Waterfowl populations of conservation concern: learning from diverse challenges, models and conservation strategies

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Abstract

There are 30 threatened or endangered species of waterfowl worldwide, and several sub-populations are also threatened. Some of these species occur in North America, and others there are also of conservation concern due to declining population trends and their importance to hunters. Here we review conservation initiatives being undertaken for several of these latter species, along with conservation measures in place in Europe, to seek common themes and approaches that could be useful in developing broad conservation guidelines. While focal species may vary in their life-histories, population threats and geopolitical context, most conservation efforts have used a systematic approach to understand factors limiting populations and to identify possible management or policy actions. This approach generally includes *a priori* identification of plausible hypotheses about population declines or status, incorporation of hypotheses into conceptual or quantitative planning models, and the use of some form of structured decision making and adaptive management to develop and implement conservation actions in the face of many uncertainties. A climate of collaboration among jurisdictions sharing these birds is important to the success of a conservation or management programme. The structured conservation approach exemplified herein provides an opportunity to involve stakeholders at all planning stages, allows for all views to be examined and incorporated into model structures, and yields a format for improved communication, cooperation and learning, which may ultimately be one of the greatest benefits of this strategy.

Key words: Anatidae, conservation strategy, decision framework, population model, status and trends.

More than 20 species or populations of waterfowl in North America, with diverse life-histories, have experienced substantial declines over the past 25 years, or their numbers remain well below conservation goals (Table 1). Duck species of conservation concern range from the non-migratory Mottled Duck *Anas fulvigula*, which has small populations of limited distribution, to migratory scaup (Greater Scaup *Aythya marila* and Lesser Scaup *A. affinis*, combined hereafter as scaup) and sea ducks (Tribe: Mergini) with continental distributions. While some species share traits, such as geographic overlap of scaup and scoter *Melanitta* sp. breeding ranges in the boreal forests of North America, others seem to have little in common (*e.g.* Northern Pintail *Anas acuta* and sea ducks). These declines and persistent low populations have concerned biologists, managers and hunters alike (Miller & Duncan 1999; Austin *et al.* 2000). One aspect shared across species is considerable uncertainty about the factors that may be limiting populations, which creates substantial challenges for developing effective conservation strategies.

A wide range of environmental factors pose threats to the persistence of many duck, sea duck and goose populations globally. Of 228 waterfowl taxa (sub-species level) investigated by Green (1996), 48 vulnerable or endangered taxa (37 ducks and sea ducks; 11 geese) were threatened mainly by habitat loss, hunting and predation by invasive species. These same threats were also the most common among the 29 threatened or endangered duck and goose species recently assessed by the International Union for Conservation of Nature (IUCN; IUCN 2013), although high degrees of uncertainty were noted regarding limiting factors. Problems associated with habitat loss, fragmentation and degradation (*e.g.* reduced water quality) have continued unabated since Green's (1996) work (An *et al.* 2007; Dahl & Stedman 2013; Junk *et al.* 2013). Hence, many challenges faced by North American waterfowl have relevance globally, even if those populations are not considered threatened by global standards.

In this paper we examine approaches to addressing contemporary challenges faced by several duck species of special management concern in North America: Mottled Duck, American Black Duck *A. rubripes* (hereafter Black Duck), Northern Pintail, scaup and sea ducks. We also examine conservation challenges facing the Common Eider *Sometaria mollissima* in western Europe, where collaborative research has developed but eider monitoring and management depends in large part on agreement among many countries. Although all of these species are designated as being of "least concern" by international nature conservation agencies, they have become focal species for several reasons. First, in the case of the North American dabbling and diving ducks, all are numerically important harvested species valued by hunters (Raftovich & Wilkins 2013). For instance, Northern Pintail, Lesser Scaup and Black Duck are highly prized by hunters in the Pacific, Mississippi and Atlantic Flyways, respectively, for a variety of cultural reasons. Second, all of these species have experienced substantial population declines at some point in the past 30 years, with no evidence of strong recoveries

Table 1. Summary of North American waterfowl species that were below conservation objectives of the North American Waterfowl Management Plan (NAWMP) in 2011, and species listed by federal agencies or International Union for the Conservation of Nature (IUCN) as being "at-risk" in 2013.

Below NAWMP objective[a]	**Species of special concern**[a,b]	**At-risk species**[b]
Northern Pintail *Anas acuta*	Mottled Duck *Anas fulvigula*	Steller's Eider (Alaska) *Polysticta stelleri*
American Black Duck *Anas rubripes*	Barrow's Goldeneye (eastern) *Bucephala islandica*	Spectacled Eider *Sometaria fischeri*
American Wigeon *Anas americana*	Black Scoter *Melanitta americana*	Laysan Duck *Anas laysanensis*
Greater Scaup *Aythya marila*	White-winged Scoter *Melanitta fusca*	Hawaiian Duck *Anas wyvilliana*
Lesser Scaup *Aythya affinis*	Long-tailed Duck *Clangula hyemalis*	
Atlantic Flyway Canada Goose (resident) *Branta canadensis*	Harlequin Duck (eastern) *Histrionicus histrionicus*	
Dusky Canada Goose *Branta c. occidentalis*	King Eider *Sometaria spectabilis*	
	Tule Goose *Anser albifrons elgasi*	
	Cackling Goose *Branta hutchinsonii*	
	Western High Arctic Brant *Branta bernicla*	
	Emperor Goose *Chen canagica*	
	Hawaiian Goose *Branta sandvicensis*	

[a]NAWMP 2012, Appendix A (Tables 1, 2, 3).
[b]Canadian Wildlife Service Waterfowl Committee 2012, USFWS 2008, IUCN 2013.

