Measuring habitat quality for waterbirds: a review

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Abstract

Quantifying habitat quality is dependent on measuring a site's relative contribution to population growth rate. This is challenging for studies of waterbirds, whose high mobility can decouple demographic rates from local habitat conditions and make sustained monitoring of individuals near-impossible. To overcome these challenges, biologists have used many direct and indirect proxies of waterbird habitat quality. However, consensus on what methods are most appropriate for a given scenario is lacking. We undertook a structured literature review of the methods used to quantify waterbird habitat quality, and provide a synthesis of the context-dependent strengths and limitations of those methods. Our structured search of the Web of Science database returned a sample of 398 studies, upon which our review was based. The reviewed studies assessed habitat quality by either measuring habitat attributes (e.g., food abundance, water quality, vegetation structure), or measuring attributes of the waterbirds themselves (e.g., demographic parameters, body condition, behaviour, distribution). Measuring habitat attributes, although they are only indirectly related to demographic rates, has the advantage of being unaffected by waterbird behavioural stochasticity. Conversely, waterbird-derived measures (e.g., body condition, peck rates) may be more directly related to demographic rates than habitat variables, but may be subject to greater stochastic variation (e.g., behavioural change due to presence of conspecifics). Therefore, caution is needed to ensure that the measured variable does influence waterbird demographic rates. This assumption was usually based on ecological theory rather than empirical evidence. Our review highlighted that there is no single best, universally applicable method to quantify waterbird habitat quality. Individual project specifics (e.g., time frame, spatial scale, funding) will influence the choice of variables measured. Where possible, practitioners should measure variables most directly related to demographic rates. Generally, measuring multiple variables yields a better chance of accurately capturing the relationship between habitat characteristics and demographic rates.

Introduction

A core aim of conservation management is optimising habitat quality for focal species (Johnson, 2005, McComb, 2016). For management to be truly optimised, a measurable understanding of what constitutes habitat quality is required (Marzluff et al., 2000). The ultimate measure of habitat quality for an individual is the individual's relative contribution to the growth rate of the population when inhabiting a given habitat (Johnson, 2007). There are two components of this measure: survival and reproduction. By defining habitat quality in terms of population growth rate, habitat quality can be assessed on a continuous temporal scale. For example, habitat quality can be measured instantaneously or as a life-time measure of habitat quality akin to the individual's fitness. There are many components that combine to influence survival and reproductive output including food availability, predation risk, habitat structure and configuration, and the presence of disturbances (e.g., human foot traffic) (Johnson, 2007).

Quantifying demographic rates (survival and reproductive output) is a challenging task (Stephens et al., 2015), as it requires sustained monitoring of individuals of known-identity. Studies that do achieve this are often conducted either on sessile organisms (e.g., Ma et al., 2014, Wang et al., 2012, Zhao et al., 2006) or large-bodied organisms that are restricted to a small geographic area (e.g., islands: (Kruuk et al., 1999, Richard et al., 2014); natal colony: (Baker and Thompson, 2007, Le Boeuf et al., 2019)). Demographic rates are also financially costly to measure (Knutson et al., 2006, Pidgeon et al., 2006), and the long time-frames for data collection can mean that research extends beyond typical funding cycles and research project lifetimes, particularly for research on long-lived species (Le Boeuf et al., 2019). Despite these challenges, there have been studies that successfully monitor survival (Valdez-Juarez et al., 2019) and reproductive performance (Pérot and Villard, 2009, Pidgeon et al., 2006, Zanette, 2001) of birds in relation to habitat quality. Outputs from these studies are often very applied with actionable recommendations for conservation decision-makers.

Waterbirds are a particularly challenging group to obtain habitat quality estimates for because multiple factors can confound the relationship between site habitat conditions and resultant demographic rates. Many waterbirds are highly dispersive and track ephemeral habitat conditions at local, regional, or even continental scales (Cumming et al., 2012, Pedler et al., 2014, Roshier et al., 2006), creating the potential for mismatches between the scale of monitoring and the scale at which demographic processes are governed. Habitat quality at a particular wetland may be high relative to other points in time, yet waterbirds do not capitalise on these favourable conditions because there are other areas of high quality habitat in the landscape (behavioural choice impacts) (Cumming et al., 2012). Consequently, habitat quality assessments based on abundance, density, or occupancy for the particular site may be decoupled from theoretical predictions if data from the broader landscape are unavailable. The distribution of many waterbird species is also influenced by social attraction (Gawlik and Crozier, 2007). As a result, areas of high quality habitat may go unused because waterbirds newly arriving in an area are drawn to sites with existing waterbird presence (Gawlik and Crozier, 2007).

Many waterbirds are also migratory. Consequently, demographic parameters in one part of the range may be decoupled from the habitat conditions experienced at that time due to carry-over effects from previous seasons (Aharon-Rotman et al., 2016a, Sedinger and Alisauskas, 2014, Swift et al., 2020). For example, survival during the breeding period and breeding success may be higher in individuals that depart their non-breeding grounds in better condition (Swift et al., 2020). Furthermore, breeding performance in one part of the range may influence parameters including abundance and population age structure on the non-breeding grounds, irrespective of the local conditions on the non-breeding grounds (Rogers and Gosbell, 2006). In addition to carryover effects, survival data may be particularly sensitive to pinch points of low-quality habitat along the migratory flyway (Piersma et al., 2016, Studds et al., 2017).

Due to the difficulties of obtaining waterbird demographic data in a given area, an array of methods have been used as proxies to measure habitat quality (Ma et al., 2010). The use of proxies also helps to overcome budget limitations of management agencies by allowing snapshot estimates of habitat quality to be made without the need for extended periods of data collection in space and time (Osborn et al., 2017). However, the many different options available for measuring habitat quality can be bewildering for research scientists and conservation practitioners (Pidgeon et al., 2006). There is little consensus on which method, or combination of methods, produces the most meaningful estimate of waterbird habitat quality, and in some cases, it is unclear as to whether particular proxies meaningfully reflect underlying habitat quality from the perspective of direct impact on population processes (Johnson, 2005, Johnson, 2007, Van Horne, 1983). For example, density of individuals may not reflect underlying habitat quality if the population does not follow the ideal free distribution (Van Horne, 1983), and time spent foraging may not reflect underlying habitat quality if individuals are constrained by prey handling time or digestive bottlenecks (Van Gils et al., 2005). Furthermore, the spatial scale at which proxies are measured may have implications for their relevance to managers (Pidgeon et al., 2006, Stephens et al., 2015).

In this review, we seek to catalogue the methods that have been used to quantify waterbird habitat quality and provide a synthesis of the conditions under which each may provide meaningful measures of habitat quality in future waterbird studies. Outputs from this review are intended to guide environmental managers on the types of data they should be collecting when attempting to quantify waterbird habitat quality. This will ensure that decisions on how to manage habitat to optimise habitat quality are based on meaningful information.

