfish harvests. Daily and weekly bans on hand gathering reduced bird mortality, but were less effective than an early-season ban. 7. The predictions of the current model, based largely on extrapolated data, show that Strangford Lough has the potential to support a licensed cockle fishery without affecting the oystercatchers that overwinter there. However, the predicted 2 oystercatcher mortality rate was highly sensitive to the cockle stocks, which should be surveyed completely to confirm this prediction.8. Suggestions are made as to how further research could remove some uncertainties in the current parameter values used in the model, enabling the model to predict more accurately the effects of different types and intensities of shellfishing on the oystercatcher population. |
| Funders: | The Environment and Heritage Service |
| Papers or reports: | West, A.D., Stillman, R.A. and Portig, A., 2002. Modelling of the interaction between oystercatchers and shellfish in Strangford Lough, Northern Ireland, Centre for Ecology and Hydrology, Dorset. |

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| Case study title: | Svalbard (Trøndelag, Vesterålen, plus Belgium, the Netherlands, Denmark, West Jutland) |
| Location: | 77.883525, 19.826522 |
| Birds: | Pink-footed goose, *Anser brachyrhynchus* |
| Issues: | n/a |
| Modelling: | MORPH |
| Abstract: | By permission of Oxford University Press:Decisions taken during migration can have a large effect on the fitness of birds. Migration must be accurately timed with food availability to allow efficient fueling but is also constrained by the optimal arrival date at the breeding site. The decision of when to leave a site can be driven by energetics (sufficient body stores to fuel flight), time-related cues (internal clock under photoperiodic control), or external cues (temperature, food resources). An individual based model (IBM) that allows a mechanistic description of a range of departure decision rules was applied to the spring migration of pink-footed geese (Anser brachyrhynchus) from wintering grounds in Denmark to breeding grounds on Svalbard via 2 Norwegian staging sites. By comparing predicted with observed departure dates, we tested 7 decision rules. The most accurate predictions were obtained from a decision rule based on a combination of cues including the amount of body stores, date, and plant phenology. Decision rules changed over the course of migration with the external cue decreasing in importance and the time-related cue increasing in importance for sites closer to breeding grounds. These results are in accordance with descriptions of goose migration, following the “green-wave”: Geese track the onset of plant growth as it moves northward in spring, with an uncoupling toward the end of the migration if time is running out. We demonstrate the potential of IBMs to study the possible mechanisms underlying stopover ecology in migratory birds and to serve as tools to predict consequences of environmental change. |
| Funders: | Marie-Curie Intra-European Fellowship within the 6th European Community Framework Programme |
| Papers or reports: | Duriez, O., Bauer, S., Destin, A., Madsen, J., Nolet, B.A., Stillman, R.A. and Klaassen, M., 2009. What decision rules might pink-footed geese use to depart on migration? An individual-based model. Behavioral Ecology, 20(3): 560-569. |

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| Case study title: | The Wash (A) |
| Location: | 52.898858, 0.216783 |
| Birds: | Oystercatcher, *Haematopus ostralegus* |
| Modelling: | Not MORPH |
| Abstract: | Goss-Custard et al. 2004:In a number of extensive coastal areas in northwest Europe, large numbers of long-lived migrant birds eat shellfish that are also commercially harvested. Competition between birds and people for this resource often leads to conflicts between commercial and conservation interests. One policy to prevent shellfishing from harming birds is to ensure that enough food remains after harvesting to meet most or all of their energy demands. Using simulations with behaviour-based models of five areas, we show here that even leaving enough shellfish to meet 100% of the birds’ demands may fail to ensure that birds survive in good condition. Up to almost eight times this amount is needed to protect them from being harmed by the shellfishery, even when the birds can consume other kinds of non-harvested prey.Stillman et al. 2003 © 2003 British Ecological Society:1. The debate over the interaction between shellfishing and shorebirds is long-running. Behaviour-based models predict how animal populations are influenced by environmental change from the behavioural responses of individual animals to this change. These models are a potential tool for addressing shellfishery problems, but to be of value they must produce reliable predictions using data that are readily available or can be collected relatively quickly.
