MILFORD HAVEN WATERWAY
ENVIRONMENTAL SURVEILLANCE GROUP

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THE VALUE OF LONG-TERM MONITORING

AND LONG-TERM RESEARCH

The Value of Long-term Monitoring and Long-term Research

Report to the Milford Haven Waterway

Environmental Surveillance Group

T. R. Birkhead

Department of Animal & Plant Sciences, University of Sheffield

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Cover Image: Guillemot coming in to land.

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EXECUTIVE SUMMARY

The long-term population study of guillemots that started on Skomer Island, Wales in 1972, has generated the necessary data to understand the population dynamics of this species. Guillemots across much of their geographic range are in decline because of climate change and deteriorating food resources. The long-term study on Skomer has created a large database that will, if continued, allow future researchers to assess and interpret future changes in the guillemot population. Such resources are rare.

Equally important, the insight gained from the guillemot study has identified lessons that are relevant to other long-term monitoring programmes. It is for this reason that the Milford Haven Waterway Environmental Surveillance Group (MHWESG), a consortium of industry and public bodies, extended an invitation to capture these insights in this review. The MHWESG has undertaken surveillance of the quality of the marine physico-chemical environment, marine biology and ornithology of the Milford Haven Waterway for the last 25 years, and potentially has a lot to gain from this information.

Key messages are that ultimately, data must inspire confidence among the end users. For this to happen, there is an absolute need for more scientific rigour and reproducibility in long-term monitoring studies. Monitoring also needs to be better valued as a component of mainstream science, particularly in these times of changing climate, increased human impacts and risk to the natural world.

CRYNODEB GWEITHREDOL

Mae'r astudiaeth hirdymor, a gychwynnodd ym 1972, o'r boblogaeth gwylogod ar Ynys Sgomer bellach wedi cynhyrchu'r data sydd eu hangen i ddeall dynameg poblogaeth y rhywogaeth hon. Lleihau y mae niferoedd y gwylogod ar draws rhan helaeth o'u cwmpas daearyddol, oherwydd y newid yn yr hinsawdd a dirywiad eu cyflenwadau bwyd. Mae'r astudiaeth ar Sgomer wedi creu cronfa ddata sylweddol a fydd, os parheir hi, yn caniatáu i ymchwilwyr asesu a dehongli newidiadau yn y boblogaeth yn y dyfodol. Mae adnodd o'r math hwn yn rhywbeth prin a gwerthfawr.

Llawn cyn bwysiced â hynny yw'r mewnwelediad a enillwyd trwy astudio'r gwylogod, a'r gwersi a ddysgwyd sy'n berthnasol hefyd i raglenni monitro hirdymor eraill. Dyna paham yr estynnwyd y gwahoddiad gan Grŵp Goruchwylio Amgylcheddol Dyfrffordd Aberdaugleddau (MHWESG), sef ein consortiwm o ddiwydiannau a chyrff cyhoeddus, gyda golwg ar gipio'r mewnwelediad a'r gwersi hynny o'r adolygiad hwn. Gan mai MHWESG a fu'n goruchwylio ansawdd ffisegol a chemegol yr amgylchedd, a bioleg forol ac adareg yn y Ddyfrffordd yn ystod y 25 mlynedd diwethaf, bydd cipio'r wybodaeth hon o fudd mawr i'r consortiwm.

Y neges allweddol yw y bydd rhaid i bob data, yn y pen draw, ennyn hyder y defnyddwyr terfynol. Ar gyfer hynny, bydd yn gwbl angenrheidiol gwella manwl gywirdeb gwyddonol ac atgynyrchioldeb yr astudiaethau monitro hirdymor. Yn ogystal, bydd rhaid bod yn fwy gwerthfawrogol o fonitro, fel cydran mewn gwyddoniaeth brif-ffrwd, yn enwedig yn y cyfnod presennol pan fo'r hinsawdd yn newid ac effeithiau dynol a'r risg i'r byd naturiol yn cynyddu.

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1. INTRODUCTION

Wildlife monitoring is a term that conjures up an image of a worthy, but dull and repetitive activity undertaken by enthusiastic amateurs rather than professional scientists.

Monitoring is sometimes all of these things, but it isn’t always. I have spent forty-six consecutive years monitoring the population of guillemots *Uria aalge* on Skomer Island, Wales, as a professional scientist and I would like to give you my perspective on this.