Methods

For the purposes of this review, we followed the definition of waterbirds used by Wetlands International (2012). This covers all species within 32 bird families that are ecologically dependent on wetlands. The most familiar of these families are the Anatidae (ducks, geese and swans), Laridae (gulls and terns), Ardeidae (herons and egrets), Scolopacidae (sandpipers), and Charadriidae (plovers). Other representatives include the Rallidae (rails and crakes), Podicipedidae (grebes), Threskiornithidae (ibises and spoonbills), and Recurvirostridae (stilts and avocets).

Systematic reviews require defining the question elements 'subject', 'intervention', 'outcome', and 'comparator' (Pullin and Stewart, 2006). The diverse nature of the waterbird habitat quality literature meant that many waterbird habitat quality studies lack one or more of these elements (e.g., most studies are descriptive rather than measuring the outcome of a management intervention relative to a control case). Consequently, conducting a formal meta-analysis was not possible. Hence, we used the 'narrative synthesis' approach recommended by Haddaway et al. (2020) for synthesising heterogeneous literature. To obtain a representative sample of the literature for synthesis, we used a structured approach to identify relevant information sources (published literature, reports, and grey literature) and use these sources to make qualitative assessments of the various methods that have been used for measuring waterbird habitat quality.

We searched the Web of Science (all databases) on 17 December 2020 to obtain a set of papers on which to base this review. The following search string, in which TS means 'Topic Search', was used:

TS = (waterbird* OR shorebird* OR wader* OR "wading bird*" OR waterfowl) AND TS = ("habitat quality" OR "habitat condition" OR "environment* quality" OR "environment* condition" OR "wetland quality" OR "wetland condition")

This returned 411 search results (398 after removing duplicates) upon which the following synthesis is based (See Table S1 for list of returned results).

Synthesis of reviewed studies

Our structured search returned studies that undertook waterbird habitat quality assessments in two main ways: studies that measured some biophysical attribute(s) of the habitat; and studies that measured some attribute(s) of waterbirds themselves to infer underlying habitat quality (Table 1). Studies that measured attributes of waterbirds themselves could be further broken down into four sub-categories: studies that directly measured waterbird demographic characteristics; studies that measured waterbird body condition; studies that measured waterbird behaviour; and studies that measured waterbird distribution (Table 1). There were also studies that used methods from a combination of these categories.

Table 1. Catalogue of methods used to assess waterbird habitat quality in studies reviewed as part of the structured literature review. For each method, examples of studies that used the method are given along with an indication of the support or lack thereof for the given method. A '—' symbol in the Supporting evidence and contradictory evidence columns indicates that no data for these cells were found in the reviewed papers. The spatial (site, region, flyway) and temporal (instantaneous, within-season, annual) scales that data collection pertains to are also given.

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Direct habitat measures				
Food availability	Prey animal biomass (Atiénzar et al., 2012, Deboelpaep et al., 2020, Herring and Gawlik, 2013, Holopainen et al., 2014, Hunt et al., 2017, Parks et al., 2016, Schultz et al., 2020) Plant-derived food density or abundance (Arzel et al., 2015, Atiénzar et al., 2012, Dugger and Feddersen, 2009)	Birds behaviourally track sites with highest prey biomass and density (Rose and Nol, 2010) Prey availability has a positive influence on reproductive performance (Herring et al., 2010) Chick condition is related to local prey abundance (Hunt et al., 2017)	Predicts occupancy but not abundance (Gillespie and Fontaine, 2017) Sites with high food densities are not always the favoured foraging sites (Hagy and Kaminski, 2015) The seeds of different plant species consumed by waterfowl have different energy content (Dugger et al., 2007) Different food items can result in different mass gain even when fed *ad libitum* (Jorde et al., 1995) Waterbirds may forage selectively on larger size-class prey items meaning that overall prey density is not reduced through waterbird foraging even though waterbirds' preferred prey size has been significantly depleted (Fonseca and Navedo, 2020)	Site/region – Instantaneous/within season/annual
Primary productivity	Normalised Difference Vegetation Index (NDVI) (Tang et al., 2016, Zhang et al., 2017) Enhanced Vegetation Index (EVI) (Guan et al., 2016)	—	The method provides an indirect indication of habitat quality with at least one further transitional state before primary productivity influences waterbird energy intake rate (Zhang et al., 2017)	Site/region/Flyway – Instantaneous/within season/annual

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Predation pressure	Predator track density (Cohen et al., 2009) Index of predator reproduction (Trinder et al., 2009) Proportion of radio-tracked individuals predated (Kenow et al., 2009, Swift et al., 2020) Proportion of real or fake nests predated (Pehlak and Lõhmus, 2008, Swift et al., 2020) Alternate prey density (Holopainen et al., 2014)	Predation can be the leading cause of waterbird nest failure (Riecke et al., 2019) Predation risk is evaluated by waterbirds and trade-offs made that may reduce other components of fitness (e.g., foraging rate) (Fernández and Lank, 2010)	Nest predation rate was not a function of predator abundance or the availability of alternate prey species (Machín et al., 2019) The influence of predation can differ depending of the waterbird population density (Lebeuf and Giroux, 2014)	Site/region – Instantaneous/within season/annual
Vegetation structure	Vegetation height (Barati et al., 2011) Vegetation cover/abundance (Atiénzar et al., 2012, Hamza et al., 2015, Hierl et al., 2007, Nyman and Chabreck, 1996) Vegetation community composition (Benedict and Hepp, 2000, Dugger and Feddersen, 2009) Presence of invasive plants (Khan, 2010, Tavernia and Reed, 2012)	Vegetation structure has implications for the suitability of a site for nest placement (Barati et al., 2011)	Dense vegetation may increase prey abundance but reduce prey capture efficiency (Lantz et al., 2011)	Site/region – Instantaneous/within season/annual

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Wetland spatial attributes	Connectivity to neighbouring wetlands (Sebastián-González et al., 2010b) Pond area (Atiénzar et al., 2012, He et al., 2009, Merendino and Ankney, 1994) Shoreline irregularity (Merendino and Ankney, 1994)	Pond size and distance to the nearest neighbouring wetland are important determinants of waterbird habitat selection (Sebastián-González et al., 2010b)	Cycles of hydrological stress (drought/non-drought) can influence waterfowl habitat preferences, with birds seeking relatively deeper water bodies during drought irrespective of other habitat variables that are influential in wet years (Atiénzar et al., 2012)	Site/region – Instantaneous/within season/annual
Water level	Drawdown (Herring and Gawlik, 2013, Townsend et al., 2006); Water level variability (Collazo et al., 2002) Availability of shallow water (Collazo et al., 2002, Gawlik and Crozier, 2007, Lantz et al., 2011) Landscape depth heterogeneity (Beerens et al., 2015)	Wading birds preferentially selected ponds that had been experimentally manipulated to have shallow rather than deep water (Gawlik and Crozier, 2007) and waterbird species richness and density correlates with the availability of shallow water habitats (Wang and So, 2003) Water level recession rate was a key influence on physiological condition of two species of waterbirds (Herring and Gawlik, 2013)	Water level variability did not influence habitat selection of wading birds (Gawlik and Crozier, 2007)	Site/region – Instantaneous/within season/annual

