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Eurasian migratory duck species represent a natural resource shared between European countries. As is evident throughout human harvest history, lack of coordinated management and monitoring at appropriate levels often leads to 'the tragedy of the commons', where shared populations suffer overexploitation. Effective management can also be hampered by poor understanding of the factors that limit and regulate migratory populations throughout their flyways, and over time. Following decades of population increase, some European duck populations now show signs of levelling off or even decline, underlining the need for more active and effective management. In Europe, the existing mechanisms for delivering effective management of duck populations are limited, despite the need and enthusiasm for establishing adaptive management (AM) schemes for wildlife populations. Existing international legal agreements already oblige European countries to sustainably manage migratory waterbirds. Although the lack of coordinated demographic and hunting data remains a challenge to sustainable management planning, AM provides a robust decision-making framework even in the presence of uncertainty regarding demographic and other information. In this paper we investigate the research and monitoring needs in Europe to successfully apply AM to ducks, and search for possible model species, focusing on freshwater species (in contrast to sea duck species) in the East Atlantic flyway. Based on current knowledge, we suggest that common teal *Anas crecca*, Eurasian wigeon *Mareca penelope* and common goldeneye *Bucephala clangula* represent the best species for testing the application of an AM modelling approach to duck populations in Europe. Applying AM to huntable species with relatively good population data as models for broader implementation represents a cost effective way of starting to develop AM on a European flyway scale for ducks, and potentially other waterbirds in the future.

Ducks provide a multitude of ecosystem services (Green and Elmberg 2014), and sustainable management of their populations and habitats supports the long-term provision of such services. In particular, many ducks are highly popular quarry species, traditionally hunted across many countries (Cooch et al. 2014) with an estimated 5.5 million shot annually in 24 European countries (Guillemain et al. 2016). As a resource shared by many, and in the absence of international coordination of harvest effort, they are at risk of becoming victims of overexploitation through the "tragedy of the commons" (Hardin 1968). Sustainable management of duck resources may require harvest regulation, but also effective wetland conservation, since two thirds of European wetlands have been lost or degraded due to human activities since the beginning of the 20th century (CEC 1995). The factors affecting abundance and population dynamics of migratory duck species during crucial periods in their annual cycle need to be better understood in order to support effective management and appropriate protection of crucial wetlands along the flyway (Elmberg et al. 2006, Madsen et al. 2015a, b).

Over-harvesting during and after the 2nd World War, when game became a primary source of meat, is assumed to have been a major reason for declines in duck abundance in Europe at that time (Kear 2005). Since then, the provision of protected staging and wintering areas and restrictions on previously largely unregulated hunting have likely contributed to gradual increases in population size and range of many species (Madsen et al. 1998, Nagy et al. 2015).

However, in the last 10 years, the population size of some species has levelled off or even shown declining trends (e.g. common pochard *Aythya ferina*, northern shoveler *Spatula clypeata*, Eurasian wigeon *Mareca penelope*, northern pintail *Anas acuta*; Nagy et al. 2015), creating management challenges for these species in the near future.

Recent dramatic increases in the abundance of some European goose populations have caused societal conflicts, especially with regard to agricultural damage, but also through issues related to air flight safety, human and animal health, ecosystem effects and conflicts with other biodiversity objectives (Elmberg et al. 2017, Fox et al. 2017, Fox and Madsen 2017). This has brought goose management into sharp focus in the last decade, necessitating both innovative management interventions to solve conflicts and improved monitoring systems to assess the effectiveness of the latter. As a result, the concept of adaptive management (AM) has been introduced to European waterfowl management, implemented through the application of flyway-level management of some European geese within the African-Eurasian Migratory Waterbird Agreement (hereafter AEWA) European Goose Management Platform (hereafter EGMP) (AEWA 2016). An adaptive harvest management (AHM) framework exists for the Svalbard population of the pink-footed goose *Anser brachyrhynchus* and taiga bean goose *A. fabalis fabalis* (for the latter species the plan was implemented due to the long-term population decline; Madsen and Williams 2012, Marjakangas et al. 2015, Madsen et al. 2016), and similar endeavours are planned for the barnacle goose *Branta leucopsis* and greylag goose *Anser anser*. One obvious development would be to expand this approach from geese to other harvested waterbirds, and to ducks in particular, in an attempt to solve the problems of those populations of shared migratory quarry species that are declining.