Let’s start by being clear what we are talking about. Monitoring is the most fundamental aspect of ecology and conservation and comprises the measurement of changes in the quality and/or abundance of something over time. Often, that ‘something’ is the size of a particular population (that is, numbers), but the quality of habitats can also be monitored. Sometimes monitoring also focuses on aspects of a species’ population biology, such as survival or reproductive success.

The monitoring of numbers is essential if we are to know whether particular populations are stable, increasing or decreasing. This is especially important for populations that are exploited, are considered pests or are of conservation concern.

Some of the most fundamental principles of animal and plant ecology have been established from long-term monitoring programmes. These include: (i) predator-prey cycles, for example demonstrated by the extraordinary 10-year predator-prey cycle of the Canadian lynx *Lynx canadensis* and its prey, the snowshoe hare *Lepus americanus,* revealed by the trapping records carefully recorded by the Hudson’s Bay Company between 1847-1903; (ii) the fundamental arithmetic of population dynamics; (iii) the factors that determine population size in any particular area, and (iv) the population processes that bring about changes in abundance (Newton 1998).

At its simplest, monitoring comprises counts (individuals, pairs, nests) over time, and in many cases this is sufficient or all that can be afforded. More detailed monitoring can record changes in population age structure, nutrient supplies or environmental threats, and in so doing provides a much richer understanding of the causes of any changes in a population’s status. This in turn provides an opportunity for intervention. If we do not know what is causing a population decline, it is impossible to do anything about it. As National Geographic magazine stated recently with respect to the 70% decline in the world’s seabirds in the last fifty years: ‘to save them, we have to understand them.’ This means understanding their population biology: how well they reproduce; how long they live on average; the age of first breeding; where and when they disperse and so on (Newton 1998).

Sadly, monitoring is often regarded as the lowest form of scientific endeavor. This is partly because, until recently, counting individuals, pairs or nests, was deemed to be a relatively undemanding task and the results not worth publishing. Too often, a volunteer or poorly paid employee is given a set of instructions, some minimal guidelines, and then sent out into the field to count and record. While that process yielded some numbers, almost invariably those numbers would be taken at face value and assumed to represent the state of the population.

Sadly, a lot of monitoring is often characterized by a complete absence of quality control. Reproducibility is a hot topic in science at the present time (McNutt 2014) - if scientific studies, whether based on observation or experiment, are not reproducible they are not really worth anything. The same is true of monitoring, but how many independent tests of monitoring programmes have you heard of?

Often, quality control in monitoring is assumed not to be a major issue, for two reasons. First, because the population changes are often large they can be apparent even without any counts. Examples of this would be the extinction of the large copper butterfly *Lycaena dispar* in the UK, or the recent expansion of the UK buzzard *Buteo buteo* population (e.g. see Hayhow et al. 2016 *The State of Nature Report* 2016). The second set of circumstances where quality control may not be a priority is with very large-scale studies involving huge numbers of individual field workers, working over large geographic areas collecting relatively simple data whose value lies in the sheer size of the sample, as in the British Trust for Ornithology’s or Cornell’s Lab of Ornithology’s breeding bird surveys. In such cases it is assumed that any errors made by a few individuals are offset or diluted by the aggregation of largely ‘correct’ observations made by a large number of individuals.

The lack of quality control is potentially damaging however, when only a small number of key sites are monitored and these are assumed to be representative of much larger areas. In this situation the accuracy of the monitoring is of upmost importance. An example of this situation is the UK’s Seabird Monitoring Programme, in which a tiny number of colonies distributed around the UK coastline each serve as an indicator of the status of seabird populations over much larger regions. The combination of a small number of key sites and little or no quality control, means that any errors are magnified and the potential for misinformation is very high.

What does quality control consist of? High quality monitoring requires all of the following: (i) unambiguous, clearly written instructions; (ii) one-on-one supervision by an expert, someone with experience and genuine commitment, including an opportunity for the field worker to ask questions and check if they are uncertain about any details at any time; (iii) checking by the supervisor in the field that the right data are being collected by the field worker, and (iv) scrutiny of the data by the supervisor at the end of the field season before any report is made. In addition to these aspects, it is essential that at strategic times, the same data are collected 'blind' (that is, independently) by two or more fieldworkers to establish that the same results are obtained.

2. LONG-TERM STUDIES

By definition, monitoring involves recording numbers or population parameters for particular species over time. Monitoring has a long history, starting with Robert Marsham's 'Indicators of Spring' (1789). More recently, the British Trust for Ornithology's 'heronries census' - a survey of grey heron *Ardea cinerea* - was started in 1928 and is one of the longest running bird monitoring programmes. The heronries census counts nests in a sample of heronries across the country to provide an index of the UK heron population. A survey (or monitoring project of this type) is not the same as a long-term population study, which typically involves collecting data on numbers AND population parameters.