2. We parameterized a behaviour-based model for the oystercatcher population of the Wash, UK, for 1990–99 using data from shellfishery (mussels and cockles), shorebird and climate monitoring schemes. During the 1990s the overwinter mortality rates of Wash oystercatchers varied widely. The model correctly identified the years in which the observed overwinter mortality was either low (1–2%) or high (10–26%) from annual variation in the food supply, oystercatcher population size and temperature.
3. Many oystercatchers were observed and predicted to die when only a fraction of the available food was consumed. Within the model at least, this was because interference competition excluded the least dominant birds from part of the food supply and the least efficient foragers died before the food supply was fully depleted. A simplified model, which excluded interference and individual variation, incorrectly predicted that all birds survived in all years. Models that exclude these two components of behaviour will tend to underestimate the effect of mussel and cockle food shortage on oystercatchers. Shellfishery management based on such predictions may cause high oystercatcher mortality rates even though enough food would appear to be reserved for the birds.
4. Synthesis and applications. This study shows how a behaviour-based model can be parameterized and predict annual variation in oystercatcher mortality using data routinely collected from the Wash. The principle on which the model is based, that animals behave in order to maximize their chances of survival and production, applies to any system, and the shellfishery, bird and climate data used to parameterize the model are widely available. The model can be used to advise how to manage shellfisheries, by predicting the proportion of the stock that needs to remain unfished in order to maintain low oystercatcher mortality rates.
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| Funders: | No information provided. |
| Papers or reports: | Goss-Custard, J.D., Stillman, R.A., West, A.D., Caldow, R.W.G., Triplet, P., le V dit Durell, S.E.A. and McGrorty, S., 2004. When enough is not enough: shorebirds and shellfishing. Proceedings. Biological Sciences, 271(1536): 233-237.Stillman, R.A., West, A.D., Goss-Custard, J.D., Caldow, R.W.G., Mcgrorty, S., Durell, S.E.A.L.V.D., Yates, M.G., Atkinson, P.W., Clark, N.A., Bell, M.C., Dare, P.J. and Mander, M., 2003. An individual behaviour-based model can predict shorebird mortality using routinely collected shellfishery data. Journal of Applied Ecology, 40(6): 1090-1101. |

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| Case study title: | The Wash (B) |
| Location: | 52.898858, 0.216783 |
| Birds: | Common scoter, *Melanitta nigra*Eider*, Somateria mollissima*Oystercatcher, *Haematopus ostralegus* |
| Modelling: | MORPH |
| Abstract: | Contains public sector information licensed under the Open Government Licence v3.0This report presents the results of a research project carried out by the Centre for Ecology and Hydrology for Natural England in order to determine the capacity of The Wash shellfish stocks to support eider ducks *Somateria mollissima*.Since 2003, mussel *Mytilus edulis* farmers on The Wash have reported high levels of mussel predation on their lays by eider ducks. In order to limit this predation some lay holders applied for consent from English Nature (now Natural England) to use scaring devices and some also applied to the Department of the Environment, Food and Rural Affairs (Defra) for a licence to shoot eiders. In advance of the public inquiry to address this conflict between eiders and the shellfish industry, Defra identified a need to develop knowledge and understanding of four key areas so that objective data would be available to facilitate decision making:1. The eider population size in The Wash.2. The number of eiders that the site can support when the mussel and cocklebeds are in favourable condition.3. The effectiveness of scaring devices in protecting the mussel stocks.4. The impact of the scaring devices on eiders and non-target species.This project was commissioned by Natural England to address the second key area. The principal aims of this project were as follows.• To conduct a literature review of the current understating of eider feeding behaviourand scoping of modelling work.• To develop and parameterise a model of eider ducks in The Wash.