We here adopt the term AM instead of AHM with the specific objective of highlighting the application of adaptive management methods other than just harvest regulation. For instance, for some species, management by harvest regulation is not an option (e.g. species which are protected or are already closed to hunting). In other cases, there is a need to apply adaptive management in habitat conservation planning, as well as harvest regulation (e.g. adapting protected area networks to mitigate climate change in a way that tests the efficacy of different conservation approaches against each other).

Flyway-level management of ducks requires knowledge about flyway definitions. Whether or not there are separate identifiable duck population flyways in Europe is the subject of continuing discussion. Traditionally, it was considered that there are two main flyways; the East Atlantic and the Black Sea/Mediterranean (Scott and Rose 1996). However, Scott and Rose (1996) and Guillemain et al. (2005) suggested it is likely that rather than constituting discrete flyways, no clear population boundaries exist. More likely, there is considerable overlap in the use of both wintering and breeding sites by individuals from these two flyways, complicated by abmigration between them. In a new analysis based on an expanded dataset of ring recoveries and new Bayesian statistical approaches, Guillemain et al. (2017) compared the ring recovery data from common teal *Anas crecca* (hereafter teal), and concluded that despite overlap, it was actually still possible to statistically delineate flyway boundaries. Because flyway-level management rests on some kind of delineation of the boundaries of such flyways, further analysis of the boundaries of different duck species in Europe is still required.

In this paper, we review the limitations of current monitoring and research to support flyway-level AM of duck species in Europe and seek model species with which to start the development of such an approach. We focus on freshwater ducks (in contrast to sea ducks) because of their importance for hunting, and because these species are relatively similar in terms of their ecology, habitats and life history characteristics. Our geographical focus is on the East Atlantic flyway covering countries in north and west Europe (hereafter NW Europe, excluding Russia), for which some data from national breeding and wintering surveys are available in addition to some national wing sample collections supplied voluntarily by hunters.

Duck management under uncertainties

The effectiveness of methods to manage natural resources depends on the specific features that characterise the resource and manager's abilities. Complex ecosystems are characterised by uncertainty in their dynamics and behaviour, which presents a challenge for the effective management of natural resources (Allen and Gunderson 2011). Socio-ecological systems encompass even greater complexity and diverse uncertainties caused by multiple interacting interests (Nuno et al. 2014). Management, be it for the purposes of harvest or conservation or both, requires methods to account for these inherent uncertainties. Four fundamental sources of uncertainty are considered to characterize waterfowl management. First, temporal and spatial gradients in environmental variation affect waterfowl populations through complicated and imperfectly understood mechanisms and dynamics. Secondly, there is structural uncertainty that arises from our incomplete understanding of ecological processes, e.g. how hunting affects game populations. Thirdly, our ability to regulate hunting to within predetermined targets is severely limited. Finally, uncertainty arises from a lack of knowledge of the key population parameters, e.g. population size, reproductive and mortality rates (Williams 1997, Johnson et al. 2015).

AM incorporates the nature of integrative learning, which allows the process to foster resilience and flexibility to deal with management issues (Allen and Gunderson 2011, Westgate et al. 2013). The basis of AM is to ensure an iterative feedback process from decision, to monitoring, assessment and technical learning to contribute to next year's decision-making. This process ensures the added benefit of the AM approach, namely that it provides a dynamic model, which focuses on reducing model uncertainty (Williams and Brown 2014). This differs from normal dynamic strategies in which harvest also varies over time with the resource availability, but where there is no focus or need to reduce model uncertainty (Williams et al. 2007, Williams and Brown 2014).

While AM has been successfully implemented in various situations in relation to plant and animal conservation and harvest (Williams et al. 2007), it may still encounter multiple challenges. Allen and Gunderson (2011) emphasized problems caused by a lack of stakeholder engagement and/or their ability to adapt. This could be a potential problem for duck management in Europe, although the situation is currently greatly improving, as judged by the successful implementation of AM for geese in recent years. Other obstacles to successful implementation include the difficulties and costs of establishing manipulative experiments, and the inability to adequately monitor the consequences of a given management strategy (e.g. as a result of partial observability and controllability; Williams et al. 2002, Nichols et al. 2007). To successfully apply AM, monitoring programmes must be designed and sufficiently resourced to be able to detect changes in populations that derive from management actions; where this has not been accomplished, AM projects have proved unsuccessful (Westgate et al. 2013).

