A review of methods used to analyse albatross diets – assessing priorities across their range

Julie C McInnes[1,2 §], Ben Raymond[2,1,3,] , Richard A. Phillips[4], Simon N Jarman[5] , Mary-Anne Lea[1,3],
Rachael Alderman[6]

[1] Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart, TAS 7001, Australia
[2] Australian Antarctic Division, 203 Channel Highway, Kingston, TAS 7050, Australia
[3] Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania, Private Bag 80, Hobart , TAS 7001, Australia
[4] British Antarctic Survey, Natural Environment Research Council, Cambridge CB3 0ET, United Kingdom
[5]CIBIO-InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto, 4485-661 Vairão, Portugal
[6] Department of Primary Industries, Parks, Water and Environment, 134 Macquarie Street Hobart TAS, 7000, Australia

[§]Corresponding author:
Julie McInnes, Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart, TAS 7001, Australia. +61 3 6226 6379. Email: julie.mcinnes@utas.edu.au

BR: ben.raymond@aad.gov.au
RP: raphil@bas.ac.uk
SNJ: simon.jarman@aad.gov.au
MAL: maryanne.Lea@utas.edu.au
RA: rachael.alderman@dpipwe.tas.gov.au

Running title: Albatross diet review

Keywords: conservation, Diomedeidae, food, management, methods, Procellariformes, regurgitates, stable isotopes, seabirds, climate change

Article Type: Review

Word count total: 6970 (including references)

Number references: 66

Number of figures: 3

Number of tables: 5

Abstract

Many seabird populations are threatened by interactions with commercial fisheries, and climate change. Understanding their prey requirements and dietary flexibility in this context is important for effective conservation and management. However, changes in the methods used to assess diet, as well as the spatial and temporal coverage of monitoring schemes, may reduce our ability to detect and monitor these marine threats. To help assess conservation priorities linked to diet, we carried out a systematic review of 109 albatross diet papers published between 1950 and 2016, which corresponded to 296 studies when stratified by sampling year, breeding site and species. We assessed the methods used, changes over time, and spatial and temporal sampling coverage by species and island group. Most albatross studies have focused on chick-rearing, and diet during other breeding phases is comparatively poorly-known. Furthermore, chicks are more commonly sampled than adults and very rarely immature birds, all of which may differ in diet composition. There was a pronounced shift over time in the preferred method of characterising diet, from the morphological examination of prey remains to stable isotope analysis (SIA) of tissue. This shift has reduced the volume of detailed taxonomic information available from morphological studies. This difference in resolution hinders the ability to detect changes in prey species, with implications for management of threatened albatrosses and for monitoring broader changes in marine ecosystems. In a knowledge gap analysis for important breeding colonies (with >5% of global population), we identified key sites where existing monitoring has provided a foundation for robust longitudinal diet studies. Maintaining and augmenting these long-term research programmes will enable analyses of the impacts of changing climate and fishing practices on seabird populations, and facilitate the timely identification and implementation of management options.

Introduction

Two of the greatest marine threats facing seabird populations are interactions with commercial fisheries and global environmental change (Croxall et al., 2002; Chambers et al., 2011). Commercial fisheries often overlap spatially and temporally with seabird foraging areas, and incidental mortality (bycatch) may occur when birds are attracted to vessels to feed on discards or bait (Brothers et al., 1999). These interactions can be major drivers of population change, and bycatch has been linked to substantial declines in some seabird species (Weimerskirch and Jouventin, 1987; Nel et al., 2002).

Environmental change, primarily driven by anthropogenic carbon emissions, are causing oceans to warm and become more acidic (Feely et al., 2009). These changes affect food-webs and drive spatial and temporal changes in prey abundance and availability, with some prey species predicted to move to cooler waters or alter breeding phenology (Constable, 2014). Top predators depend on prey that may be patchily distributed or show seasonal variation. As such, ocean warming may negatively impact predator breeding success if they have insufficient plasticity to adapt to change (Grémillet and Boulinier, 2009). Changes in prey availability or distribution can cause prey switching, increase foraging duration, or alter breeding phenology to match seasonal peaks in prey abundance (Gjerdrum et al., 2003; Le Bohec et al., 2008; Xavier et al., 2013). Environmental change may also cause changes to fisheries, including their target species (Barbraud et al., 2012).

Seabirds are highly susceptible to changes in marine ecosystems due to their high trophic position and the predominantly bottom-up control of most food webs (Frederiksen et al., 2006). Changes in prey availability can influence a variety of seabird demographic parameters including breeding success, recruitment and survival. Monitoring of these top predators is therefore important not only for their conservation and management, but also provides indicators of the status of the broader marine ecosystem (Cairns, 1987). Collection of dietary data from top predators is an important component of monitoring strategies for many management bodies. For example, in the Southern

Ocean, the Commission for the Conservation of Marine Living Resources (CCAMLR) has an Ecosystem Monitoring Program (CEMP) with the principal objective of determining the resource requirements of key top predators (e.g. Adélie penguins (*Pygoscelis adeliae*) and black-browed albatross (*Thalassarche melanophris*)) (SC-CCAMLR, 1997). Similarly, the Southern Ocean Observing System (SOOS) was established to monitor changes in physical and biochemical properties of ocean variables in relation to climate change, including monitoring of albatrosses and other land based predators (Rintoul et al., 2012).

Different types of dietary analysis provide alternative datasets for assessing environmental and fisheries-related changes in marine systems. Seabird diet studies fall into two main categories: those employing morphological analysis to identify remains of prey items from physical attributes, and those using biochemical analyses of tissue samples. Morphological analyses can provide high-level taxonomic identification of prey items, including size estimates. Material for this can be obtained from stomach contents of dead birds by dissection, from live birds by spontaneous regurgitation or stomach lavage, or from pellets (which include indigestible prey remains) or remains of food dropped in the colony (Barrett et al., 2007). Analysis of pellets (also termed boluses) identifies only prey which have indigestible hard parts, primarily cephalopod beaks and fish otoliths, allowing detailed information on species and size class of specific dietary components only (Xavier et al., 2005). Biochemical methods primarily include stable isotope analysis and fatty acids; with techniques such as DNA-based dietary analysis and compound-specific stable isotope in development (Pompanon et al., 2012; Bradley et al., 2014). Stable isotope analysis (SIA) is the main biochemical method used in seabirds and measures ratios of $^{13}C/^{12}C$ and $^{15}N/^{14}N$ (occasionally $^{34}S/^{32}S$) in feathers, blood or other tissues from the target animal, which reflects those in their prey. These measurements integrate the isotopic composition of food consumed during tissue formation, allowing comparisons of habitat use based on environmental gradients in SI ratios, or of trophic level, over periods of days or weeks (Phillips et al., 2009; Cherel et al., 2013). Fatty acid analysis identifies the fatty acid signatures within the adipose tissue of predators and provides information on individual prey groups and species (Budge et al., 2006). Morphological and biochemical analysis convey complementary diet information. Morphological studies identify prey ingested over a short timescale to a high level of taxonomic resolution, which is useful for studying prey selection or consumption of fishery discards. SIA and fatty analysis studies are less labour intensive and provide dietary information derived from prey consumed over a long period of time, which makes them suitable for studying very broad dietary differences at a population scale (Karnovsky et al., 2012).

Albatrosses are one of the most threatened seabird groups, with 16 of 22 species currently on the International Union for Conservation of Nature (IUCN) Global Red List and the other six species classified as Near-threatened (IUCN, 2015). Current conservation efforts, coordinated through bodies such as the Agreement for the Conservation of Albatross and Petrels (ACAP) and Birdlife International, are focused on mitigation of known threats to albatross populations, which include fisheries and climate change. Albatross feed on fish, cephalopods, and, in some species, crustaceans and carrion (Cherel and Klages, 1998). This paper reviews the methods used to-date to investigate albatross diet and summarises the spatial, taxonomic and temporal coverage of existing studies, with the aim of identifying gaps in knowledge. Using this threatened group as a case study for other seabirds, we develop a monitoring framework that should allow the detection of dietary responses to changes in the wider environment, including fishing practices, with recommendations for future research and management.

Methods

We conducted a literature search in February 2016 using Web of Science, Scopus and Google Scholar. Search terms were ‘albatross’ combined with: ‘prey’, ‘food’, ‘diet’, ‘stomach’, ‘ bolus’, ‘isotope’, or 'fatty acid’ in any field. Articles were included if they were published in a peer-reviewed journal from 1950 onwards and reported empirical albatross dietary data. Articles were excluded if the title and abstract were not related to albatross or diet analysis, or were based on samples already described in another article. Reference lists of articles, including reviews identified in the literature search, were checked for additional studies.