• To validate this model against independent empirical data• To conduct model simulations of a range of alternative shellfish stock/management scenarios in order to predict their effect on the level of eider duck mortality.Over 100 published scientific papers and reports principally concerned with the ecology of diving dicks in general and eider in particular were collated and reviewed. The key points of relevance to the development of a behaviour-based model of the system were added to an existing Excel database arsing from a previous project on common scoters *Melanitta nigra*. This combined database is presented as a series of appendices to this report. This literature review provided information with which to parameterise the model and other independent data against which to validate it.An existing behaviour-based model developed previously by CEH was parameterised to create a model of the populations of eider ducks and oystercatchers *Haematopus ostralegus* within The Wash and of the principle populations of shellfish that they exploit within it ie mussels, cockles *Cerastoderma edule* and American jack-knife clam *Ensis directus.* Parameterisation was based on information gleaned from the literature review and on the results of recent surveys of the shellfish stocks of The Wash conducted by Eastern Sea Fisheries Joint Committee, Centre for Environmental, Fisheries and Aquaculture Science and Ecomaris Ltd.The output generated by the model was validated against independent data concerning: the proportion of time that birds spend feeding, their daily consumption of food, daily energy expenditure, body mass, distribution and over-winter mortality. In all cases, the output of the model, when parameterised to mimic current day conditions in The Wash, fell within the likely range of expected values.One series of model simulations was conducted to explore the consequences for the existing over-wintering populations of eiders and oystercatchers of changes to the total quantity of mussels available to them on the commercially cultivated lays against a number of alternative backgrounds in which the other shellfish stocks were varied in the light of the historical variation that they have shown. These simulations served to explore the impact on theexisting eider and oystercatcher populations of a reduction in the stock of lay mussels and whether this impact varied in relation to the abundance of other shellfish stocks available to the birds.A second series of model simulations was conducted to explore the consequences for the existing over-wintering populations of eiders and oystercatchers of changes to the distribution of the current total stock of mussels available to them on the commercially cultivated lays (c 10,000 tonnes) against a number of alternative backgrounds in which the other shellfish stocks were varied in the light of the historical variation that they have shown. These simulations served to explore the impact on the existing eider and oystercatcher populations of changes to the management of the commercially cultivated mussel lays and whether this impact varied in relation to the abundance of other shellfish stocks available to the birds. In both of these series of simulations, the model was also used to predict the tonnage of shellfish removed by both eider ducks and oystercatchers from each of the shellfish stocks.A third series of simulations was conducted in which the size of the peak population of eider ducks was varied and the stocks of the two ‘un-natural’ shellfish resources in The Wash i.e. commercially cultivated lay mussels and *Ensis directus* were set to either large or small values. These simulations were conducted to establish the extent to which the maximum size of the eider population that could be supported varied in response to variation in these two shellfish resources which appear to be currently of overwhelming importance to the eider population.The key conclusions that can be drawn from all of these simulations are as follows:1. The recent aggregation of eiders on the Roger and Toft lays can be explained purely in terms of the high density of high quality shellfish of a suitable size present there.2. The proportion of the oystercatcher population that exploits the commercially cultivated mussel lays is far smaller than that of eiders.3. Over-winter losses of mussels from lays to eiders and oystercatchers are estimated to be around 600 tonnes and 100 tonnes respectively. In the case of eiders this is entirely from the Roger and Toft lays.4. The percentage of the peak eider population of 3,000 birds that cannot be supported under current circumstances is predicted to be around 4 per cent. This is in close agreement with independent estimates of the typical over winter mortality rate of eiders.5. The percentage of the peak oystercatcher population of 15,000 birds that cannot be supported under current circumstances is predicted to be zero.6. Provided that the stock of *Ensis directus* remains healthy, the stock of lay mussels could be reduced by up to 50 per cent without any significant effect upon the percentage of the eider population ‘at risk’.7. If the stock of lay mussels is reduced below around 50 per cent of its current value, the percentage of the eider population that could be supported is predicted to decline significantly, even in the presence of a healthy *Ensis* stock.8. As the abundance of mussels on the best lays is reduced, eider predation on the remaining lays will increase and they will switch to