Duck populations in North America have been managed at the flyway level within an AHM framework since 1995 (Nichols et al. 1995, 2007, Johnson et al. 2015). AHM is an iterative process that integrates monitoring, assessments and decision-making, and regular re-assessment of management target based on newly acquired knowledge. It is seen as the best, although not entirely trouble-free, method for managing waterfowl under prevailing uncertainties (Nichols et al. 2007, Johnson et al. 2015). One major benefit of AHM is that through gradual learning, the process provides itself with the knowledge needed for increasingly effective management (Johnson 2011).

AHM of waterfowl in North America has long been based on the population dynamics and harvest potential of mallard *Anas platyrhynchos*, a widespread and popular quarry species. Annual mallard harvest rates are adjusted according to the breeding expectations and target population size (Nichols et al. 1995, 2007). Other species have been managed under a similar framework, but due to differences between duck species, some (e.g. scaups *Aythya affinis/marila* and northern pintail) are currently subject to AHM strategies specifically designed for them, while regulatory alternatives designed for the mallard are applied to other species. However, intentions to develop species and even stock-specific management plans have raised concerns that such systems will be too complex and expensive to implement (Johnson et al. 2015).

In North America, AHM is used as a framework within which to set hunting regulations, while the North American Waterfowl Management Plan (NAWMP) deals more directly with habitat conservation issues (Johnson 2011). The NAWMP (launched in 1986) has been successful, and already during its first ten years the goals set to increase duck populations were achieved, so that many species exceeded their initial target population sizes (as concluded by Williams et al. 1999). While AHM and NAWMP have some shared targets, the two programmes have been developed independently (Runge et al. 2006).

European waterfowl management

Traditional waterfowl (ducks, geese and swans) management in Europe has largely been ad hoc (Elmberg et al. 2006, Williams and Brown 2014). It has long been based on scattered information, implemented through uncoordinated, independent national policies, with no shared management goals, technical foundation for management actions or adequate monitoring schemes that cover the entire annual cycle (Elmberg et al. 2006, Madsen et al. 2015b). Hence, while migrating through different countries along their flyway, waterfowl are subjected to a suite of country-specific management actions.

The need to manage waterfowl at the European level was emphasized in the 1960s, when the International Waterfowl and Wetlands Research Bureau's (now Wetlands International) Resource Harvesting Division and Hunting Rationalization Research Group was established (Priklonski 1974, Lampio 1980). Despite some subsequent development of these ideas in the 1960s, the means for achieving management of waterfowl populations and their harvest have remained very limited in Europe to the present day (Madsen et al. 2015a), notwithstanding the existence of legal frameworks through the European Union Directives and the ratification by most European countries of the AEWA. This rather chaotic situation does not conform to the concept of any sustainable use of internationally migrating ducks, even though the idea of sustainability is generally accepted as the foundation for many national and international agreements (Mooij 2005). The EEC Birds Directive (Council Directive 2009/147/EEC on the conservation of wild birds) commits EU member states to "ensure that the practice of hunting … is carried on in accordance with the national measures in force, complies with the principles of wise use and ecologically balanced control of the species of birds concerned" (Article 7.4). The same principles are found in the AEWA: "any use of migratory waterbirds is based on an assessment of the best available knowledge of their ecology and is sustainable for the species as well as for the ecological systems that support them" (Article III). In this context, wise and sustainable exploitative use of ducks as a minimum requires an annual assessment of harvest and harvestable total population size. Recent guidelines promote flyway-scale harvest management of migratory waterbird populations by adopting the concept of AHM, highlighting the need for changes to the organizational structures that deliver waterbird conservation, harvest regulation, and an understanding of responses of biological systems to intrinsic and extrinsic factors (Madsen et al. 2015a, b).

Currently in Europe (as elsewhere), we lack robust mechanisms to identify the demographic causes of declines in most duck species (i.e. whether they result from changes in long-term survival versus reproductive success). We also lack effective common European mechanisms to enable the management of duck populations before declines bring them to the brink of catastrophe. European huntable species are mostly managed through the establishment of conservation areas (i.e. habitat protection) and regulation of hunting seasons. In most European countries, open seasons are fixed at the national level, independently of the neighbouring countries, not subject to adjustments between years, usually with no daily bag limits and with no effective mechanism to adjust harvest in response to annual fluctuations in reproductive success or abundance (Lampio 1980, Mooij 2005). It is therefore unusual that in Denmark, a scientific review of changes in hunting harvest and population size is undertaken on a three-year review cycle to assess the suitability of all species for continued hunting, based on recommendations made to the government (Bregnballe et al. 2006). With this exception, the basis for hunting regulation has traditionally been straightforward: ducks have been hunted without restriction until the point where they become rare enough to prohibit hunting. For example, greater scaup *Aythya marila* was finally fully protected from hunting in Finland in 1993 after several years of population decrease there (Valkama et al. 2011). If a relatively abundant and widespread species continues to decline, we currently have no available mechanisms by which to restore its numbers and distribution in the future, unless the decline is so dramatic that an action threshold set by AEWA is exceeded and drastic measures (e.g. permanent protection) have to be implemented. Legislation to regulate the hunting kill sustainably is lacking in most European countries along with a general absence of reliable data on hunting bags (Madsen et al. 2015b).