(Zimpfer *et al.* 2013; Ekroos *et al.* 2012). Population sizes of Northern Pintail, scaup and Black Duck remain below goals established by the North American Waterfowl Management Plan (NAWMP; NAWMP 2012). Third, population management objectives achieved through harvest regulations should be guided by science, and the manifold reasons for persistently low populations have not been adequately resolved. This situation can create debates between advocates of conservative harvest regulations or season closures and proponents of liberal harvest quotas who may question the lack of evidence for adverse harvest effects on populations. And, fourth, these species provide unique opportunities to learn about the application of formal decision analysis (*e.g.* Clemen 1996; Conroy & Peterson 2012; Gregory *et al.* 2012) to address concerns surrounding the management and conservation of harvested duck populations, while these species remain relatively common. These taxa represent a range of conservation goals, geographic scope, confidence in survey results, availability of data to inform hypotheses and models, modelling approaches and organisational history. Additionally, planning efforts within each taxon generally follow a robust conservation framework (*sensu* strategic habitat conservation; Johnson *et al.* 2009) that facilitates systematic and collaborative planning, typically under the auspices of NAWMP infrastructure (NAWMP 2012). The goals of this paper are to review the conceptual framework, demonstrate how the framework was applied in case studies and highlight the value of planning models for making decisions when much uncertainty is involved. We believe this approach is applicable whether the population of concern is the Lesser Scaup, which is still common in North America, or a globally threatened species.

Conceptual framework

A conceptual framework is here defined as an organisation of ideas into a set of logical steps to solve a problem and develop strategies to achieve desired goals. For North American waterfowl, those goals are population levels sufficient to meet conservation and societal demands and are implicit in subsequent discussions. Conservation efforts generally follow a framework that begins with a broad approach to the formulation of hypotheses about why populations either decline or remain below conservation goals. The strength of this approach lies in proposing plausible hypotheses to explain low populations, a process that typically involves a thorough evaluation of existing evidence and debate about defensible and sometimes speculative explanations for population patterns. One way of visualising this is with a decision tree (adapted from Platt's (1964) logical tree), as was used to summarise and illustrate explanations for low populations of Northern Pintail (J. Eadie, University of California-Davis, cited in Miller *et al.* 2003) and scaup (Fig. 1). Mechanisms that could produce observed population changes allow for explicit predictions about the expected demographic responses to specific management or policy actions. This approach provides a stronger conceptual

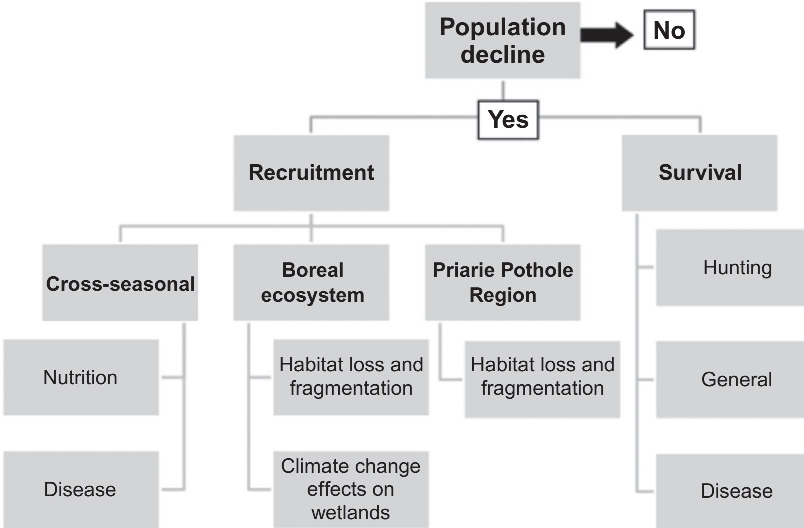

Figure 1. Graphical representation of a decision tree (modified from a logical tree; Platt 1964), designed to represent main working hypotheses proposed for scaup population status or declines (*e.g.* recruitment, survival) and putative mechanisms responsible for such changes (see Table 2). Management or policy alternatives would be implemented to improve demographic rates (survival or reproductive success), and then evaluated for effectiveness with targeted monitoring, research or adaptive management programmes. Factors affecting recruitment in the boreal ecosystem differ from those affecting recruitment in the Prairie Pothole Region; other factors affecting recruitment cross seasons for both breeding regions. Hypotheses were generated during waterfowl community workshops (Austin *et al.* 2000), as well as via research, monitoring and modelling studies.

framework for integrating critical steps by pinpointing: 1) likely bottlenecks to positive population growth rates; 2) suites of management or policy actions with the potential to alleviate these bottlenecks; 3) predicted demographic and population responses to these actions; and 4) monitoring required to evaluate the effectiveness of management interventions.

Population models, whether qualitative or quantitative, are at the core of implementing this conceptual framework. The use of population models to inform conservation actions has a long history (Shaffer 1981; Caswell 2000). The role and sophistication of models have greatly expanded over the last few decades, enabling biologists to integrate and simultaneously to model potential drivers of demographic variation encountered on breeding, staging and wintering areas, in order to predict population change (Mattsson *et al.* 2012; Osnas *et al.* 2014). Model objectives and structure reflect existing hypotheses or primary issues of concern, the availability of data and potential management actions. In addition, integrated models are increasingly able to leverage multiple sources of limited data (Schaub & Abadi 2011). Models therefore are fundamental in our case studies because they codify the decision tree and management actions, and thus allow measurable predictions about expected demographic outcomes under different management and conservation scenarios. Additionally, this structure can be applied to other management goals (*e.g.* hunter recruitment and retention; NAWMP 2012), and used to identify key uncertainties. There is considerable optimism, indeed expectation, that these model-based approaches will be pivotal in setting new, integrated objectives for NAWMP in the next several years (NAWMP 2012; Osnas *et al.* 2014). In the following case studies, we examine how application and outcomes of the framework evolved under the unique life history, data availability and socio-political settings for each duck species.

Case studies

Mottled Duck

Background – The Mottled Duck is a non-migratory species with two genetically distinct sub-populations, one in Florida, the other occurring along the Western Gulf Coast (WGC) portions of Alabama, Mississippi, Louisiana, Texas and northeast Mexico. The combined population estimate is *c.* 172,000 birds (M. Brasher, U.S. Fish and Wildlife Service, and R. Bielefeld, Florida Fish and Wildlife Commission, pers. comm.). Acquiring reliable status and trends information has been hampered by the lack of long-term, range-wide surveys corrected for visibility bias. Spring surveys in Florida suggest that the sub-population there has been stable (at *c.* 53,300) since 1984, but local surveys and indices suggest declines in coastal Texas during 1994–2005 (Johnson 2009) and relatively stable trends elsewhere (Bielefeld *et al.* 2010). It is also one of the least studied Anatini in North America. The species is considered to be of conservation concern because of its restricted distribution, relatively small population sizes, loss and degradation of key coastal habitats in the WGC (Wilson 2007) and introgressive hybridization with Mallard *Anas platyrhynchos* in the Florida sub-population (Table 2).