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Disturbance	Distance to footpaths, roads, or railways (Burton et al., 2002, Hu et al., 2016, Li et al., 2019) Human settlements (Li et al., 2019)	The presence of people and vehicles nearby ([?]50 m) reduces foraging rates (Maslo et al., 2012) Likewise, time spent foraging and flock density were reduced at a highly disturbed site (Swift et al., 2020)	Human activities (e.g., clam harvesting) may have positive effects on waterbirds, especially shorebirds (Hamza et al., 2015)	Site/region – Instantaneous/within season/annual
Foraging substrate	Sediment grain size (Reurink et al., 2015, Rose and Nol, 2010) Organic carbon content (Hamza et al., 2015, Reurink et al., 2015) Mud content (Hamza et al., 2015)	Prey biomass is strongly predicted by physical environment conditions including organic content and particle sizes of the sediments (Rose and Nol, 2010)	—	Site/region – Instantaneous/within season/annual
Land use	Proportion of agricultural land use (Austin et al., 2001, Duncan et al., 1999) Mariculture (Li et al., 2019) Mining (Li et al., 2019)	Changing land use can cause ecological traps if agricultural landscapes appear similar to natural landscapes (e.g., grasslands) but offer lower habitat quality (Buderman et al., 2020)	Factors such as traditional site use by waterbirds can confound the signal of change in response to changing land use (Tombre et al., 2005)	Site/region – Instantaneous/within season/annual

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Water chemistry	Colour/turbidity (Atiénzar et al., 2012, Merendino and Ankney, 1994) pH (Merendino and Ankney, 1994, Walsh et al., 2006) Conductivity/salinity (Atiénzar et al., 2012, Merendino and Ankney, 1994) Dissolved nutrients (Merendino and Ankney, 1994, Pöysä et al., 2001, Walsh et al., 2006) Chlorophyll-α concentration (Atiénzar et al., 2012)	Prey biomass is influenced by salinity (Rose and Nol, 2010) Water chemistry variables including pH, salinity, and nitrogen and potassium concentration can be a predictor of occurrence of breeding ducks (Walsh et al., 2006)	—	Site/region – Instantaneous/within season/annual
Bird-derived estimates				
Demographic measures				
Reproduction	Clutch size/volume (Hunt et al., 2017, Mallory et al., 1994, Powell and Powell, 1986) Number of fledglings (Powell and Powell, 1986)	A direct contributor to the per capita rate of population increase, the most proximate indicator of habitat quality	—	Site/region – Instantaneous/within season/annual
Survival	Adult survival (Alves et al., 2013, Rice et al., 2007, Swift et al., 2020) Brood survival (Aubry et al., 2013, Cohen et al., 2009, Hunt et al., 2017, Owen and Pierce, 2014, Simpson et al., 2007, Swift et al., 2020)	A direct contributor to the per capita rate of population increase, the most proximate indicator of habitat quality	—	Site/region – Instantaneous/within season/annual
Distributional measures				

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Density or abundance	Abundance (Castillo-Guerrero et al., 2009, Dugger and Feddersen, 2009, Ganzevles and Bredenbeek, 2005, Hickman, 1994, Liu et al., 2006) Species richness (Dugger and Feddersen, 2009, Hickman, 1994) Density (Loewenthal et al., 2015, Swift et al., 2020) Abundance of breeding pairs (Arzel et al., 2015, Austin et al., 2001, Sebastián-González et al., 2010a)	The density of breeding pairs increased much faster than could be explained by population growth rates following habitat management that resulted in greater food availability (Loewenthal et al., 2015) This was attributed to previously subordinate adults taking up breeding territories as territory size of existing pairs contracted (Loewenthal et al., 2015)	Can be confounded by site fidelity (O'Neil et al., 2014), lags in response to change in condition (Loewenthal et al., 2015, Meltofte, 2006), dispersal barriers or costs, and imperfect knowledge of habitat (Lewis et al., 2010) Local and regional weather influences habitat use (Kelly, 2001, Schummer et al., 2010) Reproductive output is not correlated with population density (Cohen et al., 2009) Reduction in food availability can increase shorebird density as they are concentrated into the remaining suitable patches (Kosztolányi et al., 2006) Disturbance by human activity and farming rather than habitat quality (availability of foraging areas) more strongly influences waterbird species richness and abundance (Quan et al., 2002) Requires birds to correctly perceive habitat cues, which may not always be the case (e.g., agricultural land uses may resemble native grasslands, but have much lower reproductive output) (Buderman et al., 2020)	Site/region – Instantaneous/within season/annual

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Phenology	Length of breeding period (Raquel et al., 2016) Residence times on non-breeding or stopover sites (O'Neal et al., 2012, Rice et al., 2007, Williams et al., 2019)	—	Spring migration stopover duration can decrease as a function of Julian day of the year (Williams et al., 2019)	Site/region –Within season/annual
Age class distribution	Age class distribution (Fernández and Lank, 2010)	Adult shorebirds occupy sites with greater prey availability and lower predation risk than immature birds (Fernández and Lank, 2006)	—	Site/region – Instantaneous/within season
Hunting records	Harvest numbers as an indicator of present and past habitat quality (Merendino et al., 1992)	—	—	Region – Annual
Individual condition measures				
Morphological variables	Abdominal profile index (Swift et al., 2020) Body mass (Herring and Gawlik, 2013, Hunt et al., 2017) Body condition index (Aubry et al., 2013, Parks et al., 2016) Chick growth rate (Hunt et al., 2017, Owen and Pierce, 2014)	Abdominal profile index on the non-breeding grounds was correlated with breeding ground return rates, and subsequent nest survival and chick fate (Swift et al., 2020) Chick growth rates and adult body mass were positively correlated with invertebrate abundance in breeding Piping Plovers (Hunt et al., 2017)	—	Site/region –Within season/annual

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Physiological variables	Stress markers (Aharon-Rotman et al., 2016b, Herring and Gawlik, 2013, Thomas and Swanson, 2013) Immune response markers (Buehler et al., 2009) Foraging metabolites (Lyons et al., 2008, Thomas and Swanson, 2013)	Birds that occupy sites with higher fueling rates have lower concentration of physiological markers of stress in their blood (Aharon-Rotman et al., 2016b)	Different species with different foraging strategies can have different blood physiology responses to changing availability of prey (Herring and Gawlik, 2013)	Site/region –Within season/annual
Parasite burden	Intestinal helminth load (Conner England et al., 2018) Haemosporidian parasite infection (Aharon-Rotman et al., 2016b)	—	Parasite burden negatively correlated with foraging habitat quality for some parasite taxa, but not significantly for all parasite taxa (Conner England et al., 2018)	Site/region –Within season/annual
Ptilochronology	Feather growth rate (Swift et al., 2020)	Width of feather growth bands was positively correlated with an index of body condition (abdominal profile index) and feeding rates (Swift et al., 2020)	—	Site/region –Within season/annual
Behavioural measures				