Dietary Database

We extracted the data from each paper for entry into our database as follows: 1) albatross species studied, 2) year of the study, 3) breeding site (island/peninsula), 4) breeding population (island group), 5) stage in annual cycle, 6) sample type, 7) methodology (morphological or biochemical), 8) age class, and 9) sample size (see table 1 for definitions). A study was defined as that in which diet was analysed during a specific breeding or non-breeding season for a species at a site. For example if a paper reported on samples collected from two species over three seasons at one colony, that was considered as six studies. For each study, the conservation status according to the IUCN Red List (IUCN, 2015) of each species was included and the approximate population size at that breeding site was derived from published papers, ACAP species assessments (http://www.acap.aq/en/resources/acap-species2) and the Birdlife International online database (http://www.birdlife.org/datazone/species/search).

Synthesis

We reviewed the dataset for spatial and taxonomic gaps in diet sampling, focussing on breeding sites (an individual island or peninsula) that are known to hold >5% of the global population (ACAP, 2015), hereafter termed “IBS” (Important Breeding Sites), and for breeding populations (island groups or mainland areas) that held >5% of the breeding population, hereafter termed “IBPs” (Important Breeding Populations). Key dietary monitoring sites (KDMS) for each species were identified to enable ongoing monitoring for the detection of changes over time. Sites were selected where there had been full taxonomic coverage of prey in morphological studies of at least two sets of diet samples.

Results

Search results

Of the 828 papers identified during the literature search, 109 quantified albatross diet in sufficient detail to meet the selection criteria. Of these, 18 papers reported on samples described in more detail elsewhere, therefore the final database included 91 original papers (Supplementary Table 1). When stratified by sampling year, breeding site and species, these 85 papers reported on 306 diet studies. Ten were excluded from subsequent analysis as they involved ≤3 samples. One study conducted at sea was included even though the sample size was low, because it was the only study for that species. These samples were pooled together as one study (7 samples over 6 years). The 296 studies in the final synthesis were conducted between the late 1940s and 2012 and published between 1950 and 2016.

Dietary Analysis Techniques

Overall, 65.9% (n=195) of studies used morphological techniques to identify prey, 33.1% used biochemical techniques (n=98), and three studies (1.0%) involved both techniques. Specifically, the studies were: morphological analyses of stomach contents obtained as regurgitates (45.6%), from dead birds (6.1%), by stomach flushing/lavage (3.4%) or using an unspecified method (2.7%); pellets collected from around nest sites, usually regurgitated by chicks shortly before fledging (17.6%), and, biochemical analyses either of stable isotope ratios (34.1%) or of fatty acids (0.3%). The majority of all studies used one method; however, 9.1% of studies (n=27) used a combination, mostly morphological analyses of regurgitates in combination with either pellets (n=12), stomach contents of dead birds (n=5) or stomach flushing (n=5).

Temporal span

The use of morphological diet studies peaked in the 1970s with an average of 7.0 studies per year. By the 2000s, the number of studies reduced substantially to an average of 1.3 per year from 2001-2012. The first biochemical study of albatross samples using SIA was published in 1997 (on samples collected in 1991), and the first (only) study involving fatty acids was published in 2010 (on samples collected in 2006); the use of SI studies remains high, with an average of 8.8 per year from 2001-2012 (Fig. 1).

Most studies collected samples during chick-rearing (67.9%), some during the non-breeding period (23.1 %) and more rarely, during incubation (1.0 %) and brood guard (2.2%). In 5.7% of studies, the breeding stage was not specified (Fig. 2). Considering all breeding stages, samples were obtained from adults (37.1%), chicks (33.6%), juveniles (0.6%) or multiple age classes (14.9%). The majority of combined studies comprised adults and chicks (13%), four studies of adults and juveniles (1.6%), and two of adults, chicks and juveniles (0.6%). The ages of birds sampled were un-specified in 14.0% of studies (Fig. 2). Biochemical techniques (almost exclusively SIA) were used more often in adults (77.4%) than chicks (21.5%), and rarely in juveniles (2.9%), whereas morphological techniques were more frequent for chicks (58.2%) than adults (38.9%) and again, rarely in juveniles (2.3%)(Fig. 2). Samples from both adults and chicks were collected for the same time period in 42 studies; however, only seven studies compared results from the two age classes.

Species representation

The diet of all 22 currently recognised albatross species has been studied on at least one occasion (Table 2). However, morphological data on prey are entirely lacking for Amsterdam (*Diomedea amsterdamensis)*, Chatham (*Thalassarche eremita*), Salvin's (*T. salvini*), and white-capped (*T. steadi*) albatrosses, and are limited for short-tailed albatross (*Phoebastria albatrus*) (only 7 samples over 6 years) and Tristan albatross (*D. Dabbenena* -pellets only). Of the 18 species with morphological diet data available, only in six species were these samples collected within the last 10 years (Table 2).

Spatial coverage

Diet analyses have been carried-out at 38 breeding locations, corresponding to 65 separate albatross species-site combinations (Fig. 3). However, many of these studies were at breeding sites that held relatively few birds (Supplementary Table 2). There were 67 IBS for which we are able to quantify sampling coverage. A further three island groups are estimated to hold >5% of the global population of light-mantled albatross (*Phoebetria palpebrata*), but lack reliable counts for the individual islands. Overall, dietary studies have been carried out at 58.2% of IBS (n=39). These include morphological studies at 50.7% of sites (n=34), although only 8.9% (n=6) in the last ten years, and biochemical studies (mostly SIA) at 37.3% of sites (n=25), all but two in the last ten years. There has been at least one diet study at all of the IBS of nine species, less than half the IBS of four species, and at neither of the two IBS of one species (short-tailed albatross) (Table 2). Including those for light-mantled albatross (see above), there are 49 important albatross breeding populations (island groups with separate species-site combinations that hold >5% of the population). There has been at least one diet study on 91.8% of these important breeding populations (n=45); 75.5% have had morphological studies (n=37) and 61.2% have had biochemical studies (n=30).

There have been two full morphological studies of diet for 13 species across 16 sites (28 species/site combinations), and more than two such studies for 8 species across 9 sites (16 species/site combinations), only a minority of which (for four species across five breeding sites; 9 species/site combinations) included at least two sets of samples collected in the last 35 years. These sites are proposed as key dietary monitoring sites (Table 3, Fig. 3).

Discussion

Species, spatial and temporal dietary information gaps

Many dietary studies of albatrosses have been carried out over the last 40 years, but major gaps still exist in terms of taxonomic, spatial and temporal coverage. The diets of five albatross species have never been studied using morphological methods, or the methods applied provided data with low taxonomic resolution. In addition, only seven samples have been collected over six years from the short-tailed albatross. There are no data on the prey of the critically endangered Amsterdam albatross, and although this gap is recognised in the recovery plan for this species, sampling of stomach contents by induced regurgitation or stomach lavage is currently considered too invasive (Delord et al., 2011). Other species with no prey information breed in remote locations without permanent research bases and are difficult to access for logistical or political reasons. This includes the Salvin's and white-capped albatrosses breeding on the Bounty and Disappointment islands respectively, Chatham albatross on the privately-owned Pyramid Rock (Robertson et al., 2003), and short-tailed albatross on volcanically-active Torishima Island and the disputed Minami-kojima islands (Supplementary Table 3).

The majority of published studies are restricted to the chick-rearing period, largely because chick regurgitations can be collected more easily, less invasively and with less impact than those of adults (Phillips 2006). This has resulted in a major bias in our dietary knowledge towards a single age class and breeding stage. The diet and distribution of adults, and their energy requirements, are known to change with breeding stage (Prince et al., 1994; Bevan et al., 1995). In some species, the availability of specific prey resources at certain times may be critical for successful breeding (Arata and Xavier, 2003), and extended foraging trip durations in poor food years can lead to reduced breeding success (Fernandez et al., 2001). Only two studies have investigated diet during incubation, and eight during brood guard, yet in one of the few comparisons between breeding stages, there was a clear seasonal change in prey species composition (Hedd and Gales, 2001). Breeding success, and the decision whether or not to breed by albatrosses, have been linked to environmental processes, with potential carryover effects between the breeding and non-breeding seasons (Cuthbert et al., 2003; Rolland et al., 2010). Long-lived species such as albatrosses are expected to prioritise their own survival over that of their offspring when resources are limited, and hence adults that experience poor foraging success are likely to abandon breeding rather than jeopardise their future reproductive potential (Williams, 1966). Hence, improved knowledge of how fluctuations in availability of particular prey influence the distribution, breeding success and survival of albatrosses is required to better understand the impacts of ongoing and widespread changes in the marine environment.