In the WGC, the primary conservation concerns are the degradation and loss of critical habitats, notably coastal and inland palustrine marshes, rice fields and native prairie and pastureland important for nesting (Wilson 2007). Highly variable breeding propensity, which affects population growth rates, may be tied to wetland conditions (Rigby & Haukos 2012). In Florida, similar concerns about the loss and degradation of wetland habitats have raised questions about the duck's nutritional status, which can affect reproductive success (Florida Fish and Wildlife Conservation Commission 2011). Because of small home ranges, the species can be sensitive to local habitat changes and harvest pressure. Hybridization with feral Mallard is however the main threat to Mottled Duck in Florida. Both regions share concerns about harvest rates and potential impacts of climate change on habitat conditions, with likely increased frequency of severe weather and further habitat loss (Florida Fish and Wildlife Conservation Commission 2011).

Approach – Conservation plans were developed based on expert opinion and limited existing data, and implemented for both Florida (Florida Fish and Wildlife

Table 2. Hypothesised factors causing declines or low populations of selected waterfowl species of conservation concern. Vital rates: R = recruitment, S = survival, P_b = probability of breeding. Occurrence of hybridization is noted with an X.

Presumed cause(s)	**Mottled Duck**	**Black Duck**	**Northern Pintail**	**Scaup**	**North American sea ducks**	**Baltic Common Eider**
Habitat loss and degradation on breeding grounds	R, S, P_b	R, S, P_b	R, S, P_b	R, S, P_b		
Habitat loss and degradation on wintering grounds		R, S, P_b	S	S	S	
Habitat changes on spring migration areas				R, P_b		
Habitat changes due to climate change	R, S, P_b			R, P_b	R, S, P_b	
Habitat changes related to agriculture	R, S, P_b		R, S, P_b			
Interspecific hybridization with Mallard	X	X				
Human disturbance during breeding	R, P_b					
Lead poisoning from spent shotgun pellets	S	S			S	
Over-harvest	S	S	S	S	S	S
Diseases and parasites		S	S		S	S
Contaminants (lead poisoning from spent shotgun pellets)		S			S	S
Bioaccumulation of contaminants from foods on migration and wintering areas		S		S, P_b	S, P_b	
Altered predator-prey relations on breeding grounds			R, S	R, S		R, S
Disturbance on migration and wintering areas from shipping, wind-power development					S	
Commercial exploitation of food resources on wintering grounds						R, S, P_b

Conservation Commission 2011) and WGC sub-populations (Wilson 2007). Experts identified factors most likely to limit sub-population growth, which stimulated research to elucidate how those factors were affecting vital rates, such as breeding distribution, nesting effort and survival.

Florida's plan focused on addressing uncertainties related to hybridization with Mallard by developing tools to identify species and hybrids more accurately, and on assessing the impact of wetland quality on productivity and the energy demands of this species. Results from studies on habitat use patterns for urban and rural Mottled Ducks in Florida improved predictions of Mottled Duck distribution and habitat use during multiple periods of the annual cycle and under contrasting water conditions (Bielefeld & Cox 2006; Varner 2013, 2014). The findings should improve the targeting of habitat conservation actions, and also improve the efficiency and effectiveness of the annual population surveys. Recent information on temporal and spatial patterns of survival in Florida (Bielefeld & Cox 2006) have improved predictions of how future habitat loss and alteration (including continued urbanisation and wetland creation associated with urban development and the Comprehensive Everglades Restoration Plan; Anonymous 1999), will affect the Mottled Duck sub-population. New techniques based on plumage characteristics (R. Bielefeld, pers. comm.) will be valuable for assessing the extent and distributional aspects of Mottled Duck x Mallard hybridization, and thus for identifying the most appropriate conservation actions.

In the WGC, a sex-specific matrix model identified female annual survival as an important factor in Mottled Duck population dynamics and potential target for management actions (Johnson 2009). A pattern of high breeding season survival and low breeding incidence suggested a trade-off between nesting effort and female survival (Rigby & Haukos 2012). Combined, these models indicate that improved habitat quality will be critical for conserving this species in the WGC region. Two main conservation actions identified by the model are the enhancement and restoration of coastal marshes (primarily for creating suitable (*i.e.* low salinity) brood habitat), and the restoration of coastal prairie and associated wetlands to enhance nesting propensity, nest success and brood survival. Partners have developed a spatially-explicit decision support tool to aid delivery of Mottled Duck habitat conservation in locations where demographic responses are likely to be more favourable. Finally, implementation of an annual range-wide, visibility-corrected survey of Mottled Ducks in the WGC will likely reduce uncertainties about population sizes and trends.

American Black Duck

Background – The American Black Duck is distributed in eastern North America from Ontario to the Maritime Provinces and south through states of the Mississippi Flyway and the Atlantic Flyway. Historically, it was the most abundant dabbling duck in eastern North America and also the most heavily harvested (Rusch *et al.* 1989). Estimates from the Mid-Winter Waterfowl

Inventory, conducted annually across most key wintering areas in the U.S., indicated the population experienced a rapid and sustained decline of > 50% between 1955 and the 1990s (Conroy *et al.* 2002). Christmas Bird Count data, a citizen-science survey programme conducted annually in selected areas, suggest that Black Duck numbers declined in the southern and central portion of wintering range during 1966–2003 but that populations in the northeast were stable (Link *et al.* 2006). While these wintering surveys provide the longest time period to assess trends, they both suffer from substantial shortcomings, such as temporal and spatial variation in survey effort and methodology. Breeding ground surveys conducted with more rigorous methods since 1990 indicate stable or slightly increasing trends (Zimpfer *et al.* 2013). Contrasting population trends among these three surveys could be related to counting methods or temporal shifts in winter distributions. However, some have raised questions about possible regional differences in population demographics (Conroy *et al.* 2002; Black Duck Joint Venture 2008).