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Foraging parameters	Peck/probe rate (Castillo-Guerrero et al., 2009, Mander et al., 2013) Success rate (Castillo-Guerrero et al., 2009, Swift et al., 2020) Step rate during foraging (Mander et al., 2013) Energy intake rate (Yu et al., 2020)	Positively correlated with prey density and biomass and at productive sites may not be affected by interference competition (Rose and Nol, 2010) Peck rate is correlated with defecation rate indicating that peck rate is a meaningful proxy for intake rate (Rose and Nol, 2010)	Capture success can be influenced by conspecifics, with increases in capture success occurring until conspecific density becomes high enough to induce interference competition (Stolen et al., 2012) Peck rate also reaches an upper asymptote, so may not be a true indication of habitat quality in very high productivity landscapes (Rose and Nol, 2010) Pecking rate can be significantly higher than probing rate for an equivalent energy return (Kuwae et al., 2010)	Site/region – Instantaneous/within season/annual
Time budgets	Proportion of time spent foraging (Castillo-Guerrero et al., 2009, Dugger and Feddersen, 2009, van der Kolk et al., 2019) Proportion of time in non-foraging behaviours (e.g., vigilance, disturbance) (Castillo-Guerrero et al., 2009, Maslo et al., 2012, Yu et al., 2020)	Oystercatchers that spent longer foraging had lower inferred survival (van der Kolk et al., 2019)	Time budgets may vary within an individual period of the annual cycle (e.g., between breeding stages, or within the non-breeding period) (Castillo-Guerrero et al., 2009, Mallory et al., 1999) or due to the presence of conspecifics (Kosztolányi et al., 2006, Mallory et al., 1999)	Site/region – Instantaneous/within season/annual

Method	Metrics	Supporting evidence	Contradictory evidence	Relevant spatial and temporal scales
Anti-predator behaviours	Vigilance rates (Fernández and Lank, 2010) Flight initiation distance (Gunness et al., 2001)	At sites where vigilance rates were higher, waterbirds maintained lower body mass (Fernández and Lank, 2010)	—	Site/region – Instantaneous/within season/annual
Individual movements	Home range size (Herring and Collazo, 2005) Commuting distance (Custer et al., 2004)	—	—	Site/region – Instantaneous/within season/annual
Flight speeds	Flight speeds between foraging patches (Reurink et al., 2015)	Birds fly faster when heading to patches of high prey abundance because the greater expected returns are able to offset the greater flight costs of choosing to fly faster (Reurink et al., 2015)	Requires the birds to have perfect knowledge of the resource distribution available (Reurink et al., 2015), which may not always be the case (Lewis et al., 2010)	Site/region – Instantaneous/within season/annual

3.1 Methods of habitat quality assessment

Measuring demographic parameters

By definition, the quantification of habitat quality depends on estimating a site's contribution to survival and reproduction. Therefore, any method that directly measures one or both of these parameters will be free from error propagation caused by imperfect correlation between a measured attribute and these variables. However, cautious interpretation is still required when only one of these attributes is measured, because sites with similar reproductive output can have divergent population trajectories if the population size is governed by adult survival, and vice versa (Cohen et al., 2009). Similarly, emigration or immigration at a site may also obscure the signal arising from measures of reproduction and survival (Cohen et al., 2009). Measuring demographic rates can be a lengthy, costly, and logistically challenging process. In waterbird research, directly measuring a site's contribution to survival and reproduction may be unachievable owing to the mobility of waterbird populations. Although our structured search returned examples of studies that did quantify survival (e.g., Alves et al., 2013, Rice et al., 2007, Swift et al., 2020) and/or reproduction (e.g., Hunt et al., 2017, Powell and Powell, 1986, Swift et al., 2020), most studies used proxies for one or both of these measures.

Estimating food abundance and availability

Many of the proxies in the reviewed studies assumed that a high-quality habitat provided waterbird individuals with a high net energy intake rate. The corollary assumption was that high net energy intake results in increased survival and reproductive performance. Methods used to infer net energy intake rate included measures of prey abundance, prey accessibility, and waterbird physiology or morphology as an indicator of past foraging returns (Table 1). Habitat quality assessments that are based on habitat attributes are appealing because results are independent of variation in bird behaviour caused by factors unrelated to local habitat quality (e.g., current wind and rain conditions can determine which sites waterbirds use at very local scales (Kelly, 2001) and these short term changes are not typically useful for managers). For this reason, measuring the abundance or biomass of food was used widely in the reviewed studies to assess waterbird habitat quality. There is support for this method being an appropriate proxy for habitat quality because waterbirds preferentially forage at sites with the highest prey biomass and density (Guerra et al., 2016, Rose and Nol, 2010). Moreover, prey availability has a positive influence on reproductive performance and survival (Herring et al., 2010, Holopainen et al., 2014, Swift et al., 2020). However, there are also situations where prey biomass at a site can be a poor indicator of habitat quality. For example, sites with high prey biomass are not always favoured foraging sites (Hagy and Kaminski, 2015), and although these sites might have high occupancy, they do not necessarily support high waterbird abundance (Gillespie and Fontaine, 2017). This suggests that factors such as predation risk, forager condition, and prey accessibility modulate the effect of prey biomass on habitat quality (Hagy and Kaminski, 2015). Such a relationship is also dependent on waterbirds having a perfect knowledge of the distribution of prey resources (Reurink et al., 2015), which may not always be the case (Lewis et al., 2010), and relies on researchers correctly identifying dietary preferences and requirements of focal species.

The presence of suitable water levels and variation in water levels was also used as a proxy for habitat quality in the reviewed studies. These habitat attributes can influence accessibility of prey and foraging energetics (Ma et al., 2010). In some cases only a small proportion of a wetland provides suitable water levels for waterbirds to access prey (Collazo et al., 2002). This suggests that there is value in quantifying either prey biomass or the amount of suitable habitat through water level measurements. However, the two attributes will interact to influence the net rate of energy intake possible at a site meaning studies that measure both variables may have a greater likelihood of teasing apart meaningful habitat quality relationships and informing appropriate management (Herring and Gawlik, 2013). Similarly, remotely sensed measures of primary productivity (e.g., NDVI) are expected to be correlated with prey abundance. Yet, the relationship between net energy intake rate and primary productivity is dependent on changes in primary productivity causing changes in prey abundance (e.g., invertebrates, seeds, tubers) as well as those prey items being available to feeding waterbirds (Guan et al., 2016, Zhang et al., 2017). This suggests there is a hierarchy in the ability of proxies to provide precise habitat quality estimates based on how direct the link between the variable being measured and net energy intake rates is (Figure 1).

Estimating food intake rate

The behaviour and habitat use patterns of waterbirds themselves were often used in the reviewed studies to infer underlying patterns of habitat quality (Table 1). Indicators of prey intake rate (be it current, past or expected future foraging returns) were frequently used metrics of habitat quality. Variables including peck rate, capture success rate, and the proportion of time a bird spent foraging were commonly measured to assess the current rate of energy intake supported by a habitat. Defecation rate is significantly correlated with peck rate in a visually foraging shorebird, supporting the assumption that peck rate represents a valid indicator of intake rate (Rose and Nol, 2010). Likewise, sites with a higher peck rate or probe rate had a higher rate of successful prey captures in a study where capture success could be visually verified (Kuwae et al., 2010). However, different prey items have different energy content and different processing costs within the digestive system (Dugger et al., 2007, Jorde et al., 1995). This means that the net rate of energy intake will depend on the prey type consumed. This may not be an issue in studies of diet specialists, but it may confound the interpretation of peck rate and capture success data for diet generalists. In situations where the diet of the population being studied is not well understood, investigating the prey community composition to determine prey encounter rates, or dietary studies (e.g., metabarcoding of prey DNA sequences in faecal samples) will inform whether differences in peck rate between sites or across time genuinely reflect changes in energy returns.