The last diet review for albatrosses, published >15 years ago, highlighted the paucity of diet data for the non-breeding period (Cherel and Klages, 1998). Since then, SIA has greatly increased our knowledge of trophic level and habitat use during this period, with data now published for 18 species (Phillips et al., 2009; Cherel et al., 2013; Jaeger et al., 2013). Fisheries activity that poses a threat for survival occurs throughout the year, so there remains a conservation imperative for detailed dietary information during the non-breeding season, particularly morphological studies which provide the most reliable indication of reliance on discards. The difficulty is that most albatrosses do not return to land during the non-breeding period, and although samples can be obtained from birds obtained as fisheries bycatch (Gould et al., 1997; Colabuono and Vooren, 2007), these will be biased to ship-following individuals. An alternative is to obtain samples from adults that have returned to colonies (Alvito et al., 2015), and potentially use SI ratios in feathers, natural prey and discards, to distinguish the fisheries contribution to the diet using stable isotope mixing models (Granadeiro et al., 2013) (Bugoni et al., 2010;). Understanding the diet and distribution of juveniles is also important, as survival is at its lowest between fledging and returning to breed (Terauds et al., 2006; Alderman et al., 2010). To date, only one study has presented a morphological diet breakdown for juveniles (Colabuono and Vooren, 2007), and although samples from juveniles were collected in five other studies, these were pooled with other age classes (West and Imber, 1986). Comparison of juvenile and adult foraging ecology in wandering albatrosses was recently carried out using SIA (Jaeger et al., 2014). Juveniles and non-breeding birds fed in sub-tropical waters, similar to breeding females, with males switching to colder waters during breeding. This study provides an important insight into juvenile behaviour and the different life history strategies of different age, sex and breeding classes that lead to diet variation.

Our analysis of the spatial and taxonomic coverage of dietary studies identified 28 IBS that are data-deficient. For many of these important colonies, there is no information on diet composition, including the largest breeding populations of grey-headed, shy, Buller's and northern royal albatrosses. In some cases, there are data for another breeding site in close proximity. For example, diets of grey-headed albatross at the IBS at the Paryadin Peninsula (South Georgia) and Isla Bartolome (Islas Diego Ramirez) are unknown, but there have been studies at Bird Island and Isla Gonzalo, respectively, which are within the same island groups. It is difficult to quantify the spatial scale at which diet variation occurs, given many confounding effects such as breeding stage, season, age, sex and resource availability. Diet can differ considerably between islands within relatively close proximity (Thompson, 1992); thus, any breeding site or island group that holds a substantial proportion of the global population is potentially an important target for a diet study, as is any site considered to be a conservation or management priority. By using tracking studies and SIA, it would be useful to identify IBS where birds have substantially different foraging distributions or feed at distinct trophic levels. The former could be distinguished using the Seabird Tracking Database of Birdlife International (http://www.seabirdtracking.org/index.php), and the latter using existing SI data.

Diet analyses

Each method of dietary analysis has advantages and disadvantages (for a reviews see (Barrett et al., 2007; Karnovsky et al., 2012). There is no single method that identifies all the ages, size classes and species of prey that an animal ingests. Some seabird studies have tried to achieve this by incorporating a variety of methods and models (e.g. Chiaradia et al., 2014), yet it remains difficult to characterise the true diet of top predators. The relative importance of certain prey in stomach contents can be biased by differential rates of digestion, leading to under-estimation of soft-bodied prey and over-representation of prey with hard parts, particularly squid, that tend to be retained for long periods (Furness et al., 1984). More recent studies tend to analyse fresh and old squid beaks separately to compare species composition over the short- or long-term (Cherel et al., 2000); however, underestimation of soft-bodied prey is still an issue. Pellets only include prey that have indigestible hard parts, primarily squid (Xavier et al., 2005), and large beaks (from large species and individuals) are often over-represented, as small beaks tend to degrade (Brooke and Klages, 1986). Stable isotope and fatty acid analysis does not suffer from the same issue of prey retention and provides a less biased view of prey components. Rodhouse et al. (2013), reviewed a number of studies where SIA and fatty acids have highlighted the importance of fish prey for predators that had been assumed to eat mainly squid due to the retention of beaks in stomachs. Although these biochemical techniques avoid biases from prey retention, taxonomic resolution is typically very poor because SI ratios and lipid information for many prey species are unavailable, or overlapping (Inger and Bearhop, 2008).

DNA-based approaches to diet analysis and compound-specific SIA are new techniques that may allow some of the knowledge gaps identified in this review to be filled, potentially overcoming some of the limitations of stomach contents analysis. DNA-based dietary analysis is a non-invasive means of identifying individual prey species in the diet by detecting the genetic sequences in the predator's faeces (Pompanon et al., 2012; Bowser et al., 2013; Jarman et al., 2013). This method can be used during all breeding and life-history stages when scats can be collected (Bowser et al., 2013). As no handling of birds is required, it provides an ideal method of assessing the diet of sensitive species. The limitations are that prey age, size class and mass cannot be assessed. Scats must also be available, so the approach is not feasible for determining diet during the non-breeding period for species that remain far from land. Compound-specific SIA methods have the potential to provide more detailed taxonomic identifications than standard SIA, but these methods are new and their utility is still being explored (Bradley et al., 2014).

To determine the most suitable dietary method is a balance between method limitations, disturbance and the information required (Table 4). To identify prey specific overlaps between albatrosses and fisheries, analysis of stomach contents is ideal as the majority of target prey (fish and squid) have identifiable hard-parts (Arata and Xavier, 2003). However fish prey can still be difficult to identify when no hard parts remain (e.g.Ridoux, 1994). In contrast, SIA is also very useful for identifying reliance on fisheries waste, particularly where discards from demersal or pelagic fisheries differ isotopically from natural prey (Bugoni et al., 2010). When identifying changes in diet over time due to environmental conditions, SIA and fatty acids can again highlight broad trophic changes, but would ideally be complemented with information on all prey components. Although pellets and stomach contents can identify changes in cephalopod and some other prey components, no dietary method currently used for albatrosses can reliably quantify the contribution of soft-bodied prey. This information will be important as the abundance of gelatinous prey is likely to increase with warming oceans (Attrill et al., 2007). DNA-based dietary analysis may be the ideal method to complement SIA in the future to enable detection of soft-bodied prey (McInnes et al., 2016); however, hard-part analysis will be required if changes in prey size classes are to be investigated

A synoptic strategy for albatross dietary studies

This review provides a framework for prioritising global monitoring of albatross diets. To enable the detection of prey changes resulting from climate change or fisheries practices, two key improvements are necessary: 1) an increase in the collection of taxonomically-detailed prey information and 2) maintenance and expansion of the network of long-term monitoring sites.

Increase the collection of prey information

Comprehensive morphological studies are either entirely lacking, or have not been conducted in the last 35 years, for one third of albatross species, including three Critically Endangered species (Table 2). Furthermore, in the last decade, there has been a morphological study of the diet of only six species. This general trend away from morphological techniques may reflect the more labour-intensive nature of identifying individual prey and lack of sufficient taxonomic skills, or concerns about biases associated with greater retention of hard parts and slower digestion of soft-bodied prey (Barrett et al., 2007). The number of diet studies involving stomach contents has also declined, possibly because of the perceived detrimental effects on chick survival. Although sampling in this way had minimal impact on chick condition or breeding success (Phillips, 2006), the associated disturbance and loss of a meal may be discouraging its wider use. Indeed, the management plans for several albatross species state specifically that diet information is lacking due to the invasive nature of current techniques (Delord et al., 2011; DSEWPC, 2011).

The observed shift away from morphological analysis of diet has reduced our ability to detect all but major prey shifts, and yet has occurred against a background of major perturbations in marine ecosystems, driven by a range of climate-related processes (Constable, 2014). These will continue to influence the availability of food resources for albatrosses and their prey (Hays et al., 2005). Environmental changes also alter the operation of fisheries, either by a decline or shift in distribution of target stocks. Monitoring the impacts of these changes on albatross diet would ideally involve complementary approaches: SIA to identify broad shifts in diet, and morphological analyses to provide taxonomic detail to address more targeted questions, such as the effects of changes in distribution or abundance of particular prey, or proposed changes in fisheries practices. In time, it is hoped the development of new methods e.g. DNA-based dietary analysis, may help fill this gap in taxonomic resolution, but in the meantime, resumed collection of morphological data is important to detect any prey changes.