alternative shellfish resources. This will not be sufficient to maintain the percentage of the population that can be supported at the current low value.9. In the absence of a healthy stock of *Ensis*, the percentage of the eider population that can be supported is predicted to be far more vulnerable to any loss of access to lay mussel resources.10. Variation in the abundance of cockles or mussels on the regulated beds was not predicted to significantly alter the effect on eider ducks of changes to the abundance of lay mussels.11. Given most likely future shellfish stock scenarios, the population of oystercatchers, unlike that of eiders, is not predicted to be vulnerable to changes to the abundance of the lay mussel resource.12. Increasing the extent to which the current stock of lay mussels is concentrated is predicted to increase the relative profitability of the already best areas to eider ducks and to result in increased losses from them and hence from lays as a whole (> 650 tonnes v c 600 tonnes currently).13. Decreasing the extent to which the current stock of lay mussels is concentrated is predicted to decrease the relative profitability of the best areas to eiders, reduce predation pressure on the best lays and result in the losses of lay mussels decreasing (c 400 tonnes v c 600 tonnes).14. Evening out variations in the numerical density of mussels between the lays is predicted to even out eider predation pressure between them.15. Removing the best ‘hot spots’ of high mussel density on the lays is predicted to reduce the percentage of the eider population that can be supported.16. The percentage of the oystercatcher population that is supported is predicted to be constant irrespective of changes to the way in which the lay mussel stock is distributed.17. In contrast to eiders, increasing the extent to which the current stock of lay mussels is concentrated is predicted to reduce the profitability of the best lays to oystercatchers and to reduce losses from them. In contrast, spreading the mussels out more thinly increases the profitability of the best lays to oystercatchers and results in increased losses from them.18. Because of the relatively minor predation pressure exerted on the lays by oystercatchers in comparison to eiders, changes to the overall losses from the lays mediated by changing the distribution of mussels are driven more by the responses of eider ducks than oystercatchers.19. The current stocks of wild mussels on regulated beds and cockle stocks are, on their own, sufficient to support the current peak population of 15,000 oystercatchers.20. The current peak population of 15,000 oystercatchers could not be maintained if the stocks of mussels on the regulated beds and the stocks of cockles returned to the low values seen in the early 1990s.21. Current (or greater) stocks of wild mussels on regulated beds and cockle stocks are, on their own, insufficient to support the current peak population of 3,000 eiders. This reflects the relatively poor quality of these natural shellfish resources.22. A healthy stock of *Ensis* (in combination with current or greater stocks of mussels on the regulated beds and healthy cockle stocks) cannot, in the absence of commercially cultivated mussel stocks, maintain the present peak population of eiders.23. In the absence of a healthy stock of *Ensis*, the maximum peak population of eiders that the current lay mussel stock can support, is less than the current peak population of 3,000 birds.24. The recent high peak population of eiders in The Wash probably reflects the coincidence of an unprecedented abundant stock of lay mussel resources and a peak population of the non-native *Ensis directus*. Together, these resources have the capacity to support a peak population of between 10,000 and 12,000 eiders.25. The ability of The Wash to support the current peak population of eiders is determined by the abundance of the ‘un-natural’ shellfish resources ie commercially cultivated lay mussels and non-native *Ensis directus* rather than the stocks of the wild, native shellfish.In summary, the recently observed concentration of the bulk of a large population of overwintering eider ducks in The Wash on the Roger and Toft lays is replicated by the model. This is a foraging model, and as such the only reason for it to generate an aggregation of birds in these two locations is the presence there of a large stock of suitably sized, high quality mussels growing at a high density. The model predicts that the eiders consume c 600 tonnes of mussels from these two lays. It also predicts that, as observed, the eiders switch in late winter to feed on *Ensis directus*. The model predicts that by exploiting these two resources alone, the current peak population of c 3,000 eider ducks can be supported with only around 4 per cent being at risk of not being supported. This state of affairs depends upon the continued availability of ‘hot-spots’ of high densities of high quality mussels