Intake rates over the recent and more distant past were inferred from a variety of variables including body condition, blood metabolites, and indicators of feather growth rate. These have the advantage that they reflect assimilated energy rather than gross intake including energy lost via excretion or through processing costs. However, the longer timeframe of integration meant that studies using these methods were rarely site-specific, rather they tended to assess habitat quality at regional scales (e.g., Aharon-Rotman et al., 2016b). In cases where individuals use only a small geographic area (e.g., when nesting constrains movements, or individuals have strong residency patterns) these measures may provide insights into site-specific habitat quality. For example, Swift et al. (2020) found that visually-scored body condition of non-breeding Hudsonian Godwits *Limosa haemastica* was correlated with pecking rate at individual non-breeding sites. This suggests that these birds were resident at sites long enough to integrate site-specific habitat quality information in the form of body condition. Importantly, birds with higher body condition had higher survival and reproductive output the following breeding season, indicating that body condition reliably influenced demographic rates (Swift et al., 2020).

Predation pressure

Given the direct link between predation pressure and survival, it was surprising that predation pressure was estimated relatively infrequently in the reviewed studies. This is perhaps reflective of the difficulties of censusing predator populations due to predators of waterbirds typically occurring at low density and predation events on adult waterbirds being rare. Where predation pressure was quantified, these studies often focused on nest predation (e.g., Kenow et al., 2009, Pehlak and Lõhmus, 2008, Trinder et al., 2009). Most studies that inferred an influence of predation pressure on habitat quality assumed that the abundance of predators was correlated with predation rate without explicitly testing this assumption, which may be problematic when generalist predators are involved. Some studies also assessed predation pressure by using vigilance or escape behaviours of waterbirds (Fernández and Lank, 2010, Gunness et al., 2001). This has the advantage of integrating information on the degree of lost foraging time as a result of predation pressure because lost foraging opportunities will affect reproductive performance as well as survival (Castillo-Guerrero et al., 2009).

Physical habitat attributes

Many of the reviewed studies measured various physical and/or chemical attributes of waterbird habitats to infer habitat quality. The attributes measured were purported to influence habitat quality via their contribution to supporting viable prey populations (e.g., water pH, water conductivity, sediment grain size), enabling access to sufficient quantities of food (e.g., water area, pond density in the local area and vegetation composition, as well as water level which we discussed previously), or providing shelter from predators (e.g., vegetation structure). In most cases, these environment attributes are linked indirectly to demographic rates (Figure 1) and the mechanisms governing their effects may be difficult to disentangle (Raquel et al., 2016). Nonetheless, physical attributes of the habitat may provide waterbirds with visual cues as to the quality of a site and play a role in determining patterns of site use, which can have flow-on effects on demographic rates (Buderman et al., 2020).

Other methods

A variety of other methods were used infrequently in the reviewed studies (Table 1). These included estimates of levels of human disturbance, individual movement data (e.g., home range size), and the spatial distribution of individuals in different age classes. Despite their infrequent use, these methods may provide meaningful habitat quality information. Factors such as the cost of obtaining the data or the difficulty of obtaining the data (e.g., challenges distinguishing between age classes in the field) probably contributed to their infrequent use.

Combination of methods

Many of the reviewed studies recorded data on multiple proxies for habitat quality. Multiple lines of evidence allowed researchers to tease apart complex relationships among various parameters in their respective study systems and provide powerful insight to conservation managers (Cohen et al., 2009, Hunt et al., 2017, Swift et al., 2020). In these studies, it was often possible to pinpoint factors that were limiting habitat quality, providing managers with priorities to address in order to improve habitat quality. For example, Cohen et al. (2009) recommended that restoring Piping Plover, *Charadrius melodus,* habitat adjacent to bayside intertidal flats would improve habitat quality by increasing the number of breeding pairs that could occupy a site. However, this action must be carried out in conjunction with predator management in order to achieve the desired increase in reproductive output.

Factors influencing the choice of variables to measure

Staying within the project's scope

Our synthesis of the habitat quality literature indicates that there is a hierarchy of data quality from directly monitoring demographic rates to measuring parameters that are increasingly indirectly linked to demography. Yet, practitioners typically face a trade-off between the need for accuracy of the habitat quality estimate and their particular study's aims and constraints. If it is feasible, measuring demographic rates directly generally involves extended field time, individually marked birds, limited spatial scale, and substantial costs (Buderman et al., 2020). Other factors may also influence the suitability of a proxy for the habitat quality assessment at hand including ethical considerations (Hunt et al., 2013), and the availability of appropriately trained personnel. Physiological and morphological measurements used in the reviewed studies typically required birds to be handled (but see the abdominal profile index method; Swift et al., 2020), which imposes stress on the study subjects (Karlíková et al., 2018), and capturing a large sample size of birds can be time-consuming. This may mean that methods requiring birds to be handled, including individually marking birds for quantifying demographic rates, are not feasible within the scope of a project.

Spatial and temporal scales of assessments

Another consideration that must be made prior to implementing a study on habitat quality is whether the habitat quality measure being used returns data at a relevant spatial and/or temporal scale. For example, prey abundance measures typically provide very local scale (both spatial and temporal) information on habitat conditions, but may not be representative of habitat quality across the entire wetland or extended timeframes (e.g., the entire non-breeding period). For example, Fonseca and Navedo (2020) reported a 43% reduction in invertebrate prey biomass as a result of shorebird foraging in study plots over the course of three days. Consequently, habitat quality assessments either side of this three-day period could yield vastly different inferences about local habitat quality and neither may be representative of habitat quality over an extended timeframe. The accuracy of these methods in terms of returning habitat quality data at time-scales meaningful for management will therefore be increased by repeated sampling (Murray et al., 2010). This was reflected in a number of the reviewed studies, especially those aimed at specifying management regimes, repeating sampling both spatially, and intra- and inter-annually (e.g., Gillespie and Fontaine, 2017). Whereas methods that relied on measuring attributes of the habitat typically provided snapshot estimates of habitat quality, methods reliant on waterbird body condition or physiology (e.g., abdominal profile index or red blood cell heat shock protein concentrations) often provide information integrated over longer timeframes (Herring and Gawlik, 2013). They may therefore be unsuitable for site-specific and/or instantaneous habitat quality questions, but may be applied to questions informing management of a regional wetland complex over broader timeframes. Similarly, remotely sensed measures of primary productivity offer the potential to rapidly and cost-effectively monitor habitat conditions at large spatial and temporal scales. For example, Wen et al. (2016) used remotely sensed primary productivity data to inform an assessment of waterbird habitat quality across a 810,000 km^2 study area in multiple years.