Maintain and expand the network of long-term monitoring sites

Ongoing monitoring of key sites where there are existing time-series of robust diet data is imperative for detecting dietary shifts and identifying links between prey abundance and albatross demography. Long-term diet data is invaluable for enabling management and protection of species and their prey resources, and for observing changes to the wider marine system. The CCAMLR Ecosystem Monitoring Program (CEMP) (SC-CCAMLR, 1997) uses top predators such as the black-browed albatross as indicator species to monitor change in the marine environment, particularly in relation to competition with the fishery for Antarctic krill (*Euphausia superba*), and requires predator diet information in order to estimate consumption. The ongoing CEMP diet sampling programme of black-browed albatross at Bird Island (South Georgia) has provided one of the longest diet time-series for any site (>15 years; Supplementary Table 3). However, there are very few long-term dietary projects for albatrosses; only at five sites are there more than two full dietary studies published in the last 35 years. This makes it difficult to detect diet shifts, and even harder to attribute these to fishing activity or other changes in the environment. For these reasons, the implementation of a wider diet monitoring framework for albatrosses should be encouraged by international agreements such as ACAP and CCAMLR, or NGOs, including BirdLife International, and incorporated into national plans of action and recovery plans.

The proposed KDMS are a recommended starting point for establishing long-term monitoring sites as they allow comparison with existing dietary data. However, they should not be interpreted as the only sites, as there may well be others that are biogeographic, conservation or other management priorities. This network of sites identified here should be refined in the future, by using fisheries, environmental and tracking data to determine the pressures that affect different IBSs and IBPs.

Further linkages between diet studies and other research avenues should be strengthened. Several studies have linked diet composition to foraging location using tracking data (e.g.Xavier et al., 2003), and to breeding success (e.g. Arata et al., 2004). Further work integrating longitudinal tracking and diet studies would allow assessment of changes in important foraging areas or food resources, and how this may affect breeding success. This will be important to identify projected environmental changes and how species may adapt under different climate change scenarios or fishing impacts. Furthermore, by linking tracking to diet, we can continue to identify geographic overlaps with fisheries (Xavier et al., 2004) as well as likely location of prey (Xavier et al., 2006)

An open-access database of prey and SI information would assist in establishing distributions of prey species and monitoring spatial and temporal changes. A centralised approach would ensure uniformity in data collection and reporting, and enable collaboration and coordination between management authorities. One such database has been established for the Southern Ocean (Raymond et al. 2011) and at the time of writing, the Expert Group on Birds and Marine Mammals within the Scientific Committee on Antarctic Research, are extending this database into a Southern Ocean community resource with expanded coverage of SI and other diet data (including the data compiled for the current study). Companion efforts would, ideally, broaden the database coverage to include albatross breeding sites elsewhere. An updated dietary database would provide the foundation for a thorough synthesis of prey and SI data, including a meta-analysis identifying the important prey components for each species, and spatial and temporal variation.

Conclusion

On the basis of the gaps and trends identified in this review, we have outlined key recommendations for future dietary work (Table 5). These are made specifically in the context of albatross conservation management; however, they are likely to be applicable across many other seabird groups. Our work highlights the pressing need for dietary studies both of highly threatened species and major breeding sites in general. Taxonomic, spatial and temporal gaps exist in baseline sampling coverage, particularly with regard to poorly-known stages of the breeding season, the non-breeding period, juveniles and immature birds. The development of new non-invasive techniques with high taxonomic resolution may assist in this process, and will be particularly useful for sensitive species where disturbance is a major concern. Collecting information on seabird dietary requirements is fundamental to enable monitoring of their prey, and should be designed to detect diet shifts over short and long time-scales. Understanding how these prey changes affect breeding and non-breeding birds will be crucial for gauging the threat these changing processes pose to seabird populations. Ongoing diet monitoring across a network of key sites should be seen as a high priority for conservation and management bodies, as should the continued collection of prey information to complement SIA and enable detection of fine-scale differences in abundance and utilisation of key individual taxa. The key findings, recommendations and proposed actions identified in this paper (Table 5), will hopefully enable the detection and attribution of the impacts of climate or fisheries processes on albatross populations and facilitate the timely implementation of responsive management.

Acknowledgements: Thank-you to Y. Cherel for providing suggestions and site information for the review, and I. Hodgson-Johnston and anonymous reviewers for helpful comments on the manuscript.

References

ACAP. 2015. Agreement on the Conservation of Albatrosses and Petrels. Report on Progress with the Implementation of the Agreement 2013 - 2015.

Alderman, R., Gales, R., Hobday, A. J., and Candy, S. G. 2010. Post-fledging survival and dispersal of shy albatross from three breeding colonies in Tasmania. Marine Ecology Progress Series, 405: 271-285.

Alvito, P. M., Rosa, R., Phillips, R. A., Cherel, Y., Ceia, F., Guerreiro, M., Seco, J., et al. 2015. Cephalopods in the diet of nonbreeding black-browed and grey-headed albatrosses from South Georgia. Polar Biology, 38: 631-641.

Arata, J., Robertson, G., Valencia, J., Xavier, J. C., and Moreno, C. A. 2004. Diet of grey-headed albatrosses at the Diego Ramírez Islands, Chile: ecological implications. Antarctic Science, 16: 263-275.

Arata, J., and Xavier, J. C. 2003. The diet of black-browed albatrosses at the Diego Ramirez Islands, Chile. Polar Biology, 26: 638-647.

Attrill, M. J., Wright, J., and Edwards, M. 2007. Climate-related increases in jellyfish frequency suggest a more gelatinous future for the North Sea. Limnology and Oceanography, 52: 480-485.

Barbraud, C., Rolland, V., Jenouvrier, S., Nevoux, M., Delord, K., and Weimerskirch, H. 2012. Effects of climate change and fisheries bycatch on Southern Ocean seabirds: a review. Marine Ecology Progress Series, 454: 285-307.

Barrett, R. T., Camphuysen, K., Anker-Nilssen, T., Chardine, J. W., Furness, R. W., Garthe, S., Huppop, O., et al. 2007. Diet studies of seabirds: a review and recommendations. Ices Journal of Marine Science, 64: 1675-1691.

Bevan, R. M., Butler, P. J., Woakes, A. J., and Prince, P. A. 1995. The energy expenditure of free-ranging black-browed albatrosses. Philosophical Transactions of the Royal Society B-Biological Sciences, 350: 119-131.

Bowser, A. K., Diamond, A. W., and Addison, J. A. 2013. From puffins to plankton: a DNA-based analysis of a seabird food chain in the northern Gulf of Maine. PLOS ONE, 8: e83152.

Bradley, C. J., Madigan, D. J., Block, B. A., and Popp, B. N. 2014. Amino acid isotope incorporation and enrichment factors in pacific bluefin tuna, Thunnus orientalis. PLOS ONE, 9.

Brooke, M. d. L., and Klages, N. 1986. Squid beaks regurgitated by grey-headed and yellow-nosed albatrosses, *Diomedea chrysostoma* and *D. chlororhynchos* at the Prince Edward Islands. Ostrich, 57: 203-206.

Brothers, N., Gales, R., and Reid, T. 1999. The influence of environmental variables and mitigation measures on seabird catch rates in the Japanese tuna longline fishery within the Australian Fishing Zone, 1991-1995. Biological Conservation, 88: 85-101.

Budge, S. M., Iverson, S. J., and Koopman, H. N. 2006. Studying trophic ecology in marine ecosystems using fatty acids: A primer on analysis and interpretation. Marine Mammal Science, 22: 759-801.

Bugoni, L., McGill, R. A. R., and Furness, R. W. 2010. The importance of pelagic longline fishery discards for a seabird community determined through stable isotope analysis. Journal of Experimental Marine Biology and Ecology, 391: 190-200.

Cairns, D. K. 1987. Seabirds as indicators of marine food supplies. Biological Oceanography, 5: 261-271.

Chambers, L. E., Devney, C. A., Congdon, B. C., Dunlop, N., Woehler, E. J., and Dann, P. 2011. Observed and predicted effects of climate on Australian seabirds. Emu, 111: 235-251.