such as those available on the Roger and Toft lays, and upon a continued presence of a healthy stock of *Ensis directus*. The current stock and distribution of lay mussels, in combination with a healthy stock of *Ensis directus*, has the capacity to support a far larger peak population of eider ducks than has ever been observed in The Wash. However, in the absence of either of these two resources, there is predicted to be a significant increase in the percentage of the current peak populationthat will be at risk of not being supported. The health of the stocks of mussels on the regulated beds and cockle beds appear to be relatively unimportant in determining the wellbeing of the eider population in The Wash. The ability of the shellfish resources in The Wash to sustain the current peak population of c 3,00 birds is primarily a result of the coincidence of a large stock of highly aggregated, high quality lay mussels and a healthy stock of *Ensis directus* ie the stocks of the shellfish which are not a ‘natural’ part of the Wash ecosystem. |
| Funders: | Centre of Ecology and Hydrology (internal), Natural England |
| Papers or reports: | Caldow, R.W.G., Stillman, R.A. and West, A., 2003. Modelling study to determine the capacity of The Wash shellfish stocks to support eider Somateria mollissima, Centre of Ecology and Hydrology, Dorset. http://nora.nerc.ac.uk/id/eprint/1589/ |

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| Case study title: | The Wash (C) |
| Location: | 52.898858, 0.216783 |
| Birds: | Grey plover, *Pluvialis squatarola*Oystercatcher, *Haematopus ostralegus*Curlew, *Numenius arquata*Bar-tailed godwit, *Limosa lapponica*Black-tailed godwit, *Limosa limosa*Dunlin, *Calidris alpine*Knot, *Calidris canutus*Redshank, *Tringa tetanus* |
| Modelling: | MORPH |
| Abstract: | Reproduced with permission from Elservier:Conservation managers responsible for estuaries are often required to monitor their site to ensure that the conservation status of any bird species for which the site is considered important is not affected by deterioration of their habitat or by disturbance of the birds themselves. Here, we use an individuals-based model to predict the quality of the Wash embayment, UK, defined in this case as overwinter survival rate, for eight shorebird species. We use the model to predict how site quality would be affected by changes in the types of prey available, prey density, mudflat area and the rate at which birds are disturbed. The results suggested that Macoma, Hydrobia and Corophium had relatively little influence on sitequality for any species modelled except black-tailed godwit, despite being the preferred prey for some bird species. Arenicola marina, other annelids and Cerastoderma edule were found to be important influences on site quality. Birds began to starve, when autumn, estuary-wide food biomass density was below about 5 g AFDMm−2 and survival rates fell below 90% at 4 g AFDMm−2. One possible conservation objective for the Wash estuary would be to monitorwhether the 99% confidence limit of biomass density falls below one of these limits, to determine whether site quality is being maintained. The system as a whole was predicted to be relatively insensitive to habitat loss. Black-tailed godwits were the most sensitive species, but their survival was not affected until 40% of the feeding grounds were removed. The survival of all species in the model remained high at fewer than 20 disturbances/hour. Although disturbance rates on the Wash were not measured during this study it is unlikely that present-day rates of disturbance on the Wash represent a threat to the survival of the bird species modelled. Our results show how an individuals-based model can assess present-day site quality and how it may change in the future. The model predicted prey biomasses below which survival rate decreased, which shorebird species were most vulnerable to changes in site quality, and that prey density was a more important factor in shorebird survival than habitat area on the Wash. They also show such models can be used to set maximum disturbance rates for each species by predicting how disturbance rates influence shorebird survival. |
| Funders: | Centre of Ecology and Hydrology (internal), English Nature |
| Papers or reports: | West, A.D., Yates, M.G., McGrorty, S. and Stillman, R.A., 2007. Predicting site quality for shorebird communities: A case study on the Wash embayment, UK. Ecological Modelling, 202(3): 527-539. |

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| Case study title: | Western Europe (Bassin d’Arcachon, Dutch/West German/North German/Danish Wadden Sea, Morbihan French west, southern English, Norfolk coast and Essex and Thames estuaries) |
| Location: |  |
| Birds: | Brent goose, *Branta bernicla* |
| Modelling: | MORPH |