In conclusion, there is a growing need for an agreed framework for waterfowl management in Europe, under which changes in population status would trigger successful and timely management actions (e.g. through adjusted harvest and/or sympathetic habitat management). We have no common European mechanisms that would lead to more subtle regulation in the case of restricting harvest of declining species or adjusting harvest based on annual variation in the level of allowable sustainable take. An early warning system is needed to act as a catalyst for action long before populations reach critical conservation status, e.g. through IUCN Red-listing. Such listing automatically requires an immediate response such as closure of hunting, and if hunting is continued, implementation of an adaptive management framework (or other targeted management) is required to enhance the species conservation status under AEWA. The risks of not adopting a common European AM for ducks are thus the inevitable consequences of belated management of declining species. These include the need to develop a series of independent management plans, potentially one each for several species. Since most duck species remain relatively poorly studied, this will impose urgent and heavy resource demands to fill current gaps in our knowledge under such emergency conservation imperatives. Furthermore, ecosystem services (e.g. those resulting from hunting harvest and bird watching) of collapsing populations would also likely be lost in the meanwhile. Finally, uncoordinated management interventions could also lead to political and social conflicts e.g. due to the unequal division of conservation actions and hunting opportunities between countries.

Improving the European system

The flyway-level processes developed and implemented for geese in Europe can serve as administrative and procedural frameworks for developing a future programme of AM for ducks as well. The different existing monitoring programmes and modelling processes applied to species or species groups could be incorporated within a similar administrative structure to deliver the flyway-level harvest decisions to national-level implementation and hunting regulation changes. The goose framework relies upon regular monitoring, reporting and integration of population size and harvest data, which are urgently needed for ducks too (Elmberg et al. 2006, Madsen et al. 2015a). Although monitoring is essential for effective resource management, AM provides a decision-making framework designed also for situations where there are challenges to effective decision making; management plans can be implemented in systems with information gaps and high levels of uncertainty (Nichols et al. 2007, Johnson et al. 2018). It is actually under such prevailing conditions of relatively poor knowledge that AM is the most beneficial compared to other methods, owing to a double-loop learning system (annual reframing of objectives, actions and models, and longer-term improvement of knowledge through confrontation of model outputs to field surveys; Williams and Brown 2014).

Population parameters

In North America, waterfowl regulation is based on breeding season surveys (mainly for ducks) and winter surveys (mainly for geese), backed by large-scale marking programmes (Johnson 1998, Nichols et al. 2007). In Europe, the International Waterbird Census (IWC) provides annual mid-winter assessments of the approximate numbers of ducks and their distribution within the wintering range, but suffers serious gaps in coverage in time and space (Johnson 1998, Elmberg et al. 2006). Survey results can be compared from year to year to establish fairly robust trends, but we frequently do not know how many birds there are in total, nor if the birds counted represent the same population from year to year. The mid-January IWC also generates population size estimates largely post hunting mortality, since in most countries it is carried out towards the end of the hunting season. Because there are insufficient ringing-recovery data to allow estimation of seasonal survival rates and to identify sources of mortality, mid-January IWC counts cannot be used to differentiate between natural and hunting mortality (Elmberg et al. 2006), and cannot provide any estimate of total annual mortality.

Individuals from different breeding areas mix and aggregate at high densities in winter, making it cost-efficient to count at this time, hence the historical choice to undertake international counts in January. However, surveys of large aggregations of birds can also generate estimation errors (Frederick et al. 2003). They also mask local changes in population distribution and abundance; for example, long-term declines in Finnish-breeding Eurasian wigeon (hereafter wigeon, Lehikoinen et al. 2016, Pöysä et al. 2017) contrast overall stable European wintering numbers (BirdLife International 2015, but see Fox et al. 2016a), where they are diluted by far greater numbers of Russian-breeding wigeon. Long-term assessment of annual abundance is also hampered by shifts in wintering distributions, both short-term (e.g. winter harshness associated with energy costs, Gourlay-Larour et al. 2012), and long-term (by climate change driven shifts, Lehikoinen et al. 2013). For instance, wigeons leave the Baltic Sea during severe winters to move further southwest (Ridgill and Fox 1990, Pihl et al. 1995). However, in recent warmer winters, the species has increased in abundance in the northeastern part of the winter range and declined in the south-west, although the core wintering areas of the species have not shifted (Dalby 2013, Fox et al. 2016a). High turnover rates within certain wintering areas can also challenge monitoring schemes, especially when some areas are more difficult to cover than others (Caizergues et al. 2011).