Long-term studies are few and far between (Newton 1998), for several reasons. Research councils award most funding for fundamental population research for three- or sometimes five-year periods. Sustaining population studies over successive grant periods is difficult and requires considerable tenacity on the part of the study leader, the Principle Investigator (PI). To maintain a long-term study through a succession of research council grants the PI needs also to continue to produce a continuous stream of novel, high quality publications to satisfy the grant-awarding bodies (and thus one's employers). It is often impractical and unrealistic to do this: by definition, long-term studies are those taking place over long periods of time and it can take years to accumulate sufficient new monitoring data to generate new insights. For most researchers, there are much easier ways of carving out an academic career.

Examples of long-term population studies of birds (with their starting date) include the following: Great tit *Parus major* Wytham, Oxford, UK 1947; Lesser Snow Goose *Anser caerulescens*, Churchill Manitoba, Canada 1967; Song sparrow *Melospiza melodia* Mandarte Island, BC, Canada 1975; Fulmar petrel *Fulmarus glacialils*, Orkney, UK 1950; Bewick's swan *Cygnus bewickii*, Slimbridge, UK 1964; Florida Scrub Jay *Aphelocoma coerulescens* Florida, USA 1969; Acorn woodpecker *Melanerpes formicivorus* Hastings Reservation, California, USA 1971; Common guillemot Skomer Island, Wales 1972 (Clutton-Brock & Sheldon 2010).

It is deeply ironic that funding bodies are so reluctant to commit funds to long-term studies, because such studies have been shown to be disproportionately successful and productive. The accumulated knowledge from a long-term study means that researchers have a much better understanding of their study species or habitat, and are therefore much more likely to interpret data in a biologically appropriate manner (Clutton-Brock & Sheldon 2010).

3. THE LONG-TERM STUDY OF GUILLEMOTS ON SKOMER ISLAND, WALES

Skomer Island - together with the nearby islands of Skokholm and Grassholm - hold some of the most important seabird colonies in the UK (Buxton & Lockley 1950; Cramp et al. 1974; Lloyd et al. 1991). In 1962 David Saunders, the first warden of Skomer Island National Nature Reserve, initiated what were to become some of the first long-term monitoring programmes of UK seabirds.

Saunders' annual census on Skomer provided counts of the total number of individuals or nests of many of Skomer's twelve seabird species[1]. His motivation was concern over the

[1] Lesser Black-backed Gull *Larus fuscus*, Herring Gull *L. argentatus*, Great Black-backed Gull *L. marinus*, Kittiwake *Rissa tridactyla*, Common Guillemot *Uria aalge*, Razorbill *Alca torda*, Atlantic Puffin *Fratercula arctica*, Northern Fulmar *Fulmarus glacialis*, Shag *Phalacrocorax aristotelis*, Cormorant *P. carbo*, Manx Shearwater *Puffinus puffinus*, Storm Petrel *Hydrobates pelagicus*.

decline of certain species, notably guillemots and puffins whose decrease in number was qualitatively obvious from previous accounts and from photographs taken in earlier decades (e.g. Buxton & Lockley 1950; see also Birkhead 2016).

The value of Saunders' annual counts became even more important as guillemot numbers continued to decline through the 1960s, first as a result of the *Torrey Canyon* oiling incident, in the spring of 1967 in which at least 15,000 seabirds died (Cramp et al. 1974), and second as a result of the Irish Seabird Wreck in the Autumn of 1969 in which at least 12,000 birds, mainly guillemots died (Holdgate 1971).

From 1959, Skomer Island National Nature Reserve (NNR) was run by the Nature Conservancy Council (NCC), but leased to, and managed by, the West Wales Field Society. The NCC was dismantled in 1983 by Conservative Environment Secretary Nicholas Ridley (because it spoke up too loudly for conservation) and was eventually replaced by the Countryside Council for Wales (CCW) in 1991, who took over the ownership of Skomer Island NNR. The day-to-day management of the island, including the annual seabird counts started by Saunders, remained the responsibility of the local wildlife trust (now the Wildlife Trust for South and West Wales (WTSWW).