Researchers and managers have proposed several hypotheses to explain the historic decline of Black Duck populations (Table 2), including over-harvest, competition and hybridization with Mallard, decrease in quality and quantity of wintering and breeding habitat, parasites and disease (*e.g.* duck viral enteritis) and environmental contaminants (*e.g.* lead shot, mercury, DDT). Conroy *et al.* (2002) found support for four major, continental-scope factors that may influence Black Duck populations: 1) loss in the quantity or quality of breeding habitats; 2) loss in the quantity or quality of wintering habitats; 3) harvest; and 4) competitive interactions or hybridization with Mallards. They concluded that no single factor could explain the Black Duck decline. A common theme across these issues and trends is uncertainty about the role of density dependence on reproduction and survival, and potential cross-seasonal influences of putative density-dependent effects. Also unclear is the degree to which competition and hybridization with Mallards may have interacted with other factors such as harvest and habitat changes (Nudds *et al.* 1996; Petrie *et al.* 2000). Although numerous investigations have addressed these issues, there is a lack of consensus about the role these factors play in limiting the population.

Approach – The Black Duck Joint Venture (BDJV) was established in 1989 as the first "species joint venture" (JV) to implement and coordinate a cooperative population monitoring, research and communications programme to provide information required to manage Black Duck populations and restore numbers to the NAWMP goal of 640,000 breeding birds (NAWMP 2012). Initial priorities included development and implementation of improved surveys to monitor breeding populations and harvest, directed projects to provide estimates of vital rates and habitat requirements, research to incorporate spatial information into the breeding ground survey to identify habitat features affecting Black Duck abundance, and development of a life-cycle model (Conroy *et al.* 2002) and a model to estimate autumn age-ratios.

The annual life-cycle model provides a

mechanistic description of population growth, assesses hypotheses concerning factors potentially limiting Black Duck population growth, and links hypotheses to parameters that could be estimated from available data. Sensitivity analyses were used to explore effects of statistical uncertainty in parameter values on population growth rates. Results indicated that reproductive rates were positively influenced by breeding habitat quantity and negatively influenced by Black Duck and Mallard densities, and that the proportion of Black Ducks harvested also declined with increasing densities of both species (Conroy *et al*. 2002). Conroy *et al*.'s (2002) modelling work formalised uncertainties about factors that influence the Black Duck population and provided the foundation for an adaptive management framework.

The BDJV, in partnership with the Eastern Habitat and Atlantic Coast JVs, is developing a decision framework that integrates habitat and population management that will enable the JV to produce an objective, science-based estimate of carrying capacity and make recommendations for revising the NAWMP population goal (Black Duck Joint Venture 2008; Devers *et al*. 2011). The framework focuses on area of habitat restored or protected at the Bird Conservation Region (BCR; North American Bird Conservation Initiative 2000) level, framed as a resource allocation issue. Decision framework objectives include: 1) achieving the NAWMP population goal under a harvest strategy of 98% maximum sustainable yield; 2) maintaining current distribution of breeding and wintering Black Ducks corresponding to the 1990–2012 period; 3) maintaining habitat to support desired abundance, distribution and harvest opportunity; and 4) increasing understanding of the density-dependence mechanism and of factors limiting the species to make increasingly more informed decisions. Underlying the framework is the Conroy *et al*. (2002) model of Black Duck population dynamics and habitat, with competing hypotheses on the role of density dependence on reproduction on the breeding grounds, survival on wintering grounds (post-hunting season), carry-over effects of wintering habitat conditions and changes in movement patterns from breeding to wintering areas. Drivers of vital rates include weather and carrying capacity as affected by habitat loss and habitat management. Strength of density dependence in winter is assumed to be related to energy intake and expenditure (*e.g.* per capita food supply and weather conditions). Harvest is included in the decision framework but is not a focus of management actions. Research is underway to address key uncertainties related to energetic capacities on the wintering grounds, return on investment for winter habitat restoration and to improve parameter estimates such as post-season survival rates in relation to variation in weather and food (Osnas *et al*. 2014).

Northern Pintail

Background – The Northern Pintail is one of the most abundant dabbling ducks in North America. The main breeding habitats are in Alaska and the Prairie Pothole Region of southern Canada and the northern U.S.

Great Plains, and winter habitats are along the coasts and throughout the southern U.S.A. The species is closely associated with temporary and seasonal wetlands, and historically pintail numbers have tracked wetland conditions on the prairies (Miller *et al.* 2003). Population levels were high during the 1950s and 1970s (5.5–9.9 million), periodically fell below 4 million birds during short-term droughts on the prairies during the 1960s–1980s, then fell to record lows during an extensive prairie drought in 1988–1991 (1.8–2.3 million). Despite greatly improved wetland conditions in the prairies since the mid-1990s, pintail numbers over the last decade have averaged 3.2 million, 43% below the NAWMP goal of 5.6 million (Zimpfer *et al.* 2013). Most of the recent decline occurred in Prairie Canada, and the once-close relationship between numbers of breeding pintail and number of prairie wetlands has weakened substantially since the 1990s (Podruzny *et al.* 2002).

Three main biological hypotheses have been suggested to account for the pintail decline. The most plausible is that conversion of prairie to cropland and changing cropping practices on the breeding grounds, especially in prairie Canada, has reduced nest success (Table 2). But it was also speculated that fewer females nested (persistently) due to cross-seasonal effects from reduced habitat quality during winter and spring migration. Finally, over-harvest and higher mortality of adult females during the breeding season due to diseases (primarily Avian Botulism *Clostridium botulinum* and Avian Cholera *Pasturella multocida*) and predation have also been suggested. Meanwhile, biologists have also expressed uncertainty about the ability of the traditional waterfowl survey (survey strata 1–50; Zimpfer *et al.* 2013) to count breeding Northern Pintail reliably during dry years on the prairies, when the pintails may overfly the region to settle in unsurveyed areas further north.