For the reasons mentioned above, we do not necessarily know the total number of ducks in Europe, a parameter measure which would be needed to set possible harvest limits and to monitor the effects of management interventions. Marine fish populations represent a similarly migratory and harvestable natural resource, and are managed in the EU by its Common Fisheries Policy (CFP) (European Union 2016). For the effective management of fish stocks, the CFP is science-based and seeks to create transparent governance and implement fair sets of rules for fishermen. Under the CFP, a variety of institutions at different levels (international and national) contribute to the management system (Rätz et al. 2010). By comparison, for duck population management, such international coordination is totally lacking and national practises are dispersed and uncoordinated. As a result, the current situation is neither transparent nor can it guarantee a fair and coordinated set of rules for hunters in different countries. An European-level duck management structure, relying on shared and efficient monitoring schemes as well as mechanisms to guarantee fair local delivery, is needed to be able to tackle the political and social issues involved in delivering effective management strategies while keeping governance transparent.

In North America, several parameter estimates relating to breeding and survival rates are required to support the mallard AHM: the size of the breeding population, the proportion of males in the breeding population, survival rates of adult and juvenile of both sexes, reproduction rate, and female summer survival compared to that of males (Johnson 2011). In Europe, we lack such regular breeding and survival data for all species, despite their critical importance to annual duck population dynamics (Stewart and Kantrud 1974, Wiens 1989, Krapu et al. 2000). Long-term annual breeding surveys of population size and reproductive success from the East Atlantic Flyway only exist at the national scale from Finland (where monitoring of breeding pairs started in 1986 and that of broods in 1989; Pöysä et al. 1993, Pöysä 1998, Rintala 2016). In addition, some local scale surveys that extend over different time periods and species compositions may exist (Broyer et al. 2017). The trends in the Finnish surveys are worrying; data indicate declines among duck species both in breeding population size and reproductive output (Pöysä et al. 2013, Lehikoinen et al. 2016, Rintala et al. 2016). Improved methods and coverage provided by breeding population monitoring programmes should be established to generate robust estimates of annual reproduction rate in relation to survival which, when combined, could then be used to adjust the harvest bag in the following hunting season according to a set target population size.

Harvest rate

About 15 million ducks and geese are harvested annually in the Western Palearctic, of which approximately half are taken in the European Union (Hirschfeld and Heyd 2005). However, Europe lacks reliable and complete harvest data; although hunting bag statistics are collected in some areas (Mooij 2005, Madsen et al. 2015a, b, Guillemain et al. 2016, Solokha and Gorokhovsky 2017), the quality of harvest data is generally poor, and highly variable from one country to another (Hirschfeld and Heyd 2005, Mooij 2005). Wing samples from the East Atlantic Flyway are collected nationally and annually only in Denmark, while some other countries carry out such collections less frequently or have done so recently for only a limited number of years (Mitchell et al. 2008, Guillemain et al. 2013b, Christensen and Fox 2014).

A report from the Waterbird Harvest Specialist Group underlined the lack of European harvest data for waterbirds at the flyway level (Madsen et al. 2015b). Sustainability represents a laudable basis for responsible harvesting, but to achieve this goal annual population size and harvest need to be measured (Elmberg et al. 2006). Utilizing adaptive harvest in the most efficient and sustainable way would mean that hunting is adjusted according to population size, taking account of the number of young birds produced. By updating the models on an annual basis through confrontation with real-world monitoring data, model uncertainty could be reduced (Sutherland 2001, Johnson et al. 2002, Williams et al. 2007). Harvest data from all the countries along the NW European flyway, collected in a coherent manner on an annual basis, are therefore a fundamental necessity.