Following on-going declines in seabird numbers both on Skomer and elsewhere in the UK (see Cramp et al. 1974), David Lack and Chris Perrins at the Edward Grey Institute (EGI) in Oxford initiated studies of the puffin and guillemot on Skomer Island with a view to better understanding their population biology. The EGI specialized in the analysis and understanding of bird populations and had conducted studies on Skokholm for many years. In 1970, Perrins started a population study of the razorbills *Alca torda* on Skokholm with Clare Lloyd as the named researcher, and in 1973 Ruth Ashcroft began a DPhil study on puffins on Skomer. I spent the 1972 season on Skomer studying guillemots, prior to starting my DPhil in 1973. The main remit of all three studies was to obtain a better understanding of the population biology of each species in the hope of identifying the cause of the population decline and halting it.

The population study of guillemots on Skomer has continued to this day.

At the outset, one of my priorities was to develop methods for accurately censusing guillemots. It had become clear as a result of *Operation Seafarer* in 1969-1970 - the first concerted effort to estimate the number of UK seabirds - that there were numerous methodological problems associated with assessing seabird population sizes (Cramp et al. 1974).

Guillemots were considered difficult to count, partly because they often breed in very dense aggregations without a nest and converting counts of individuals into breeding pairs was difficult. For this reason, counts were often reported as ‘individuals’, although sometimes ‘individuals’ and ‘breeding pairs’ were confounded or assumed to be the same. For example, Buxton & Lockely (1950: 76) reported that in 1946 ‘there were …. 5000 guillemots on Skomer’s cliffs …. or approximately that number of pairs’.

Developing a reliable census method involved estimating the true number of breeding guillemot pairs in a particular area. I achieved this through patient, protracted daily observations of breeding birds, noting the precise location of individuals and using the presence of an egg to indicate a breeding pair. I found that on average, one hundred individual birds on the breeding ledges represented 67 breeding pairs. In guillemots, one member of a pair incubates the egg or broods the chick continuously; the additional birds on the ledges are off-duty breeders, which often stand beside their partner, or immature, non-breeding individuals (Birkhead & Nettleship 1980).

Fig.1. Typical breeding density of guillemots on Skomer Island (Photo: TRB).

The second aspect of monitoring that I tackled was to establish the best time to make counts, both within a season and within any particular part of the day. Extensive counts made between dawn and dusk on several occasions throughout the season and at the same time each day, showed that numbers were least variable during the incubation period, which in the 1970s was mainly June, and between 0800h and 1600h local time (Birkhead 1977). It was also obvious that conducting whole island counts (i.e. counts of the entire Skomer population) was both difficult and laborious, and as a result could be undertaken only once each season. A sampling regime, with repeated counts at specified sites was necessary. To do this I selected three discrete cliff faces as ‘study plots’ and counted the birds there on ten separate occasions each June to provide a mean, together with a standard deviation (a measure of the variability of those counts around that mean). Crucially, these three study plots, either alone or combined showed a strong positive relationship with the whole island counts, indicating that the study plots provide a reliable index of the entire population size. Started in 1973, these counts became incorporated into the general monitoring of guillemot numbers on Skomer and have been continued each year since.

Monitoring numbers is only one way of assessing the health of a population and it tells us nothing about the processes underlying changes in population size. Therefore, each year since the mid-1980s my colleagues and I have monitored several other aspects of guillemot population biology, including the annual survival of adult guillemots, immature survival, the timing of breeding, breeding success, and the rate at which guillemot chicks are fed, and their diet. These data, acquired over a span of 46 years, provide a comprehensive understanding of how the Skomer guillemot population functions (e.g. Hatchwell & Birkhead 1991; Votier et al 2005; 2008; 2009; Meade et al 2012).

These various population parameters, together with the study plot counts, give us the best chance of detecting and understanding changes in the guillemot’s fortunes. Counts of individuals on their own are adequate for some purposes, but can sometimes be misleading. For example, we found that when an oil spill or a ‘wreck’ (as in 2014 - see below) kills huge numbers of birds, as evidenced by large numbers of recoveries of Skomer-ringed guillemots, the counts of individuals on the cliffs the following year may not seem to have been affected. We are still trying to understand the reason for this, but it is probably because: (i) the margin of error in our counts mask real but small changes in the total size of the Skomer population, and, (ii) because young, non-breeding birds appear to detect the ‘gaps’ in the breeding population and thus become breeders earlier than they would otherwise have done.