There is no rule that governs whether the spatial or temporal scale of a particular proxy is appropriate for a particular application because even labour-intensive or costly methods that return site-specific information may be suitable for large-scale projects if the budget enables sufficiently widespread sampling (e.g., sites and time points). We provide some recommendations as to the spatial and temporal scales that methods for habitat quality assessments are typically carried out at (Table 1). Readers may also find papers such as Behney and colleagues' (2014) guide to determining the optimum number of benthic core samples to collect useful for planning how much field effort is likely to be involved when planning a sampling regime.

What makes for a good habitat quality assessment?

Measuring habitat quality enables conservation managers to assess the need for or effectiveness of management actions (e.g., Schultz et al., 2020). The ultimate objective of conservation management is to influence demographic parameters of conservation targets to improve conservation status. Therefore, assessments of habitat quality inherently must determine a site's contribution to survival probability and/or reproductive output. This requires there to be a link between the variable, or combination of variables, used to measure habitat quality and demographic rates (Figure 1). Before commencing an assessment of habitat quality, the researcher must carefully consider whether the selected measure does actually influence demographic rates. For example, quantifying the time budgets of waterbirds is a commonly used method for inferring differences in habitat quality (Dugger and Feddersen, 2009, van der Kolk et al., 2019). However, the inferences derived from time budget comparisons may not actually reflect changes in underlying habitat quality. Time budgets can be flexible to buffer intrinsic changes in requirements (Mallory et al., 1999). For example, this may be due to individuals dedicating more time to foraging to meet the metabolic demands of producing a clutch of eggs (Mallory et al., 1999), or dedicating more time to feeding to fatten up for migration (Castillo-Guerrero et al., 2009). That is not to say that time budgets are unsuitable for quantifying habitat quality, but care must be taken to ensure that appropriate comparison groups are being used (e.g., sampling at the same time of year).

Researchers must also be aware that inferences made about populations that are not at equilibrium may depart from theoretical relationships underpinning many habitat quality proxies. For example, populations that have been reduced below carrying capacity by historical or offsite factors may not show any temporal differences in various local habitat quality proxies (e.g., foraging success, stress markers, body condition, and time budgets) because individuals are easily able to meet their resource requirements even if local habitat quality is declining. Similarly, there may be differences in the relevance of some habitat quality proxies depending on whether the conservation target is a resident population, or a dispersive or migratory population (Loewenthal et al., 2015). Abundance and density are clearly linked to local habitat quality for resident populations, but may not be truly reflective of local habitat quality for populations that undertake large-scale movements exposing individuals to factors that limit population size elsewhere in the range. For example, Jia et al. (2018) reported declines in abundance of migratory shorebirds at a migratory staging site, but none of the measured proxy variables for habitat quality could explain these declines. They suggest that factors in other parts of the migratory range may be responsible for driving the observed declines in abundance rather than changes in habitat quality at their study site.

Many of the habitat quality proxies identified in this review assume individuals have perfect knowledge of the resource distribution at a site and behave such that the net rate of energy gain is being maximised at any given time (Reurink et al., 2015). Several factors can result in waterbirds using their habitat in ways that do not conform to these assumptions. The choice of foraging site for many waterbirds is strongly influenced by conspecific attraction (Gawlik and Crozier, 2007, Herring et al., 2015, Smith, 1995). This is also true for the selection of nest sites (Sebastián-González et al., 2010c). Furthermore, fidelity to areas that have provided favourable habitat conditions in the past may decouple patterns of waterbird habitat use from current habitat conditions (O'Neil et al., 2014). Waterbird habitat requirements may also change with breeding stage (Holopainen et al., 2014), and during less energetically demanding parts of the annual cycle, such as the non-breeding period, individuals may be less selective in their habitat use decisions (Sebastián-González et al., 2010b).

Most of the reviewed studies provided a relative assessment of habitat quality (i.e., they compared waterbird habitat quality at a site to previous points in time, or made comparisons between sites). These studies allow researchers to determine habitat quality trends or identify the best and worst sites in a landscape, but do not enable managers to determine whether the habitat quality is sufficient to maintain viable waterbird populations. There were some studies that sought to determine whether the habitat quality at a site was sufficient to support population growth or whether the site represented a sink habitat (e.g., Roy et al., 2019, Sabatier et al., 2010). These studies do enable managers to determine whether management intervention is necessary rather than arbitrarily setting a reference site as the standard against which to decide whether management is warranted. In particular, studies seeking to identify whether a site had sufficient habitat quality to support population growth tended to focus directly on reproductive output or survival data (Roy et al., 2019, Weiser et al., 2018), or in some cases focused on energetic demands relative to prey resources (West et al., 2005).

Together, the potentially confounding factors mean that there is no universally applicable habitat quality proxy. Yet, with careful consideration and a detailed understanding of the ecology of the study system, waterbird researchers and management practitioners can derive meaningful measures of habitat quality.

Conclusions

This review of the literature comprising almost 400 articles strongly suggests that there is no one broadly accepted method for assessing waterbird habitat quality. Directly measuring breeding success and survival rate are the most reliable measures, but it is unfeasible to obtain these data in many cases. A variety of proxy measures are available, but their interpretation requires substantive contextualisation and a good understanding of their appropriateness to a specific project aim.

In general, if it is not possible to measure direct demographic parameters, projects should consider the suite of available proxy measures (Table 1) and consider which are most suitable to their site, budget and timeframe. Often, developing a protocol based on multiple proxies will increase confidence in results over the use of a single proxy. For example, studies investigating the comparative habitat quality of multiple sites could use a combination of waterbird abundance, behaviour and body condition coupled with a measure of prey availability to gain insight into which site(s) are providing better food resources. Studies assessing if a single site is profitable for waterbirds from an energy perspective (i.e. habitat quality is sufficiently high to support population growth) could use a combination of waterbird behaviour and available energy density to assess whether daily energy requirements are being met at the site. All studies using proxy measures should be mindful of the potential for interactions between features of the habitat (e.g., prey abundance and prey accessibility) to influence the direction of the relationship between habitat conditions and resultant demographic rates.

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Conflict of interest

The authors have no conflict of interest to declare.

Author contributions

Funding acquisition was carried out by PC, JB, DR, JO and TP. RM and TP were responsible for methodology. RM carried out data curation. RM, TP and MJ undertook the investigation. All authors contributed to conceptualisation of the study and writing, review and editing of the original and subsequent drafts.

Data accessibility

Data are available in article appendix Table A1

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Appendix

Table A1. List of the results returned by the Web of Science search using the search string TS=(waterbird* OR shorebird* OR wader* OR "wading bird*" OR waterfowl) AND TS=("habitat quality" OR "habitat condition" OR "environment* quality" OR "environment* condition" OR "wetland quality" OR "wetland condition").