Empirical research since the 2001 Pintail Workshop (Miller *et al.* 2003), undertaken both at breeding sites and on the wintering grounds, has helped to fill many information gaps and reduced some uncertainties, such as those relating agricultural practices to nest survival (Podruzny *et al.* 2002; Kowalchuck 2012; J. Devries, Ducks Unlimited Canada, unpubl. data) and migration chronology relative to timing of surveys within traditional survey areas (Miller *et al.* 2005). For the migration and winter periods, research findings have generally downplayed the importance of low survival rates (Miller *et al.* 2005; Haukos *et al.* 2006; Fleskes *et al.* 2007; Rice *et al.* 2010). However, studies of Northern Pintail wintering on the Texas Gulf Coast identified new concerns about low overwinter survival associated with the loss of wetlands and rice agriculture (Moon & Haukos 2006; Anderson 2008). These unexpected results and the implementation of a national harvest strategy for Northern Pintail in 1997 (USFWS 2010) were among the factors elevating the importance of harvest rates in population dynamics models.

Approach – The Pintail Action Group (PAG) was created in 2003, operating as a working group under NAWMP, with a mission to advocate and support the coordination and evaluation of Northern

Pintail management and research among JVs, North American Flyways, government agencies, and organisations (Duncan *et al.* 2003). JVs have since pursued large-scale habitat programmes on key breeding areas and maintenance of key migration and wintering areas. For example, the Prairie Habitat JV, which encompasses the Prairie Pothole Region in Canada, has developed programmes to encourage conversion of spring-seeded cropland to more pintail-friendly uses (Devries *et al.* 2008), such as Winter Wheat *Triticum aestivum* and forage crops. Other conservation efforts include direct land protection and enhancement, agricultural partnerships, and policy initiatives. The PAG coordinated work to construct an empirically based meta-population model that integrates the effects of habitat and harvest on vital rates, and provides a platform to link habitat change and regional management actions to key demographic rates and population responses (Mattson *et al.* 2012). The model approach and structure is described below and by Osnas *et al.* (2014).

The predictive life-cycle model (Mattson *et al.* 2012) enables evaluation of how alternative habitat and harvest management strategies simultaneously influence continental-scale pintail population dynamics. This was the first model to integrate habitat and harvest explicitly into a modelling framework, the goal of the NAWMP Joint Task Group (Anderson *et al.* 2007). Mattson *et al.* (2012) discuss the general assumptions, common to most other species models, that population dynamics are regulated by external (*i.e.* habitat and harvest management) and internal (*i.e.* density-dependent) mechanisms, and that those mechanisms may interact. These assumptions in turn lead to the dual assumptions that habitat management by JVs (or JVs encompassing main pintail regions of North America) has a direct influence, and that harvest management has an indirect influence on population-specific vital rates through density-dependent mechanisms. This linkage allows simultaneous prediction of the effects of harvest and habitat management on continental pintail population dynamics (Table 3).

Greater and Lesser Scaup

Background – Greater and Lesser Scaup cannot be distinguished in aerial surveys so the species are usually combined and identified as 'scaup' in population estimates. Their combined range is the most widespread of North American diving ducks. Greater Scaup breed primarily in tundra regions from western Alaska to eastern Canada, with some also breeding in the boreal forest, whereas Lesser Scaup breed largely in boreal and prairie regions. In winter most scaup are found along the coasts of the Pacific and Atlantic Oceans, the Gulf of Mexico and the Great Lakes, although Lesser Scaup also winter on inland waters. The combined breeding populations of scaup declined from 5.7–7.6 million birds in the 1970s to a record low of 3.25 million birds in 2006 before showing signs of partial recovery; 4.2 million scaup were reported in 2013 (Zimpfer *et al.* 2013). The current population estimate remains 33% below the NAWMP goal of 6.3 million. The prolonged decline and uncertainties about

Table 3. Examples of conceptual and predictive models developed for species of conservation concern in North America, and their uses in guiding research and conservation programmes. References that describe details of these models are given in respective case-studies.

Species	Model	Conservation applications
Mottled Duck	*Florida*: Model to differentiate Mottled Duck age and sex, and to identify Mottled Duck-Mallard hybrids based on plumage characteristics	Accurate identification of species and hybrids in surveys and where hybrids are most prevalent. Improve population and harvest estimates; research.
	Western Gulf Coast: Sex-specific annual life-cycle model	Pinpoint critical vital rates (female annual survival) in population dynamics. Clarify relationship between female survival and nesting effort under different habitat conditions. Guide habitat actions (protection and restoration of critical wetlands).
Black Duck[a]	Integrated life-cycle and habitat model	Guide habitat actions; identify best areas or actions to achieve conservation goals.
Northern Pintail[a]	Integrated life-cycle and habitat model	Simultaneously evaluate effects of harvest and habitat management on continental-scale population dynamics. Framework for cost-effective allocation of conservation resources.
Scaup[a]	Integrated life-cycle, habitat and hunter model	Identify research and management priorities. Evaluate estimated costs and benefits of management actions. Simultaneously evaluate effects of harvest and habitat management on continental-scale scaup population dynamics and hunter recruitment and retention. Identify best areas or actions to manage species.

Table 3 (*continued*).

Species	Model	Conservation applications
Sea ducks		
Atlantic Common Eider	Demographic model	Sustainability of harvest and recommendations for harvest levels.
		Impact of periodic mortality events from avian cholera on population dynamics.
Pacific Common Eider	Stochastic, stage-based, matrix life-cycle model	Identify research and management priorities.
Long-tailed Duck	Matrix population model	Determine impacts of lead poisoning and subsistence harvest on population dynamics.
Spectacled Eider	Energy balance simulation model for wintering in the Bering Sea	Assess implications of changing climate, changing food resource availability and design of marine protected areas.

[a]See Osnas *et al.* (2014) for details.

factors contributing to the low numbers resulted in both species being listed as "focal species of concern" by the U.S. Fish and Wildlife Service (USFWS 2011). The largest decline occurred in the boreal forest, the core breeding region for Lesser Scaup, but numbers also declined in prairie Canada. Numbers of scaup in the tundra survey strata, presumed to be Greater Scaup, have been stable or slightly increasing since the 1970s. Hence, the main focus of concern is on Lesser Scaup.