Simply using counts to determine the health of a population is therefore analogous to you asking a doctor to assess the state of your heart on the basis of a single assay, such as an ECG (electrocardiograph) trace. An ECG reading may remain stable, even when one’s heart is working twice as hard as it should. In other words, although you appear to be healthy on the basis of a single, superficial assay, in reality you are on the way to a heart attack. It is obvious that the more comprehensive the monitoring system in a colony, the more likely it is to detect a population health issue. The long-term study of guillemots effectively provides a comprehensive annual health check for the Skomer guillemot population.

The decision, in early 2014 by Natural Resources Wales (NRW) to terminate the funding for the long-term study of guillemots on Skomer was especially disappointing for two reasons (Birkhead 2014; 2018). First, because NRW did not recognize the value of the substantial repository of information accumulated during the previous 40 or more years in helping to detect and rectify future environmental issues. Second, NRW naively or disingenuously claimed that the termination of the long-term guillemot study would not result in the loss of any data. Instead, they claimed that the monitoring system *they* had in place provided the necessary information. However, as I had demonstrated to them, NRW’s system for monitoring guillemot breeding success was flawed, and their monitoring system did not include any information on survival or chick diet.

4. OTHER MONITORING PROGRAMMES IN THE MILFORD HAVEN WATERWAY / PEMBROKESHIRE ISLANDS AREA

The Milford Haven Waterway Environmental Surveillance Group (MHWESG) has conducted various valuable monitoring schemes since its establishment over 25 years ago (see Appendix 1 for purpose and terms of reference for the MHWESG). These include annual estimates of summer Shelduck *Tadorna tadorna* populations, intertidal rocky shore surveillance, macrobenthic community surveillance and the development of a timeline for sediment contaminants using 40 years of data (MHWESG 2017). Other monitoring programmes exist that are also relevant to the Milford Haven Waterway and offshore islands - monitoring of marine species and seabed habitats within the Skomer Marine Conservation

Zone (formerly known as Skomer Marine Nature Reserve) and also monitoring of the Pembrokeshire Marine Special Area of Conservation, both by Natural Resources Wales.

The Milford Haven Waterway provides an important link between freshwater and marine environments. Nutrients flowing out from the waterway contribute to the productivity of the local marine environment, but the waterway also provides a conduit for possible pollutants into the sea. The Milford Haven Waterway is still an oil port today after 50 years of tanker activity. Although environmental standards and operating procedures have improved, there is still a very real threat from oil pollution resulting from accidents (such as the Sea Empress in February 1996) and also operational activities. The Milford Haven Waterway also provides a conduit for heavy metals to the sea and can have a negative effect on different forms of animal and plant life.

Given the links that might exist between ecological processes with the Milford Haven Waterway system (e.g. nutrients, pollutants, fish populations) and the Pembrokeshire seabird islands, it is essential that all of these monitoring programmes continue. At some future date it may be that the data obtained by the Milford Haven Waterway Environmental Surveillance Group and other sources, will contribute to our understanding of the broader ecological interactions in this area.

5. MAJOR FINDINGS FROM THE LONG-TERM SKOMER GUILLEMOT STUDY

In addition to monitoring the size of the local guillemot breeding population, a major aim of the Skomer guillemot study has been to understand the species' population dynamics. A breeding population of birds (or any other organism) tends to increase when breeding success and the survival rates of adult and immature birds are high, and to decrease when survival rates and breeding success are low. Measuring these population parameters for Skomer's guillemots has therefore been a major objective since the start of my study.

Breeding success: In the 1970s, the Skomer study pioneered the development of non-invasive methods of measuring guillemot breeding success. This was done using a combination of photographs of study plots and detailed observations identifying a sample of 100-500 breeding pairs and recording the timing of egg laying, hatching and the departure of the chick from the colony. Guillemots lay only a single egg and breeding success is measured as the proportion of pairs rearing a chick to leave the colony. Previous studies of guillemot breeding success (Belopol'skii 1957; Tuck 1961) involved disturbing the birds to count eggs and chicks, inevitably causing the loss of eggs and chicks - thus creating incorrectly low estimates of natural breeding success.

The single most striking aspect of guillemot breeding biology is the density at which they breed. Breeding success in guillemots is determined largely by breeding density: the greater the breeding density, the greater the success. Guillemots breed on open ledges in dense groups and rely on group defence to minimize the predation of eggs and chicks by aerial predators such as gulls and corvids. When a guillemot population declines (as it did, dramatically on Skomer after WWII), breeding density declines (because birds are very site tenacious and there is a lag in how birds respond to the decline), and as a result breeding success declines because the guillemots are vulnerable to predation by gulls and corvids. This was very apparent on Skomer in the early 1970s when the population was at its lowest level. My data confirmed that breeding success was low (0.66 chicks/pair) at that time compared with later (and currently) when the population (and breeding density) increased, and breeding success averaged over 0.80 chicks/per pair (Birkhead 1977; Votier et al. 2005; Meade et al. 2012).