Cherel, Y., Jaeger, A., Alderman, R., Jaquemet, S., Richard, P., Wanless, R. M., Phillips, R. A., et al. 2013. A comprehensive isotopic investigation of habitat preferences in nonbreeding albatrosses from the Southern Ocean. Ecography, 36: 277-286.

Cherel, Y., and Klages, N. 1998. A review of the food of albatrosses. Albatross: Biology and Conservation: 113-136.

Cherel, Y., Weimerskirch, H., and Trouvé, C. 2000. Food and feeding ecology of the neritic-slope forager black-browed albatross and its relationships with commercial fisheries in Kerguelen waters. Marine Ecology Progress Series, 207: 183-199.

Chiaradia, A., Forero, M. G., McInnes, J. C., and Ramírez, F. 2014. Searching for the true diet of marine predators: Incorporating Bayesian priors into stable isotope mixing models. PLOS ONE, 9.

Colabuono, F. I., and Vooren, C. M. 2007. Diet of Black-browed Thalassarche melanophrys and Atlantic Yellow-nosed T-chlororhynchos albatrosses and White-chinned Procellaria aequinoctialis and Spectacled P-conspicillata Petrels off southern Brazil. Marine Ornithology, 35: 9-20.

Constable, e. a. 2014. Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. Glob Chang Biol, 20: 3004-3025.

Croxall, J. P., Trathan, P. N., and Murphy, E. J. 2002. Environmental change and Antarctic seabird populations. Science, 297: 1510-1514.

Cuthbert, R., Ryan, P. G., Cooper, J., and Hilton, G. 2003. Demography and population trends of the Atlantic Yellow-nosed Albatross. Condor, 105: 439-452.

Delord, K., Micol, T., and Marteau, C. 2011. National Plan of Actions for the Amsterdam albatross Diomedea amsterdamensis 2011 – 2015.

DSEWPC. 2011. National recovery plan for threatened albatrosses and giant petrels 2011-2016.

Feely, R. A., Doney, S. C., and Cooley, S. R. 2009. Ocean acidification: Present conditions and future changes in a high-CO 2 world. Oceanography, 22: 36-47.

Fernandez, P., Anderson, D. J., Sievert, P. R., and Huyvaert, K. 2001. Foraging destinations of three low-latitude albatross (Phoebastria) species. Journal of Zoology, 254: 391-404.

Frederiksen, M., Edwards, M., Richardson, A. J., Halliday, N. C., and Wanless, S. 2006. From plankton to top predators: Bottom-up control of a marine food web across four trophic levels. Journal of Animal Ecology, 75: 1259-1268.

Furness, B. L., Laugksch, R. C., and Duffy, D. C. 1984. Cephalopod beaks and studies of seabird diets. Auk, 101: 619-620.

Gjerdrum, C., Vallee, A. M., St Clair, C. C., Bertram, D. F., Ryder, J. L., and Blackburn, G. S. 2003. Tufted puffin reproduction reveals ocean climate variability. Proc Natl Acad Sci U S A, 100: 9377-9382.

Gould, P., Ostrom, P., and Walker, W. 1997. Trophic relationships of albatrosses associated with squid and large-mesh drift-net fisheries in the North Pacific Ocean. Canadian Journal of Zoology-Revue Canadienne De Zoologie, 75: 549-562.

Granadeiro, J. P., Brickle, P., and Catry, P. 2013. Do individual seabirds specialize in fisheries' waste? The case of black-browed albatrosses foraging over the Patagonian Shelf. Animal Conservation, 17: 19-26.

Grémillet, D., and Boulinier, T. 2009. Spatial ecology and conservation of seabirds facing global climate change: a review. Marine Ecology Progress Series, 391: 121-137.

Hays, G. C., Richardson, A. J., and Robinson, C. 2005. Climate change and marine plankton. TRENDS in Ecology and Evolution, 20: 337-344.

Hedd, A., and Gales, R. 2001. The diet of shy albatrosses (*Thalassarche cauta*) at Albatross Island, Tasmania. Journal of Zoology London, 253: 69-90.

Inger, R., and Bearhop, S. 2008. Applications of stable isotope analyses to avian ecology. Ibis, 150: 447-461.

IUCN 2015. IUCN Red List of Threatened Species. *In* Downloaded on 28 February 2016.

Jaeger, A., Goutte, A., Lecomte, V. J., Richard, P., Chastel, O., Barbraud, C., Weimerskirch, H., et al. 2014. Age, sex, and breeding status shape a complex foraging pattern in an extremely long-lived seabird. Ecology, 95: 2324-2333.

Jaeger, A., Jaquemet, S., Phillips, R. A., Wanless, R. M., Richard, P., and Cherel, Y. 2013. Stable isotopes document inter- and intra-specific variation in feeding ecology of nine large southern Procellariiformes. Marine Ecology Progress Series, 490: 255-266.

Jarman, S. N., McInnes, J. C., Faux, C., Polanowski, A. M., Marthick, J., Deagle, B. E., Southwell, C., et al. 2013. Adélie penguin population diet monitoring by analysis of food DNA in scats. PLOS ONE, 8: e82227.

Karnovsky, N. J., Hobson, K. A., and Iverson, S. J. 2012. From lavage to lipids: Estimating diets of seabirds. Marine Ecology Progress Series, 451: 263-284.

Le Bohec, C., Durant, J. M., Gauthier-Clerc, M., Stenseth, N. C., Park, Y.-H., Pradel, R., Grémillet, D., et al. 2008. King Penguin population threatened by Southern Ocean warming. Ecology, 105: 2493-2497.

McInnes, J. C., Emmerson, L., Southwell, C., Faux, C., and Jarman, S. N. 2016. Simultaneous DNA-based diet analysis of breeding, non-breeding and chick Adélie penguins. Royal Society Open Science, 3.

Nel, D. C., Ryan, P. G., Crawford, R. J. M., Cooper, J., and Huyser, O. A. W. 2002. Population trends of albatrosses and petrels at sub-Antarctic Marion Island. Polar Biology, 25: 81-89.

Phillips, R. A. 2006. Efficacy and effects of diet sampling of albatross chicks. Emu, 106: 305-308.

Phillips, R. A., Bearhop, S., Mcgill, R. A. R., and Dawson, D. A. 2009. Stable isotopes reveal individual variation in migration strategies and habitat preferences in a suite of seabirds during the nonbreeding period. Oecologia, 160: 795-806.

Pompanon, F., Deagle, B. E., Symondson, W. O., Brown, D. S., Jarman, S. N., and Taberlet, P. 2012. Who is eating what: diet assessment using next generation sequencing. Mol Ecol, 21: 1931-1950.

Prince, P. A., Rothery, P., Croxall, J. P., and Wood, A. G. 1994. Population dynamics of black-browed and gray-headed albatrosses *Diomedea melanophris and D. chrysostoma* at Bird Island, South Georgia. Ibis, 136: 50-71.

Ridoux, V. 1994. The diets and dietary segregation of seabirds at the subantarctic Crozet Islands. Marine Ornithology, 22: 1-192.

Rintoul, S. R., Sparrow, M., Meredith, M. P., Wadley, V., Speer, K., Hofmann, E., Summerhayes, C., et al. 2012. The Southern Ocean Observing System: Initial Science and Implementation Strategy, Scientific Committee on Oceanic Research and Scientific Committee on Antarctic Research.

Robertson, C. J. R., Bell, D., and Scofield, P. 2003. Population assessment of the Chatham mollymawk at The Pyramid, December 2001.

Rodhouse, P. G. K. 2013. Role of squid in the Southern Ocean pelagic ecosystem and the possible consequences of climate change. Deep Sea Research Part II: Topical Studies in Oceanography, 95: 129-138.

Rolland, V., Weimerskirch, H., and Barbraud, C. 2010. Relative influence of fisheries and climate on the demography of four albatross species. Global change biology, 16: 1910-1922.

SC-CCAMLR 1997. CCAMLR Ecosystem Monitoring Program: Standard Methods for Monitoring Studies., CCAMLR, Hobart, Australia.

Terauds, A., Gales, R., Baker, G. B., and Alderman, R. 2006. Population and survival trends of Wandering Albatrosses (Diomedea exulans) breeding on Macquarie Island. Emu, 106: 211-218.

Thompson, K. R. 1992. Quantitative analysis of the use of discards from squid trawlers by black-browed albatrosses Diomedea melanophris in the vicinity of the Falkland Islands. Ibis, 134: 11-21.

Weimerskirch, H., and Jouventin, P. 1987. Population dynamics of the wandering albatross, Diomedea exulans, of the Crozet Islands: causes and consequences of the population decline. Oikos, 49: 315-322.