| Abstract: | Contains public sector information licensed under the Open Government Licence v3.0Overall: The overall aim of this project was to provide for policy-makers and their scientific advisors a suite of field-tested predictive population models with which they can devise local and Europe-wide management plans for maintaining the biodiversity of migratory (wintering/on passage) coastal birds (waders and wildfowl) that feed on inter-tidal and, often, supra-tidal (supplementary) habitats. The original project objective was to achieve this by adapting, simplifying and parameterising two existing individual-based population models so that they could be applied rapidly to a variety of species whenever policy decisions were required and at any geographic scale. Both predicted the body condition and mortality rate over the non-breeding season of classes of individuals within the population. Both models assumed that, when responding to management-induced changes in their feeding environment, individual birds chose the options that maximize their intake rate. Both were individual-based, in the sense that they tracked the location, foraging decisions and ultimate fate of each individual within the population, and predicted population level responses to environmental change (e.g. mortality rate) from the behaviour and fates of individuals (e.g. the proportion of individuals which die). One model, the *single-site wader model*, was a single-site (e.g. estuary) model for the non-breeding season which had been developed, parameterized and extensively (and successfully) tested for one common European wader species. The other, the *multi-site goose model*, was a multi-site, Europe-wide model which had been parameterized and tested, in a preliminary fashion, for one common wildfowl species. The aim of the project was to build, test and define the utility of the models for a much wider range of species in order to rapidly provide, at whatever geographic scale required, bird population predictions for a range of policy options. The original objective of adapting two existing models was extended during the project, and instead a completely new model was developed capable of making predictions for both waders and geese, at either the single or multi-site scale. The new model can be applied to a much wider range of systems and issues than could either of the initial models. The new model is based on the same principles as the existing models and is also individual-based. It builds on the strengths of the existing models, and adds improvements where the previous models were limited. Three key scientific advances were made during the project. * *Development of a general individual-based modelling framework*. The development of the new individual-based model has been one of the major scientific advances made during the project. The new model has the following advantages over the initial models. (i) It is much more flexible than the original models and so can be applied to a wider range of environmental issues. (ii) Using a single model for both geese and waders highlighted the similarities between these systems, rather than differences. (iii) The new model has been developed in a more general way than the previous models and so it not simply restricted to waders and geese, increasing the potential application of the model in the future.
* *Development of a general equation to predict the feeding rate of waders*. The project showed that the a simple equation could be used to predict the feeding rate of wading birds feeding on a range of prey species. Feeding rate is one of the most important parameters in the model. All that needs to be known is the mass of the wading bird species, and the mass and abundance of the prey. This breakthrough meant that wader models could be developed much more quickly and for a wider range of species than would have been possible if feeding rate needed to be measured for each new wader and prey species.
* *Rapid application of models to real-world issues*. If individual-based models are to be valuable tools for advising policy, they must be developed within a relatively short time span (e.g. a few years) and produce realistic predictions. Three site-specific multi-species wader models (Bahia de Cadiz, Spain, Baie de Somme, France and Exe Estuary, England) and a multi-site brent goose model (throughout western Europe) were successfully parameterised using data collected or collated during the four years of the project. The models successfully predicted much of the observed behaviour (e.g. amount of time spent feeding, rate of consuming food) and ecology (e.g. distribution between habitats) of the birds in the real systems. They were also used to answer a wide range of key site or system specific policy issues (e.g. hunting, disturbance, habitat loss of saltpans, fish farms, intertidal vegetation and sandflats). The successful parameterisation, testing and application of the wader and goose models is one of the key scientific advances made during the project, because it shows the potential of the approach to address European coastal issues.