Survival: We had no knowledge of the survival rates of guillemots of Skomer prior to the start of my study, although we did know that, like many other seabirds, guillemots are relatively long-lived. The accurate determination of adult and immature survival rates depends upon following the fate (survival) of individually-marked birds. This is facilitated by the high breeding-site fidelity and philopatry exhibited by guillemots. Starting in 1973, we have colour-ringed cohorts of 300 or more chicks and ~ 50 adult guillemots each year, with over 15,000 birds ringed to date. The re-sighting of these birds each year allows us to calculate both adult and immature annual survival rates. The values for adult guillemots average over 90% returning from one year to the next, indicating a mean breeding life span of 20-25 years. About 50% of all chicks that leave the colony at the age of 21 days survive (at least) up to breeding age at the age of 7 years.

Population dynamics: The combination of survival rates and breeding success allowed us to model the Skomer guillemot population size, and to predict how we expect numbers to change over time. Skomer is unusual among UK guillemot colonies in that numbers have been increasing steadily (at about 5 per cent per annum) since 1980 (Meade et al. 2012). This is the maximum intrinsic rate of increase in a population of this size that is possible without immigration. Indeed, our model shows that the observed levels of survival and breeding success generates a predicted rate of increase that matches the observed rate of increase extremely closely. This close match between predicted and observed population growth confirms not only that we measure guillemot population parameters accurately, but also that we understand very well how the population functions. This level of detail is unusual among bird population studies.

Value of population measures: Our data reveal that annual adult survival rates constitute a very sensitive measure of how well or badly the Skomer guillemot population is performing. One of the most devastating effects on guillemot populations is oiling, and major oil spills in particular. There have been four major oil spills during the course of the Skomer long term study, and the effects of those - some which occurred hundreds of kilometers away from Skomer, such as the *Aegean Sea* (1992) and *Prestige* (2002) - were detectable in the survival data we collect at the breeding colony (Votier et al. 2005). This effect from distant oil spills is partly a consequence of how far Skomer guillemots disperse outside the breeding season. Geolocator tracking (conducted in collaboration with the Oxford group, also working on Skomer) has revealed that guillemots that breed on Skomer regularly and predictably travel as far south as the Bay of Biscay, and as far north as the Faeroes.

A second major environmental effect on Skomer’s guillemots is climate change, due to at least two inter-related effects: (i) global warming and (ii) an increase in the frequency and intensity of winter storms.

(i) In terms of global warming, one of the most striking results from our long-term study is the overall advance in breeding dates. Guillemots on Skomer currently (2010s) breed two weeks earlier than they did in the 1970s. The timing of breeding is also now less predictable. The long-term consequences of an advance in breeding date (also seen among other UK birds) are unknown. If the temporal shift in the timing of breeding coincides with a similar shift in the abundance of food for chick-rearing, then in the short term this may not be disadvantageous. The causes and consequences of the increase in year-to-year variability in the timing of breeding also remains to be seen.

The negative impact of ocean warming on guillemot populations was dramatically demonstrated in Alaska in 2014/15, when sea temperatures rose by 2°C causing a massive failure in fish populations followed by the death of at least 500,000 guillemots (J. Piatt, pers. comm.). There have been similar climate-related changes in fish populations around the UK coast, most notably in the North Sea and in Scottish waters, resulting in huge shifts in sand eel distribution with large negative consequences for guillemot and other seabird populations. It is striking that in the UK, guillemot populations reliant on sand eels for rearing their chicks have suffered disproportionately, whereas those, like the birds on Skomer, reliant on Sprats *Sprattus sprattus*, have fared much better. It is for this reason that it is important that we continue to monitor the food brought to guillemot chicks since this may be our most sensitive measure of changes in the marine environment (Riordan & Birkhead 2017).