West, J. A., and Imber, M. J. 1986. Some foods of Buller's mollymawk *Diomedea bulleri*. New Zealand Journal of Zoology, 13: 169-174.

Williams, G. C. 1966. Natural selection, the costs of reproduction and a refinement of Lack’s principle. American Naturalist: 687-690.

Xavier, J. C., Croxall, J. P., and Cresswell, K. A. 2005. Boluses: An effective method for assessing the proportions of cephalopods in the diet of albatrosses. Auk, 122: 1182-1190.

Xavier, J. C., Croxall, J. P., Trathan, P. N., and Wood, A. G. 2003. Feeding strategies and diets of breeding grey-headed and wandering albatrosses at South Georgia. Marine Biology, 143: 221-232.

Xavier, J. C., Louzao, M., Thorpe, S. E., Ward, P., Hill, C., Roberts, D., Croxall, J. P., et al. 2013. Seasonal changes in the diet and feeding behaviour of a top predator indicate a flexible response to deteriorating oceanographic conditions. Marine Biology, 160: 1597-1606.

Xavier, J. C., Tarling, G. A., and Croxall, J. P. 2006. Determining prey distribution patterns from stomach-contents of satellite-tracked high-predators of the Southern Ocean. Ecography, 29: 260-272.

Xavier, J. C., Trathan, P. N., Croxall, J. P., Wood, A. G., Podesta, G., and Rodhouse, P. G. 2004. Foraging ecology and interactions with fisheries of wandering albatrosses (Diomedea exulans) breeding at South Georgia. Fisheries oceanography, 13: 324-344.

Table 1: Parameters used to categorise diet studies included within the database.

Category	Definition
Scientific name	Based on the 22 species recognised currently by ACAP, BirdLife International and IUCN.
Common name	
Analysis year	The nonbreeding or breeding period that the samples represent. Austral summers were categorised according to the year in which the chicks fledge (e.g. the 2002/2003 season was recorded as 2003). Feathers collected from adults at colonies were assumed to represent the preceding nonbreeding period.
Breeding site	An island with breeding pairs, or in a few cases, a peninsula/clearly disjunct piece of land on the same island.
Breeding population	An island group with pairs breeding, may contain numerous breeding sites
Stage (in annual cycle)	incubation, brood-guard, chick-rearing or nonbreeding period
Sample type	stomach contents (regurgitation, stomach lavage, whole stomach), pellet/bolus/cast, stable isotope (SIA), fatty acid (FAA)
Methodology	morphological, biochemical
Age class	adult, chick or juvenile
Sample size	number of samples analysed (studies with $n \leq 3$ were excluded from analysis). A sample was defined as either a bolus, blood collection, feather or stomach content taken from an individual bird.
IUCN Status	IUCN conservation status, February 2016.
Population size	number of pairs at the breeding site (ACAP 2015).
Reference	

Table 2: Gap analysis of dietary studies using morphological and biochemical approaches for each albatross species. IBS - important breeding sites (an island or peninsula with >5% of the population), IBP - important breeding populations (an island group with >5% of the population). The latest study for each technique is the year the study was carried out.

Species	IUCN Status [a]	Latest morphological Study (year)	No. Morphological studies	Latest biochemical study (year)	No. Biochemical studies	No. IBS	No. IBS with Morphological data	No. IBS with Biochemical data	% IBS with Morphological data	% IBS with Biochemical data	No. IBP	No. IBP with Morphological data	No. IBP with Biochemical data	% IBP with Morphological data	% IBP with Biochemical data
Amsterdam (*Diomedea amsterdamensis*)	CR		0	2007	2	1	0	1	0	100	1	0	1	0	100
Antipodean (*Diomedea antipodensis*)	VU	2001	4	2004	2	2	2	2	100	100	2	2	2	100	100
Atlantic yellow-nosed (*Thalassarche chlororhynchos*)	EN	2004 [d]	2	2007	5	3	1	1	33	33	2	1	1	50	50
Black-browed (*Thalassarche melanophris*)	NT	2009	30 [e]	2012	21 [e]	4	2	1	50	25	4	3	2	75	50
Black-footed (*Phoebastria nigripes*)	NT	1991	13	2006	4	4	3	0	75	0	1	1	0	100	0
Buller's (*Thalassarche bulleri*)	NT	1997	7	2009	2	3	2	1	67	33	3	3	2	100	67
Campbell (*Thalassarche impavida*)	VU	1997	1	1997	1	1	1	1	100	100	1	1	1	100	100
Chatham (*Thalassarche eremita*)	VU	-	0	2008	1	1	0	1	0	100	1	0	1	0	100

Grey-headed (*Thalassarche chrysostoma*)	EN	2009	35 [e]	2005	8 [e]	9	5	3	56	33	6	6	3	100	50
Indian yellow-nosed (*Thalassarche carteri*)	EN	2001	8	2008	3	3	3	2	100	67	3	3	2	100	67
Laysan (*Phoebastria immutabilis*)	NT	2000	14	2007	7	2	2	1	100	50	1	1	0	100	100
Light-mantled (*Phoebetria palpebrata*)	NT	2009	13	2007	9	4 [b]	3	1	75	25	7 [c]	5	3	63	38
Northern royal (*Diomedea sanfordi*)	EN	1993	10	2009	1	3	1	0	33	0	1	1	0	100	0
Salvin's (*Thalassarche salvini*)	VU	-	0	2008	2	8	0	1	0	13	1	0	1	0	100
Short-tailed (*Phoebastria albatrus*)	VU	2014[d]	1	2006	2	2	0	0	0	0	2	0	0	0	0
Shy (*Thalassarche cauta*)	NT	1998	5	2009	1	2	1	1	50	50	1	1	1	100	100
Sooty (*Phoebetria fusca*)	EN	2009	9	2006	5	5	2	2	40	40	4	3	3	75	75
Southern royal (*Diomedea epomophora*)	VU	1996	7	2004	1	1	1	0	100	0	1	1	0	100	0
Tristan (*Diomedea dabbenena*)	CR	1979	1	2006	3	1	1	1	100	100	1	1	1	100	100
Wandering (*Diomedea exulans*)	VU	2009	36 [e]	2009	19 [e]	5	3	3	60	60	4	3	4	75	100
Waved (*Phoebastria irrorata*)	CR	1971	2	2004	1	1	1	1	100	100	1	1	1	100	100
White-capped (*Thalassarche steadi*)	NT	-	0	2008	1	2	0	1	0	50	1	0	1	0	100
Overall			198 [e]		101 [e]	67	34	25	51%	37%	49	37	30	75%	61%

[a] CR- Critically Endangered; EN- Endangered; VU- Vulnerable; NT- Near Threatened

[b] population count data is unavailable for IBS for some island groups, therefore there may be more IBS for this species that hold >5% of the population

[c] includes three island groups where the individual IBS counts are unavailable, however the total island counts are >5% of the population

[d] samples collected at-sea over numerous years and pooled together for analysis, this is the final year of collection, however only one sample per year.

[e] Three studies have used a combination of both morphological and biochemical methods and are included in both columns.

Table 3: Key dietary monitoring sites. These sites have had at least two full morphological diet studies carried out.

Breeding Site	**Breeding Population**	**Species**
Albatross Island	Tasmania	Shy [c]
Bird Island	South Georgia	Black-browed[a,c] Grey-headed [c] Wandering [c]
Campbell Island	Campbell Island	Grey-headed
Falaise d'Entrecasteaux	Amsterdam Island	Indian yellow-nosed
French Frigate Shoals	Hawaii	Black-footed[b] Laysan[a]
Isla Gonzalo	Diego Ramírez	Grey-headed [c] Black-browed[a,c]
Île de la Possession	Crozet Island	Sooty[a] Wandering[a,c]
Isla Espanola	Galapagos Islands	Waved [b]
Jeanne d'Arc Peninsula	Kerguelen	Black-browed[a]
Kure Atoll	Hawaii	Black-footed[b] Laysan[b]
Laysan Island	Hawaii	Black-footed[b] Laysan[b]
Marion Island	Prince Edward Islands	Grey-headed [c] Light-mantled[a] Sooty Wandering [c]

Midway Atoll	Hawaii	Black-footed[b] Laysan[b]
North-East Island	Snares Island	Buller's
Taiaroa Head	New Zealand	Northern royal[a]
The Little (Middle) Sister	Chatham Islands	Northern royal Buller's[a]

[a] Contain less than 5% of the breeding population.