Specific hypotheses explaining the population decline were first put forward by Austin *et al.* (2000) and Afton & Anderson (2001) and with further debate evolved into six key hypotheses (Table 2, Fig. 1). The *Disease Hypothesis* (*i.e.* contaminants) proposes that environmental contaminants have had a negative effect on scaup survival and productivity; this was based on known environmental contamination of wintering and staging areas (primarily selenium and PCBs) and on high levels of contaminants recorded in some preferred scaup foods such as the exotic Zebra Mussels *Dreissena polymorpha* (Custer and Custer 2000; Petrie *et al.* 2007). The *Spring Condition Hypothesis* posits that body condition during migration and pre-breeding has declined compared to historic levels due to reduced food abundance or quality on spring migration areas, and subsequently reduced body condition has negatively affected scaup survival and productivity (*e.g.* through lower breeding propensity, smaller clutch sizes, and later nest initiation dates). Original concerns about widespread habitat changes on the breeding grounds have been refocused to two inter-related hypotheses. The *Climate Change-Habitat Hypothesis* suggests that warming climate in northern breeding regions has reduced the abundance or quality of wetland habitats for scaup at large scales, potentially reducing food resources, availability of nesting or brood-rearing habitat, and breeding propensity; altered habitat conditions may also have altered scaup's exposure to predators, reducing nest success or adult female survival. This hypothesis is founded on data indicating that the greatest change in annual mean temperatures coincides with the location of core Lesser Scaup breeding habitats in the western boreal forest, and evidence for substantial long-term declines in wetland areas in Alaska's boreal region (Riordan *et al.* 2006). The *Climate Change-Mismatch Hypothesis* asserts that earlier spring phenology and warmer water temperatures in northern breeding wetlands has caused invertebrates (the scaup's main food resource) to advance their reproductive cycles, possibly reducing their availability to scaup later in the season (see Drever *et al.* 2012). The *Predation Hypothesis* postulates that fluctuations in predators and alternate prey indirectly affect waterfowl productivity (Brook *et al.* 2005). A *Harvest Impact Hypothesis* was put forward to acknowledge possible links between harvest management and scaup population size, but was not considered a strong contributor to the scaup decline (Afton & Anderson 2001).

Approach – A Scaup Action Team (SAT) was created in 2008, also as a special working group under the auspices of the NAWMP, to help strengthen the biological foundations of conservation programmes. The interests of the SAT and the listing of scaup as a "Migratory Birds of Management Concern" (USFWS 2011) led to development of a conservation action plan. The SAT is using a structured decision-making process, starting by framing the problem (resource allocation among alternative management actions) and identifying fundamental objectives of scaup conservation planning not only in terms of objectives for scaup populations and their habitats but also for scaup hunter populations. The foundation of the decision framework is based on predictive models for both scaup and hunter populations, linked via harvest rate, the former building on work of Flint *et al.* (2006) and Koons *et al.* (2006).

The prototype predictive model for scaup is designed as a top-down decision framework to address three objectives: 1) achieve landscape conditions (continental carrying capacity, *i.e.* habitat) capable of supporting target populations; 2) ensure desired levels of sustainable harvest; and 3) sustain the diving duck hunting tradition (*i.e.* diving duck hunter population). The framework provides a means to identify the best areas or actions to be targeted for managing scaup and for learning (reducing uncertainty). The framework explicitly links two life-cycle models, one for scaup populations and a second for diving duck hunters, and identifies alternative management actions and their (inter-) relationships to scaup and/or hunter vital rates.

The scaup life-cycle model incorporates separate population estimates and respective vital rates for three breeding regions: prairie and boreal regions (Lesser Scaup) and tundra (Greater Scaup). In workshops (*e.g.* Austin *et al.* 2010), experts formulated competing hypotheses about causes of population changes (Fig. 1) and identified measurable features (attributes), such as wetland density or percent of the landscape in cropland, that likely influenced vital rates (Table 2) and that could be influenced through management (or policy) actions. Functional relationships were then developed for each vital rate and measurable attribute and incorporated into the scaup model (Austin *et al.* 2010). Density dependence is incorporated in two parts of the life-cycle model. During breeding, the mechanism of density dependence is via probability of breeding (habitat and/or food limitation in boreal and tundra regions). For birds in late winter (*i.e.* after the hunting season), density dependence may operate through survival, with food limitation as the primary mechanism. The model relates the number of ducks in the post-hunting population to survival during the following season (here, late winter–early spring) with either compensatory or additive harvest mortality. The process allowed many issues of uncertainty to be identified (*e.g.* interactions among alternative actions, lag effects of environmental change and reliability of vital rate estimates).

The scaup life-cycle model is explicitly linked to a simple model of diving duck hunters, which identifies putative factors and their functional relationships affecting hunter recruitment and retention. The two models are linked via an empirically based harvest rate parameter, and are both projected forward through time to estimate numbers of scaup, number of scaup harvested, and numbers of diving duck hunters under different habitat and harvest regulations scenarios. The model also can be used to explore potential impacts of large-scale ecosystem change on scaup reproduction and carrying capacity. Ultimately, the model will provide the necessary framework to perform decision analyses and evaluate estimated costs and benefits of specific management actions as well as to make transparent, informed trade-offs among multiple objectives.

North American sea ducks

Background – Among the least studied of North American waterfowl are 15 species of sea ducks (Mergini). Their distributions fall largely in remote arctic or marine areas, outside of traditional survey areas, so reliable indices of their populations and productivity have been lacking. Moreover, some groups of sea ducks have not been differentiated to species during surveys (three species of scoters *Melanitta* sp.; Common Goldeneye *Bucephala clangula* and Barrow's Goldeneye *B. islandica*; and Red-breasted Merganser *Mergus serrator* and Common Merganser *M. merganser*). Consequently, abundance, relative densities and population trends cannot be accurately estimated for most sea duck populations. Eight of 22 species or populations are thought to be below historic levels and 5 are thought to be at or above historic levels; the status of remaining species remains unknown (Bowman *et al.* 2015). Since 1986, Barrow's Goldeneye and the eastern population of Harlequin Ducks *Histrionicus histrionicus* have been listed as species of concern in Canada and as threatened in Maine (Table 1). Spectacled Eider *Sometaria fisheri* and Alaskan-breeding population of Steller's Eiders *Polysticta stelleri* are listed as threatened in the U.S. Where population data do exist, trends of several sea duck species were correlated with large-scale oceanic regime shifts, although the direction of relationships varied within and among species, and these populations appear to have been stable or increasing for the last 20 years (Flint 2013).