(ii) The increased frequency and intensity of winter storms, also has a negative impact on guillemot populations. This was most clearly seen in early 2014 when a succession of storms resulted in widespread additional mortality, in what is referred to as a 'wreck'. In this instance at least 50,000 birds (mainly puffins and guillemots, including ringed birds of both species known to breed on Skomer) were found dead along the Atlantic seaboard of Europe. The increased mortality was also apparent in our survival data. At its simplest level, one might have expected this 'wreck' to reduce numbers such that in subsequent years the population continued to increase at its original rate but at a lower level. Instead, the 'wreck' resulted in a complex set of interactions that we have yet to fully understand. Essentially, the 'wreck' increased the mortality of both adult (breeding) and immature (pre-breeding age) birds. The 'gaps' in the breeding population caused by the increased mortality of breeding birds were, it seems, filled by birds breeding earlier than they would otherwise have done, minimizing the apparent effect on the breeding population. Because it takes at least two years to accurately estimate adult survival rates and as long as seven years to assess the impact of such changes on immature birds, we have not yet fully analysed the effects of the 2014 'wreck' on Skomer's guillemots.

6. OVERVIEW OF THE ACHIEVEMENTS OF THE SKOMER GUILLEMOT STUDY

The achievements of the Skomer guillemot study have been both scientific and methodological/strategic:

Scientific achievements

1. Development of appropriate non-disruptive methodologies for measuring population size and breeding parameters.

2. Identification of several negative and some apparently (so far) neutral effects of climate change on the Skomer guillemot population.

3. Identification and measurement of the changes in guillemot numbers breeding on Skomer between 1930 and 2018: the population of ~ 100,000 pairs in the 1930s, followed by massive decline to a low of around 2000 pairs in the early 1970s, followed by a steady (5%) increase since 1980 up to the current 25,000 pairs.

4. Demonstration of the way the Skomer guillemot population works, allowing us to anticipate future changes in numbers.

5. Demonstration of the value in monitoring several different population parameters.

6. Recognition that successful monitoring requires knowing the magnitude of change that one hopes to be able to detect. This in turn depends on knowing how variable the estimated parameters are likely to be. The Skomer management plan (WTSWW unpublished document) specifies ‘ideal’ levels of population size, survival and breeding success for guillemots and other seabirds. The monitoring systems that are implemented must therefore be fit for purpose in the sense that they are able to detect appropriate levels of variation in seabird populations across years.

7. Demonstration of the value of training over twenty field biologists, many of whom have gone on to permanent employment in ecology and conservation.

Methodological/strategic achievements:

1. Identification (or reaffirmation of) of the absolute necessity of applying consistent methodology over years for obtaining reliable data.

2. Identification of some crucial, but often overlooked aspects of monitoring. The identification of these features came about through what we might call a ‘natural experiment’ in which two separate bodies (one being the long-term Skomer guillemot study) independently measured some of the same guillemot population parameters in the same years. Alarmingly, the results from the two studies could not have been more different. The other study was conducted with different personnel each year, relatively little supervision or guidance and no analysis or checking of results. This investigation revealed the full cost of failing to monitor in a scientifically robust manner and with no supervision, quality control or validation.

3. Recognition of the fact that if monitoring is to be worthwhile it must meet certain minimum criteria and it must be consistent from year to year, regardless of the personnel involved. To ensure consistency, personnel require training and appropriate supervision. The results from monitoring should be checked at regular intervals by professionals, to ensure that all criteria have been met. Personnel conducting monitoring should not be allowed to ‘make improvements’ without consulting the managing body. Any changes to methodology jeopardise the consistency that is the key to the success and value of monitoring. Of course, changes may have to be made occasionally as techniques improve but they must be made in such a way as to retain consistency, and they should be made only after expert consultation. They should also be clearly documented.

4. Recognition of the fact that, if funding for monitoring is limited (as it will be), agencies interested in monitoring must develop robust, efficient schemes to maximize the use of available funds. But, at the same time agencies must put in place checks on quality control to ensure that the data acquired achieves the desired goal. Without supervision and quality control it is all too easy for methodologies to drift, for monitoring to become a tick-box exercise and for the results to be meaningless.

By insisting on methodological consistency, by training and supervising field assistants, and by careful, objective scientific evaluation of the data (including peer review of our scientific publications – see References, below), the long-term guillemot study on Skomer Island has produced the best possible guillemot health check.

7. SYNTHESIS

In a world in which environmental conditions continue to deteriorate as a result of direct and indirect human impact, monitoring the state of the natural world is more important than ever. It is ironic that as the need for monitoring has increased, the will to finance such work seems to have decreased. It is now almost universally recognized that the most ubiquitous environmental threat is climate change. This is apparent globally in terms of the increased risks of flooding and fires, but also more locally in terms of the advancement of 'spring' manifest in the earlier bud burst and flowering of plants and earlier breeding by birds. It is also apparent in the changes in the geographic distribution and availability of fish for seabirds, and the effect that extreme events have on survival and longevity of marine birds, for example.