Citation	**Source**
Buderman et al. 2020	Journal of Animal Ecology
de Fouw et al. 2020	Journal of Experimental Marine Biology and Ecology
Deboelpaep et al. 2020	Freshwater Biology
Fonseca & Navedo 2020	Journal of Environmental Management
Gao et al. 2020	Landscape Ecology
Gherardi-Fuentes et al. 2020	Acta Oecologica-International Journal of Ecology
Hassab et al. 2020	Alexandria Journal of Veterinary Sciences
Howell et al. 2020	Ibis
Jia et al. 2020	Ecological Indicators
Moon et al. 2020	Ocean and Polar Research
Mullins & Craig 2020	Ostrich
Patton et al. 2020	Wetlands
Schultz et al. 2020	Wetlands
Swift et al. 2020	Journal of Animal Ecology
van der Kolk et al. 2020	Behavioral Ecology
Wang et al. 2020	Integrative Zoology
Yu et al. 2020	Environmental Science and Pollution Research
Zhou et al. 2020	Science of the Total Environment
Ali et al. 2019	International Journal of Environmental Science and Technology
Bai et al. 2019	Huanjing Kexue Yanjiu
Bailey et al. 2019	Journal of Animal Ecology
Carneiro et al. 2019	Frontiers in Ecology and Evolution
Chambon et al. 2019	Animal Behaviour
Gibson et al. 2019	Ecography
Jackson et al. 2019	Ecology and Evolution
Choudhury et al. 2019	Environment and Ecology
Jia et al. 2019	Sustainability
Li et al. 2019	Wetlands
Liu et al. 2019	Environmental Science and Pollution Research
Liu et al. 2019	Bulletin of Environmental Contamination and Toxicology
Machin et al. 2019	Polar Biology
Otto et al. 2019	United States Geological Survey
Pierce et al. 2019	Wilson Journal of Ornithology

Citation	Source
Raquel et al. 2019	Oecologia
Riecke et al. 2019	Waterbirds
Roy et al. 2019	Journal of Wildlife Management
Sedinger et al. 2019	Ecology and Evolution
Tangen et al. 2019	U S Geological Survey Open-File Report
Williams et al. 2019	Wildlife Society Bulletin
Wood et al. 2019	Biological Conservation
Amira et al. 2018	Wetlands Ecology and Management
Alvarez-Vazquez et al. 2018	Science of the Total Environment
Aticho et al. 2018	Global Ecology and Conservation
Barboza & Jorde 2018	Journal of Comparative Physiology B-Biochemical Systems and Environmental Phy
Bieri et al. 2018	Natural Resource Modeling
Cheng et al. 2018	Acta Ecologica Sinica
Colwell & Feucht 2018	Wader Study
Craig et al. 2018	Records of the Western Australian Museum
Duettmann et al. 2018	Bird Study
England et al. 2018	Parasitology Research
Giuliano et al. 2018	Agriculture Ecosystems & Environment
Jia et al. 2018	Biological Conservation
Johns et al. 2018	Functional Ecology
Karlikova et al. 2018	Journal of Ornithology
Kentie et al. 2018	Global Change Biology
Kuo & Wang 2018	Irrigation and Drainage
Lee et al. 2018	Bird Conservation International
Loonstra et al. 2018	Ibis
Poysa et al. 2018	Journal of Ornithology
Prince et al. 2018	Journal of Applied Ecology
Rozenfeld et al. 2018	Nature Conservation Research
Sonsthagen et al. 2018	Condor
Weiser et al. 2018	Ibis
Weiser et al. 2018	Journal of Avian Biology
Weiser et al. 2018	Auk
Wood et al. 2018	Animal Conservation
Yetter et al. 2018	Journal of Wildlife Management
Zhang et al. 2018	Ecological Indicators
Zmihorski et al. 2018	Agriculture Ecosystems & Environment
Bellio et al. 2017	Marine and Freshwater Research
Binkowski 2017	Chemosphere
Ceron & Ferreiro 2017	Wilson Journal of Ornithology
Conklin et al. 2017	Journal of Avian Biology
Gillespie & Fontaine 2017	Journal of Wildlife Management
Goncalves & Marques 2017	Ecological Indicators
Hunt et al. 2017	Wilson Journal of Ornithology
Johnstone et al. 2017	Bird Study
Lemke et al. 2017	Hydrobiologia
Lopez-Islas et al. 2017	Journal of Toxicology and Environmental Health-Part A-Current Issues
Manier & Rover 2017	U S Geological Survey Open-File Report
Nergiz & Durmus 2017	Applied Ecology and Environmental Research
Neubauer et al. 2017	Plos One
Osborn et al. 2017	Wildlife Society Bulletin

Citation	Source
Pearce-Higgins et al. 2017	Bird Conservation International
Rannap et al. 2017	Journal For Nature Conservation
Rozenfeld et al. 2017	Biology Bulletin
Shao et al. 2017	Acta Ecologica Sinica
Suk-Hwan et al. 2017	Journal of Wetlands Researh
van der Burg et al. 2017	Journal of Fish and Wildlife Management
Weithman et al. 2017	Ecology and Evolution
Zhang et al. 2017	Journal of Ornithology
Zhang et al. 2017	Journal of Environmental Engineering and Landscape Management
Aharon-Rotman et al. 2016	Emu
Aharon-Rotman et al. 2016	Oecologia
Bock et al. 2016	Journal of Coastal Research
Broyer et al. 2016	European Journal of Wildlife Research
Carneiro et al. 2016	Avian Biology Research
Chaudhari-Pachpande & Pejaver 2016	Journal of Threatened Taxa
Clark et al. 2016	Oikos
Clausen & Madsen 2016	Journal of Ornithology
Guan et al. 2016	Journal of Beijing Forestry University
Guan et al. 2016	Freshwater Biology
Guan et al. 2016	Ecological Engineering
Guerra et al. 2016	Pacific Science
Hagy & McKnight 2016	Journal of Fish and Wildlife Management
Hu et al. 2016	Zoological Science
Huck et al. 2016	Journal of Wildlife Diseases
Leito et al. 2016	Baltic Forestry
McCallum et al. 2016	Agriculture Ecosystems & Environment
Meller et al. 2016	Journal of Animal Ecology
Nadjafzadeh et al. 2016	Journal of Ornithology
Parks et al. 2016	Waterbirds
Raquel et al. 2016	Canadian Journal of Zoology
Reurink et al. 2016	Behavioral Ecology
Sesser et al. 2016	Biological Conservation
Sharps et al. 2016	Agriculture Ecosystems & Environment
Tang et al. 2016	Science of the Total Environment
Thompson et al. 2016	Journal of Applied Ecology
Wan et al. 2016	Avian Research
Wen et al. 2016	Ecology and Evolution
Wiggers et al. 2016	Journal For Nature Conservation
Winton et al. 2016	Water Air and Soil Pollution
Wong et al. 2016	Figshare
Anderson et al. 2015	Polar Research
Arzel et al. 2015	Annales Zoologici Fennici
Beatty et al. 2015	Journal of Wildlife Management
Beerens et al. 2015	Ecology and Evolution
Beerens et al. 2015	Plos One
Bourque et al. 2015	Avian Conservation and Ecology
Colloff et al. 2015	Marine and Freshwater Research
Daly et al. 2015	Journal of Field Ornithology
Duijns et al. 2015	Royal Society Open Science
Dybala et al. 2015	Condor