For many species, ecological knowledge in the early 1990s was insufficient to identify priority threats or factors contributing to apparent declines. Threats related to loss and degradation of breeding and wintering habitats, and the implications to long-term health and security of populations, are shared by multiple sea duck populations (Table 2). Habitat-related threats include oil, gas and wind power development, shellfish aquaculture on staging and wintering areas, and effects of changing climate on critical habitat. Harvest threatens several populations (SDJV Management Board 2008). Other issues of concern include bioaccumulation of contaminants, effects of disease and parasites (*e.g.* Avian Cholera die-offs affecting Common Eiders), consumption of spent lead shot and disturbances from shipping lanes and offshore wind power development.

Approach – Evolving awareness and concerns surrounding habitat, contaminants and harvest for all sea duck species led to the establishment of the Sea Duck JV (SDJV) in 1998 as a multi-species JV to advance sea duck conservation. The focus of the SDJV to date has primarily been to fill key information gaps on population trends, vital rates, habitat use, and delineation of functional populations (SDJV Management Board 2008). Conservation efforts involve a coordinated international approach (mainly U.S. and Canada, but also Russia and Greenland). Partners used existing data and expert opinion to rank species and research priorities for species known or believed to be facing significant threats. The SDJV has supported programmes to develop and improve population monitoring and delineation, such as winter sea duck surveys off the Atlantic Coast and on the Great Lakes, counting Black Scoters *Melanitta americana* molting in James Bay, and delineating functional populations using satellite telemetry and genetic markers. Because of the diversity of species and issues, biologists have pursued targeted research projects rather than broad conceptual models more generally applicable to seaducks.

The targeted sea duck projects have led to development of at least eight different population models that have or can aid decision-makers (see Table 3 for examples). Model types included stage-based matrix projections (for Common Eider: Gilliland *et al.* 2009; Iles 2012; Wilson *et al.* 2012; for King Eider *Sometaria spectabilis:* Bentzen & Powell 2012; for Long-tailed Duck *Clangula hyemalis*: Schamber *et al.* 2009), reverse-time capture-recapture (White-winged Scoter *Melanitta fusca*: Alisauskas *et al.* 2004), individual-based models (Harlequin Duck: Harwell *et al.* 2012), and spatially-explicit simulations of energy balance (Spectacled Eider: Lovvorn *et al.* 2009). While these models are too numerous to review here, they have been used to assess and guide regulations towards sustainable harvest levels, identify vital rates most responsive to management action or requiring further research, quantify population-level risk to the Exxon Valdez oil spill, and assess size requirements for marine protected areas. Most models generally demonstrated high and stable annual female survival, the vital rate to which population changes were most sensitive. However, given these patterns in adult survival, fecundity parameters (nest success and especially duckling survival) were more often indicated as potential targets for management actions.

Common Eider in the Baltic

Background – The Common Eiders of the Baltic/Wadden Sea flyway breed in Sweden, Finland, Denmark, Norway, Estonia, the Netherlands and Germany and winter mainly in Denmark, Germany, the Netherlands, Sweden, Norway and Poland. This population has been well-studied and has been the subject of long-term international monitoring programmes because of its status in the European harvest. Recent evidence from mid-winter surveys suggests the population may have experienced a substantial decline. Coordinated aerial surveys in the Dutch, German and Danish Wadden Sea show numbers halved from *c.* 320,000 in 1993 to *c.* 160,000 in 2007; coordination of counts in other winter regions is weaker, leading to substantial uncertainties in overall trends (Ekroos *et al.* 2012). Ability to assess population trends across the entire winter range is further compromised by changes in count methodology from "total counts" to aerial survey methods that rely on distance sampling and spatial modelling. The "best" estimates of winter totals for the years 1991, 2000, and 2009 were of 1,181,000, 760,000 and 976,000 Common Eiders, respectively. Ekroos *et al.* (2012) questioned whether the apparent increase between 2000 and 2009 was real or due to: 1) changes in survey methods; 2) the generation of mid-winter counts from some states using data collected over several winters during 2006–2010; or 3) birds short-stopping further east in response to milder winters, where they may be less well counted. These negative population trends contrast with breeding-ground surveys that show no consistent trends in breeding abundance (Desholm *et al.* 2002; BirdLife International 2004). Desholm *et al.* (2002) suggested the decline may represent a decline in numbers of non-breeding "floaters", which would not be represented in breeding ground counts but would be included in winter counts. There is also evidence of a decline in the adult sex ratio among Common Eiders harvested in Denmark (Ekroos *et al.* 2012). Hence, there are substantial underlying uncertainties about winter survey data and population demographics within different breeding regions.

The most immediate threat to the Baltic/Wadden Sea population is commercial exploitation of shellfish, which has likely reduced food availability to eiders and is linked to mass starvation of Common Eiders in some years (Table 2) and regional reductions in other years (Camphuysen *et al.* 2002). Furthermore, declines may be related to unknown factors causing delays among females in first year of breeding combined with reduced breeding propensity. Decline in some nesting colonies have been attributed to varying causes, usually associated with changes in predation, including greater predation of incubating females and eggs by White-tailed Sea Eagles *Haliaeetus albicilla* in Finland and invasive American Mink *Neovison vison* that have reduced reproductive success and female survival in Sweden (Desholm *et al.* 2002). Declines in other colonies have been linked to lower duckling survival (related to density dependent regulation and viral disease), competition with other waterbirds, and poor pre-nesting body condition in spring (Desholm *et al.* 2002). Other issues of concern include disease and parasite infestations affecting survival and reproduction, pollutants generally, lead poisoning in Finland, avian cholera in Denmark, bycatch in gill nets, and offshore collisions with high-speed boats and offshore structures such as wind turbines and bridges. The impact of harvest on the population is also unclear (Gilliland *et al.* 2009).