Our understanding of environmental threats, including climate change, depends on the data from long-term monitoring programmes. For example, the BTO's bird surveys conducted since the 1960s allow us to see the extraordinary magnitude of the population reductions that have taken place since that time. Without this information we (and governments) may have been even more complacent than we are now about the negative impact of human activity on the natural world.

Long-term studies and long-term monitoring programmes are generally given low priority by governments partly because the goals of those agencies are usually short term, but also because long-term studies are revelatory only occasionally, for example, when an ecological catastrophe takes place. Thus, long-term studies and monitoring programmes can seem to be using up resources to little effect. But that is an extremely short-sighted view, especially in the present day when environmental issues are more pressing than ever before.

Long-term studies and monitoring programs are like insurance policies: one continues to pay in year in year out, on the understanding that one day the policy might pay for itself. In the case of environmental issues, that pay back seems increasing likely. We cannot afford to fail to monitor the state of the natural environment. While it is neither feasible nor necessary to monitor all aspects of the environment, we need to identify priorities and continue to fund already-existing, tried and tested (i.e. scientifically robust), long-term studies.

Fig.2. Feeding guillemot coming in to land (Photo: TRB).

Long-term studies allow us to continue to monitor on-going situations, but also to investigate environmental problems that we have not yet anticipated. When the long-term study of guillemots on Skomer Island started in the 1970s, no one had heard of climate change, yet that study provides some of the clearest evidence for an effect. Moreover, it also seems likely also that as the climate continues to change, more and more effects will be detected that can be usefully investigated using our 46-year database.

A final issue concerns the way monitoring is undertaken and valued. We need to stop thinking about monitoring as the poor relation to science, and instead start to recognize that to be useful and trustworthy, monitoring needs to be undertaken professionally and treated with the same respect and rigor as mainstream science. Good quality monitoring may sometimes be expensive, but monitoring is only worth doing if it is done appropriately. Bad data are worse than no data at all.

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APPENDIX 1: MILFORD HAVEN WATERWAY ENVIRONMENTAL SURVEILLANCE GROUP - PURPOSE AND TERMS OF REFERENCE

The Milford Haven Waterway[2] is an extensive natural inlet of the sea with a long and distinguished maritime history. Its deep waters provide a natural harbour of significant economic importance. It is one of the best examples of a ria system in Britain and supports a particularly diverse range of high quality marine and estuarine habitats and biological communities.

The identification and consideration of political and management issues or the setting of environmental standards are specifically excluded from these Terms of Reference. However, Group members are free, and are expected to use the Group's outputs to help meet their own requirements.

Purpose

To provide high quality environmental information to enable members of the Group, and other authorities and industry working in and adjacent to the Waterway, to contribute to the maintenance and enhancement of the rich and diverse marine environment of the Waterway.

Terms of Reference

The Milford Haven Waterway Environmental Monitoring Steering Group will:

1. Maintain surveillance of the quality of the marine physico-chemical environment, marine biology and ornithology of the Milford Haven Waterway

2. Undertake surveillance of the foreshore, seabed and waters of the Milford Haven Waterway from a line between St Anne's Head and Sheep Island to the tidal reaches of the Eastern and Western Cleddau Rivers and other tributaries to normal tidal limits by:

2.1 keeping under review all relevant survey, surveillance and monitoring;

2.2 commissioning surveys to fill gaps in knowledge and to establish baselines;

2.3 undertaking surveillance projects;

2.4 maintaining a literature and information database.

3. Jointly maintain, and keep under review, a prioritised programme of survey and surveillance projects.

4. Share technical output equally under joint ownership and copyright.

5. Function as a technical, science based, group.

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[2] The term Waterway in this document specifically refers to the waters, seabed and foreshore of the Milford Haven Waterway and the Daugleddau Estuary from a line between St Anne's Head and Sheep Island to the tidal reaches of the Eastern and Western Cleddau Rivers and other tributaries to normal tidal limits.

6. Form and appoint specific sub-groups to undertake specific responsibilities as required.

7. Publish an annual report which will comprise a summary of work undertaken, the executive summaries from individual project reports, a financial statement and the planned work programme.

8. Make its output available to the wider community in addition to its membership.

Membership and Funding

Membership is comprised of statutory authorities, industry and others with an interest in the environmental quality of the Waterway. Membership will be at the invitation and discretion of the Group’s existing members.

Each member will contribute to the functioning of the Group, either in monetary terms or ‘in kind’.