The site and system-specific wader and goose models predicted the effect of a wide range of environmental issues (e.g. disturbance from people, hunting, habitat loss, sedimentation, encroachment of saltmarsh vegetation onto mudflats) on the survival and body condition of birds. These specific predictions are detailed in the report. In addition, the following more general policy recommendations can be derived from the results of the project. • *Monitor bird food reserves as well as bird numbers*. Estuary managers are often required to monitor the quality of a site for important bird species or to assess how potential changes to a site may influence site quality. The conservation importance of an estuary is often measured in terms of bird numbers using the estuary, but monitoring numbers is not necessarily a reliable way of assessing changes in site quality. In particular, this is because the numbers of birds using a site depend not only on the conditions at the site, but also the conditions at other sites both within the non-breeding and breeding seasons. Changes in the food supply can be used in combination with bird numbers to determine whether any decline in bird numbers is likely to reflect a problem on the site itself. Decreasing bird numbers in combination with a decrease in the amount of food would indicate that the problem was within the site, whereas decreasing bird numbers without a decrease in the food supply would indicate either that the problem was not limited food within the site, or that the decrease in bird numbers was due to factors outside of the site. A policy derived from these predictions would be to establish a monitoring programme to record the abundance of food on sites at the start of winter as well as continuing the usual procedure of monitoring bird numbers. * *Monitor the use of marginal habitats and feeding times*. The models developed during this project all predicted that birds fed in the most profitable and safest places and times when feeding conditions were good and survival rates high, behaviour which mimicked that of real birds. In contrast, birds were predicted to feed more in marginal habitats or at more risky times when feeding conditions were poorer, again behaviour which mimicked that of real birds. A possible policy would be to establish a monitoring programme to detect such changes in the behaviour of bird populations as an early warning that survival rates are likely to be falling. This approach would pick up possible detrimental changes on a site before increases in mortality rate could be detected through traditional approaches based on bird ringing programmes, increasing the chance that management can be implemented to improve conditions before bird survival declines greatly.

• *Maintain a network of sites*. The multi-site models predicted that birds emigrated from a site when the feeding conditions declined on the site. The consequences for the population depended on whether emigrating birds were able to find and survive on an alternative site. Birds could not survive if they did not have the energy reserves to successfully fly between the two sites (i.e. alternative sites must be relatively close together). A simple policy derived from this prediction is that wherever possible a network of high-quality sites should be maintained. This maximises the chance that emigrating birds are able to find and survive on an alternative site, if conditions deteriorate on their initial site. • *Include terrestrial habitats in conservation areas*. Birds were predicted to use terrestrial habitats when feeding conditions declined on their intertidal habitats, a pattern also observed in real birds. For example, brent geese in northern Europe fed on grass when intertidal *Zostera* and algae biomass declined during winter. Waders consumed more earthworms from terrestrial fields when intertidal food was depleted in late winter. These terrestrial habitats are often critical to the survival of waders and geese, even though they are often considered as marginal habitats. These habitats are often excluded from the designation of Special Protection Areas, but this means that vital habitat is not being protected and as a result may be lost to building developments, or suffer high disturbance levels. A simple policy derived from these predictions is that wherever possible conservation areas should include the terrestrial habitats around estuaries as well as the intertidal habitats of the estuary itself. This would ensure that the full range of habitats required by birds are protected. The model developed in this contract provides a means for predicting the effects of environmental issues on the survival and body condition of wading birds and wildfowl. As such, it is a tool which can be used by decision-makers concerned with the management of the coastal zone throughout Europe, whether they represent governments, fisheries organisations or nature conservation bodies. The model also provides the basis for further research into the interaction between coastal birds and their environment, and could be expanded in a number of directions, including application to the breeding season and to species other than waders and geese.Chapter 10: This chapter describes the work conducted in work package 5 of the project. The objective of this work package was to parameterize and test a multi-site, year-round model for oneexemplary, herbivorous wildfowl species, the brent goose, which is currently the focus of much debate as to how best to limit its conflict with various human activities, including agriculture, while protecting its most important sites. As explained in Chapter 1 the modelMORPH was used in this work package. This model has been developed during the project, and replaces the multi-site model which existed at the start of the project, and which was originally planned to be used during the project. The model was parameterised using acombination of literature review within each of the partner countries and new fieldwork, conducted largely in France. |
| Funders: | European Commission EVK2-2000-00612 |
| Papers or reports: | Stillman, R.A., Caldow, R.W.G., le V. dit Durell, S.E.A., West, A.D., McGrorty, S., Goss-Custard, J.D., Pérez-Hurtado, A., Castro, M., Estrella, S., Masero, J.A., Rodríguez-Pascual, F.H., Triplet, P., Loquet, N., Desprez, M., Fritz, H., Clausen, P., Ebbinge, B., Norris, K. and Mattison, E., 2005. Coastal bird diversity. Maintaining migratory coastal bird diversity: management through individual-based predictive population modelling. Centre for Ecology and Hydrology, Winfrith Newburgh, Dorset. |