[b] Most recent morphological diet study > 35 years ago.

[c] Species/sites with *greater* than two full morphological diet studies < 35 years ago.

649 Table 4: Dietary methods used to assess albatross diet, with requirements, associated biases, disturbance and additional information obtained.

Method	**Sample period**	**Taxonomic Resolution**	**Prey database required**	**Relative Disturbance**	**Key limitations**	**Unit of Measure**	**Additional Information**
Regurgitation	Days (flesh remains) Weeks (hard-part remains)	Species/group	Prey hard-parts	Medium	Over-estimation of prey with hard parts, under-estimation of soft-bodied prey, provisioning diet only for many species, potentially only partial stomach contents obtained.	FOC, Mass, proportion of items	Prey size, reconstituted meal mass
Stomach flushing	Days (flesh remains) Weeks (hard-part remains)	Species/group	Prey hard-parts	High	Over-estimation of prey with hard parts, under-estimation of soft-bodied prey.	FOC, Mass, proportion of items	Prey size, reconstituted meal mass
Stomach content of dead birds	Days (flesh remains) Weeks (hard-part remains)	Species/group	Prey hard-parts	Low	Over-estimation of prey with hard parts, under-estimation of soft-bodied prey, potentially confounded by cause of mortality.	FOC, Mass, proportion of items	Prey size, reconstituted meal mass
Pellets (boluses)	Weeks (hard-part remains)	Species with hard parts	Prey hard-parts	Low	Only identifies prey with hard-parts.	FOC, Proportion of items	Prey size
SIA	Days (using blood) Months (using feathers)	Trophic level	Prey stable isotope signatures	Medium-High	Low taxonomic resolution (potentially improved using multi-source isotope mixing model).	FOC, relative proportions from mixing models	Foraging habitat (carbon source)
DNA	Days (faeces)	Species/Genus and broad diet	Prey genetic sequences	Low	Lacks mass and size information of prey, semi-quantitative.	FOC, proportion of sequences	Bird sex, parasites

Fatty Acids	Days (using blood) Months (using muscle or fat)	Trophic level	Prey fatty acid signatures	High	Low taxonomic resolution.	FOC, relative proportions from mixing models	Foraging habitat

FOC= Frequency of co-occurrence

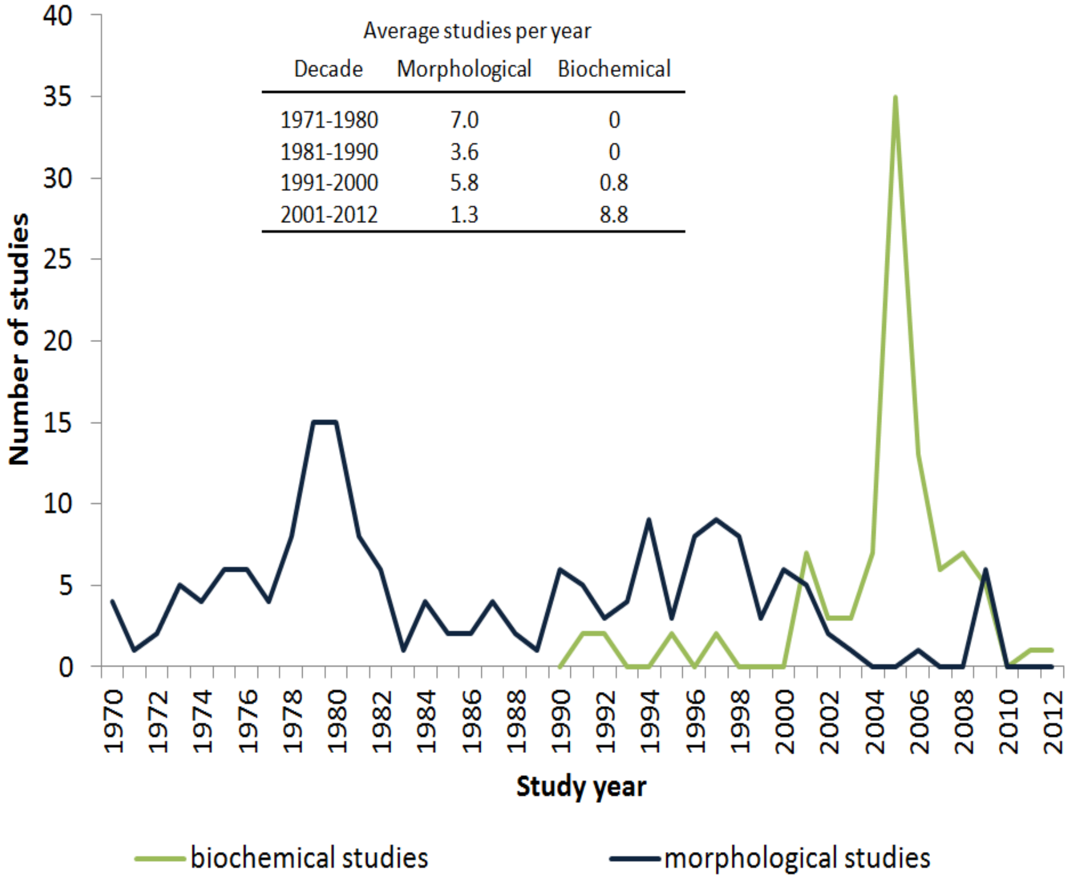
Table 5: Summary of key findings, recommendations and actions for ongoing albatross dietary monitoring.

Key Findings	**Recommendation**	**Proposed Action**
Knowledge gaps Significant gaps in prey information exist for: Amsterdam, Chatham, Salvin's, and white-capped albatross, with limited information for Tristan and short-tailed albatross. Prey information mostly restricted to chick rearing Reduction in resolution of information on prey items consumed due to changes in	Prioritise filling the gaps for the species and sites where such information is needed to make a difference to conservation and management. Increase monitoring to incorporate other stages of the breeding and non-breeding seasons. This may potentially be facilitated by a combination of SIA and the utilisation of new techniques such as DNA dietary analysis. Continue to progress the application of DNA and other forensic dietary analyses for albatross. DNA analysis may allow some of these gaps to be filled as it is logistically straightforward to collect	ACAP/Birdlife International to facilitate the prioritisation of species and IBS to investigate diet. Potentially use tracking databases and existing stable isotope and prey data to determine monitoring priorities. Incorporate appropriate dietary studies as an integral component of species recovery and management plans. Elevate the importance of dietary studies in long term monitoring plans to link observed demographic parameters to ecological drivers. Undertake trials to check the feasibility of DNA and other forensic methods for albatross.

methodology	and provides detailed prey information. Resume collection of prey information either using morphological examination of hard parts or DNA dietary techniques, to complement SIA.	
Detecting change Difficulty in detecting change due to limited long-term data collection.	Maintain long-term research at key sites to enable robust longitudinal diet assessment and maximise the outputs from past investment in such studies. Compile diet data including prey and SIA at a centralised location to enable detection of changes over time To achieve consistency in data collection, adopt	Use the key dietary monitoring sites (Table 3) as a basis for an implementation plan to enable longer time-series data to be collected. Develop a centralised top-predator database of diet information to facilitate quantification of changes in prey over temporal and spatial scales. Such a database could include similar information from other marine predators to allow evaluation of impacts of climate and fisheries changes at an ecosystem level. Co-ordination

	standardised methods of collecting and reporting dietary data that enables comparisons over time. These should likely be based on existing protocols such as the CCAMLR Ecosystem Monitoring Program Standard Methods (SC-CCAMR 1997).	with EGBAMM within SCAR* who have begun a similar database for SI data. Work with organisations such as ACAP to encourage signatories to improve diet monitoring. Repeat SIA studies at the same sites to identify any major shifts in prey or habitat use.

*EGBAMM – expert group on birds and marine mammals within the Scientific Committee on Antarctic Research (SCAR)



Average studies per year

Decade	Morphological	Biochemical
1971-1980	7.0	0
1981-1990	3.6	0
1991-2000	5.8	0.8
2001-2012	1.3	8.8

Fig. 1: The number of diet studies of albatrosses over time using different methods. Morphological - prey identified from physical characteristics (including analysis of regurgitations, stomach contents and pellets). Biochemical - predominantly stable isotope analysis, with one fatty acid study. Ten morphological studies and five biochemical studies were excluded from this graph as the study year was unspecified (Nine morphological studies excluded were published before 1999, and one in 2015).