Approach – Because of its global importance to many waterbirds in the flyway, the Danish Wadden Sea has been recognised as a Ramsar site, a Natura-2000 site, an Important Bird Area, a Man and Biosphere Reserve, and a World Heritage Site. It is encompassed under the Western Palearctic Anatidae Agreement (WPAA), Trilateral Governmental Conference (The Netherlands, Germany and Denmark), and the 1995 Agreement on the Conservation of African-Eurasian Migratory Waterbirds (AEWA; Boere & Piersma 2012). The latter provides the best legal, intergovernmental instrument for collaborative management of the Wadden Sea. However, these international conventions and collaborative partnerships have not been entirely effective in protecting waterbirds and their habitats in the Wadden Sea (Boere & Piersma 2012). Conflicting economic and political interests of the multiple nations continue to challenge conservation planning and implementation in the Baltic/Wadden Sea region. Conservation and management of the Common Eider, and other sea ducks in Europe, would be greatly enhanced by the development of a conservation plan to help prioritise, coordinate and implement research, monitoring and management actions (also see Elmberg *et al.* 2006).

Decision making in the face of uncertainty

We have outlined a basic framework that integrates critical steps for defining actions to conserve populations of concern, ranging from identifying plausible hypotheses about factors influencing demographic parameters and population status to determining suites of potentially effective management or policy actions to monitoring the outcomes of those actions. We also provided examples of how this framework has been used for several waterfowl taxa, including the development of sophisticated planning models that quantify key relationships between stressors, demography and desired management outcomes (Table 3). These are essential steps towards addressing population concerns and revealing critical research needs. Uncertainties exist at each stage of the framework, which generally can be grouped into the following categories:

(1) *Population Assessments.* While many species are of concern because of low numbers or perceptions of substantial population decline, robust data for assessing population trajectories are often lacking. As well, spatial variation in demographic rates, where such data exist, suggests that population trajectories might be driven by sub-populations. However, demographically distinct sub-populations are not clearly identified for many species.

(2) *Demographic trends and relationships.* We have little information on spatial and temporal patterns in survival and reproduction for many species of conservation concern. Furthermore, functional relationships between demographic parameters and habitat quality or other limiting factors, plus underlying biological mechanisms driving those patterns, are often unknown. These include harvest, cross-seasonal and density-dependent effects.

(3) *Status and trends of key limiting factors.* Models assume linkages between demography and habitat quantity and quality or the presence of other stressors, *e.g.* "invasive" species (genetic competitors), contaminants, or predators. Key to targeting conservation action and evaluating the outcome of management actions is an understanding of how environmental conditions change due to and in spite of management actions. However, such information is often absent at spatial or temporal scales consistent with the scale of conservation concerns.

(4) *Predicting future relationships in a changing world*. Modelled relationships between limiting factors and waterfowl demography are built on expert opinion and/or existing data. However, managers cannot assume that systems they are trying to manage are static (*i.e.* constant through time and space), and therefore that known current values are useful for predicting future patterns. For example, climate change may induce changes in the ecological processes that drive patterns of waterfowl distribution and demography, which may alter those patterns (Nichols *et al* 2011). This potential change in system dynamics through time may be difficult to predict, but is valuable to explore (Drever *et al.* 2012).

(5) *Predicting outcomes and cost effectiveness of management or policy actions*. Uncertainty in the above categories can hinder the identification and implementation of appropriate conservation actions. For example, competing hypotheses about relationships between limiting factors and demography may lead to different management strategies. Moreover, limited ability to control how management actions are deployed (*e.g.* due to unplanned financial constraints), and also the effectiveness of actions given environmental variation, make predicting and also realising desired outcomes challenging. Uncertainty regarding the success of conservation outcomes confounds estimating return on investment, an essential component in determining how best to allocate the limited finances allocated to conservation.

Despite these many uncertainties, many conservation decisions must be made now. Often these decisions are time sensitive and cannot wait for perfect information. As Nichols *et al.* (2011) highlight, such decisions are regular occurrences for population managers. There is a large field of adaptive management and structured decision-making that describes an active, transparent and defensible process for arriving at decisions and reducing uncertainty to inform future decisions (*e.g.* Williams *et al.* 2002; Conroy *et al.* 2012). It is not our intent to repeat this information here, but rather to focus on the use of population models for advancing adaptive decision-making.

We recognise that models are an over-simplification of complex relationships, with inherent errors, uncertainties and assumptions. However, models are key components to adaptive management because they provide a defensible structure from which to communicate, make decisions, and learn about population dynamics and the impacts of our decisions. Both conceptual and quantitative models articulate contrasting views about how the systems we are trying to influence operate, allowing us to predict potential outcomes of alternate conservation actions. Further, by specifying key relationships, parameterizing equations and conducting sensitivity analyses, we bring key information gaps and debate into greater focus. This focus can inform research agendas, strengthen fundraising efforts, and guide development of conservation programmes. Finally, competing hypotheses about relationships between limiting factors and demography can be weighted based upon the degree of confidence we have in the probability that they are correct (Nichols *et al.* 2011). These weights can be modified as we learn through directed research or implementation of conservation programmes arising from strategic decision-making, thereby improving future decisions. Thus, while not a panacea for every situation, models provide a mechanism for structured, long-term learning; the most crucial research questions and monitoring needs typically emerge during this process and can be integrated with conservation action plans.

Conclusions

The structure of conservation efforts has evolved somewhat differently for each of the waterfowl species of concern, reflecting different issues, histories, geopolitical context and associated uncertainties about current and future system dynamics and management effectiveness. However, the examples we present share common components: formulation of hypotheses at initial stages; application of conceptual and quantitative models that integrate hypotheses with conservation actions; development of formal conservation frameworks and plans based on adaptive management; and use of collaborations and partnerships, largely through the NAWMP's JVs. We believe this approach provides the most defensible, and perhaps repeatable, method for allocating limited resources and advancing learning.

Review of IUCN threats for threatened and endangered waterfowl worldwide indicated great uncertainty in fully understanding the limiting factors and actions required to alleviate their impacts (Green 1996). While the approach we described herein has been used for several data-rich species, we argue that it is equally applicable for data-poor species. This benefit is due, in part, to the ability of conceptual models to help shape and communicate biological reasoning. However, we fully recognise the challenges associated with conserving species that migrate across multiple countries that potentially have different levels of resources (people and financial resources) and perspectives on goals and collaboration for conservation. The approach we outlined can be useful for rapidly assessing risks and guiding conservation efforts for diverse waterfowl species of conservation concern.

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Photograph: Common Eider males and females at Joekulsarlon, Iceland, by Imagebroker/FLPA.