Citation	Source
Fu et al. 2015	Journal of Environmental Management
Gill 2015	Journal of Animal Ecology
Hagy & Kaminski 2015	Plos One
Hamza et al. 2015	Estuarine Coastal and Shelf Science
Harter et al. 2015	Conservation Physiology
Herring et al. 2015	Waterbirds
Hua et al. 2015	Bird Conservation International
Kentie et al. 2015	Ibis
Loewenthal et al. 2015	Ostrich
Mackintosh et al. 2015	Science of the Total Environment
Mason & Smart 2015	Wader Study
Pakanen et al. 2015	Ornis Fennica
Pernollet et al. 2015	Biological Conservation
Ringelman et al. 2015	Journal of Wildlife Management
Schmaltz et al. 2015	Population Ecology
Sebastian-Gonzalez et al. 2015	Ardeola
Sun et al. 2015	Journal of Mountain Science
Vitense et al. 2015	Minnesota Department of Natural Resources Summaries of Wildlife Research Findi
Anastacio et al. 2014	Aquatic Ecology
Batbayar et al. 2014	Waterbirds
Bates & Ballard 2014	Waterbirds
Behney et al. 2014	Wetlands
Brandt & Glemnitz 2014	Environmental Monitoring and Assessment
Ceron & Boy 2014	Waterbirds
Chang et al. 2014	International Symposium on Fuzzy Systems, Knowledge Discovery and Natural Co
CHIL et al. 2014	Korean Journal of Environmental Agriculture
Grond et al. 2014	Journal of Ornithology
Holopainen et al. 2014	Freshwater Biology
Hsu et al. 2014	Wetlands
Jiang et al. 2014	Giscience & Remote Sensing
Kang & King 2014	Waterbirds
Kasprzykowski et al. 2014	Turkish Journal of Zoology
Kleijn et al. 2014	Journal of Applied Ecology
Lebeuf & Giroux 2014	Journal of Avian Biology
Lok et al. 2014	Ardea
Lopez-Saut et al. 2014	Acta Zoologica Mexicana Nueva Serie
Milot et al. 2014	Dryad
O'Neil et al. 2014	Animal Behaviour
Owen & Pierce 2014	Waterbirds
Perez-Garcia et al. 2014	European Journal of Wildlife Research
Robinson & Jennings 2014	Journal of Fish and Wildlife Management
Salamat et al. 2014	Ecotoxicology and Environmental Safety
Alves et al. 2013	Ecology
Aubry et al. 2013	Global Change Biology
Chang et al. 2013	Paddy and Water Environment
Gehrold & Koehler 2013	Journal of Ornithology
Gronroos et al. 2013	Journal of Ornithology
Herring et al. 2013	Science of the Total Environment
Herring & Gawlik 2013	Journal of Wildlife Management
Hobson et al. 2013	Avian Conservation and Ecology

Citation	Source
Hunt et al. 2013	Journal of Field Ornithology
Kraus & Krauss 2013	Ornithologischer Anzeiger
Krone et al. 2013	Journal of Ornithology
Lapointe et al. 2013	Auk
Luczak et al. 2013	Open Journal of Marine Science
Malpas et al. 2013	Bird Study
Mander et al. 2013	Estuarine Coastal and Shelf Science
Martinez-Abrain et al. 2013	Biological Conservation
Meyer et al. 2013	Wetlands
Nadjafzadeh et al. 2013	Journal of Wildlife Management
Ofula et al. 2013	Vector-Borne and Zoonotic Diseases
Orlowski 2013	Ecological Engineering
Owen & Pierce 2013	Waterbirds
Rogers et al. 2013	Environmental Monitoring and Assessment
Ruthrauff et al. 2013	Canadian Journal of Zoology
Saalfeld et al. 2013	Western North American Naturalist
San Roman et al. 2013	International Journal of Ecology and Environmental Sciences
Smart et al. 2013	Journal of Applied Ecology
Thomas & Swanson 2013	Auk
Twedt 2013	Wetlands
van Toor et al. 2013	Plos One
Andres et al. 2012	Waterbirds
Atienzar et al. 2012	Zoological Studies
Carss et al. 2012	Hydrobiologia
Cumming et al. 2012	Freshwater Biology
Darby et al. 2012	Condor
Duriez et al. 2012	Oikos
Gauthier et al. 2012	Arctic Wildlife Observatories Linking Vulnerable EcoSystems. Final synthesis repo
Gunnarsson et al. 2012	Proceedings of the Royal Society B-Biological Sciences
Kern et al. 2012	Journal of Wildlife Management
Korbut 2012	Zoologichesky Zhurnal
Lameed 2012	African Journal of Food, Agriculture, Nutrition and Development
Maslo et al. 2012	Journal of Wildlife Management
Mattsson et al. 2012	Ecological Modelling
O'Neal et al. 2012	Journal of Wildlife Management
Rooney & Bayley 2012	Ecological Indicators
Stolen et al. 2012	Condor
Tavernia & Reed 2012	American Midland Naturalist
Toral et al. 2012	Biological Conservation
Tracy-Smith et al. 2012	River Research and Applications
Wilson & Bayley 2012	Ecological Indicators
Barati et al. 2011	Avian Biology Research
Beltman et al. 2011	Restoration Ecology
Cardador et al. 2011	Animal Conservation
Cassey et al. 2011	Avian Biology Research
Chaichana et al. 2011	Hydrobiologia
Clarkson 2011	Ecological Indicators
Corrigan et al. 2011	Avian Conservation and Ecology
Kohler et al. 2011	Marine Ecology Progress Series
Lantz et al. 2011	Waterbirds

Citation	Source
Lok et al. 2011	Journal of Wildlife Management
MacDonald et al. 2011	Australian Journal of Agricultural and Resource Economics
Martinez-Abrain et al. 2011	Conservation Biology
Noor et al. 2011	Australian Journal of Basic and Applied Sciences
Perez-Fuentetaja et al. 2011	Journal of Great Lakes Research
Rakhimberdiev et al. 2011	Diversity and Distributions
Sjoberg et al. 2011	European Journal of Wildlife Research
Webb et al. 2011	Waterbirds
Wen et al. 2011	19th International Congress on Modelling and Simulation (Modsim2011)
Zhang et al. 2011	Hupo Kexue
Zhang & Ma 2011	3rd International Conference on Environmental Science and Information Applicatio
Amat & Green 2010	Conservation Monitoring in Freshwater Habitats: A Practical Guide and Case Stud
Fernandez & Lank 2010	Journal of Ornithology
Foster et al. 2010	Proceedings of the Annual Conference Southeastern Association of Fish and Wildli
Herring et al. 2010	Auk
Khan 2010	Current Science
Kleijn et al. 2010	Ibis
Kuwae et al. 2010	Marine Ecology Progress Series
Lewis et al. 2010	Ibis
Ma et al. 2010	Wetlands
Mabry & Dettman 2010	Ecological Restoration
Murray et al. 2010	Ecology
Pereira 2010	Journal of Arid Environments
Pouliot & Frenette 2010	Canadian Field-Naturalist
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