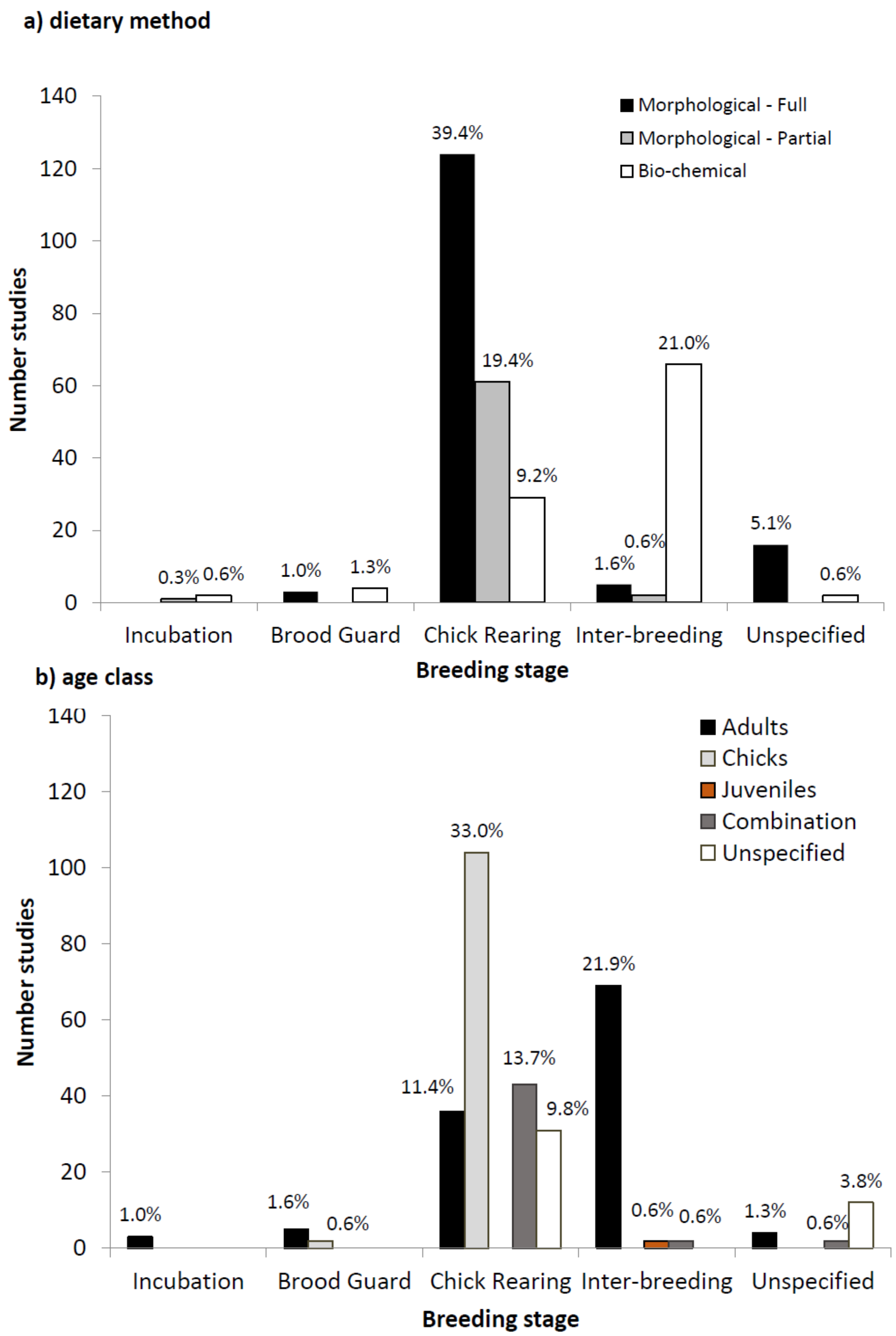


Fig. 2: Summary of the number of albatross diet studies conducted during each major breeding phase, grouped by (a) investigation method (i.e. morphological or bio-chemical analysis) and (b) age class of sampled birds. Each morphological study was categorised as either full or partial, depending on whether multiple prey groups or a single prey group (e.g. cephalopods or fish) were identified.

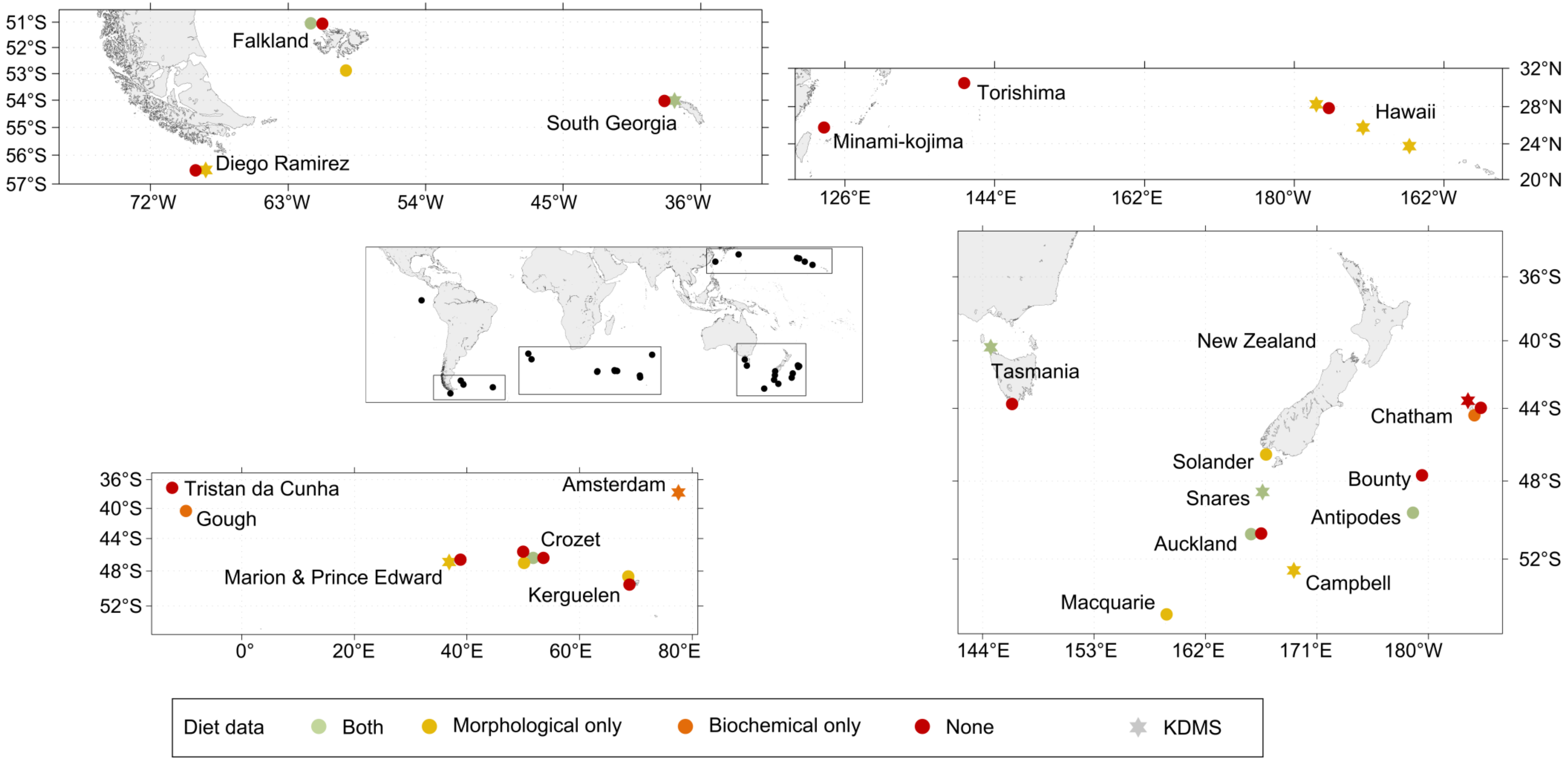


Fig. 3: Gaps in albatross dietary information at important breeding sites (sites with >5% of the population) and key dietary monitoring sites for ongoing monitoring. Coloured points represent the species at the site with the least dietary information. A star represents a key dietary monitoring site (KDMS), where diet information of high taxonomic resolution has been collected and ongoing monitoring to detect change would be highly beneficial. Not shown in

detail on the figure is Isla Espanola in the Galapagos, which is a key dietary monitoring site for waved albatross with both biochemical and morphological dietary information.