Habitat and climate monitoring

Annual variability in the number, extent and quality of North American prairie wetlands generates major between-year variation in breeding numbers and duckling production (Stewart and Kantrud 1974, Krapu et al. 2000). For this reason, the annual number and extent of prairie ponds in May is used as a proxy for expected annual breeding output (Nichols et al. 2007). Such habitat dynamics do not exist in the European boreal zone, where long-term changes, such as eutrophication, probably play more important roles in affecting reproductive output (Pöysä et al. 2013, 2017). Nevertheless, Pöysä et al. (2016) found that populations of European ducks breeding in stable habitats were neither less variable nor more strongly density-dependent than populations of North American ducks breeding in highly variable breeding habitats, although the contribution of environmental variability to population dynamics was greater in North America than in Europe. However, in Russian Siberia, where many European ducks breed, the abundance of boreal wetlands can vary much within summers and between years (Andreev 2004, Mialon et al. 2005). Unfortunately our current knowledge about breeding ducks in Russia, and their dependence on habitat variation, is poor (Holopainen et al. 2015). Thus, gathering duck breeding dynamics data represents a major challenge to future waterfowl management in Europe, not only from northwestern Europe but also from Russia. The possible role of annual variation in the prevailing hydrology of the Siberian floodplains in determining the size and composition of the autumn duck flight could be resolved by appropriate modelling of habitat variation as a fundamental part of the northwestern European AM.

It is clear that, in order to feed a European AM scheme with robust population models and realistic parameter estimates, more work is needed to identify the most important drivers of duck population dynamics in Europe, including the importance of environmental versus density-dependent effects.

Selection criteria for model species

Monitoring of waterbird populations and hunting bags in addition to running the administrative part of a management framework demands adequate resourcing. Establishing species-specific AM or corresponding management plans for all 28 native duck species in Europe (BirdLife International 2004) would require major resourcing, and coordinating regulation would be extremely complicated. An alternative would be to launch AM for one or a few species to establish the process, with the longer-term ambition of extension to other species or groups in a resource-efficient way, balancing between complexity and species-specific needs (e.g. combining certain species when possible). Not all species of ducks are equally suitable as candidate AM model species. We here list those freshwater species that could potentially be suitable to start with, based on the extent of existing monitoring data so as to reduce initial uncertainty. Mallard was a natural choice as a model species to launch AHM in North America, being widely distributed and well-studied with regard to its population dynamics, as well as making a major contribution to the annual waterfowl harvest (Mack and Morrison 2006, Johnson 2011, Raftovich 2014). It is also the most abundant duck species in Europe, with a wintering population of 7.5 million, and generally the most harvested duck by far in European countries (Guillemain et al. 2016). However, in Europe wild mallard populations are affected by large-scale introductions of farmed birds; over 3 million farmed mallards are released every year for hunting purposes (Champagnon et al. 2013, Dalby et al. 2013, Söderquist 2015). Even though many are shot soon after release, it is obvious that such a huge addition to the wild stock affects population parameters and biases bag statistics (Champagnon et al. 2012). Mallard population dynamics are therefore unlikely to be representative for other species, making it unsuitable as a model species in Europe.

By virtue of our own interests, our geographical target area considered here is northwestern Europe, the area utilized by ducks in the East-Atlantic flyway. To find a possible model species for devising an initial European adaptive duck management plan, we first considered freshwater duck species ranging widely in northwestern Europe, i.e. traits that would promote participation and adhesion by many countries (Table 1). Fish-eating *Mergellus* and *Mergus* species were not considered here due to their different ecology and limited importance for hunting.

We start the selection by recognizing the requirements set by European-level AM for the possible model species. To implement AM widely among European countries, we are looking for a species that would be abundant in as many countries as possible. Firstly, the cornerstone consideration is that sufficient population and hunting bag data exist (or alternatively, if such data are considered feasible to gather in the future). This basically means that we are looking for widely ranging, commonly hunted freshwater duck species. Based on existing monitoring data, currently we can exploit European-wide mid-winter population surveys, Finnish breeding surveys and Danish harvest monitoring data to build population dynamics models. The most urgently needed parameters are annual population size and harvest rate, which represent minimum starting requirements.

Table 1. Common European freshwater duck species. Population trends and status for 27 EU countries (EU27) and Geographic Europe (E) (BirdLife International 2015) based on breeding pairs; LC = least concern, VU = vulnerable.

Species	Population trend	Population status
Mallard *Anas platyrhynchos*	E, EU27: stable	E, EU27: LC
Common teal *Anas crecca*	E: unknown EU27: decreasing	E, EU27: LC
Eurasian wigeon *Mareca penelope*	E: stable EU27: decreasing	E: LC, EU27: VU
Northern pintail *Anas acuta*	E, EU27: decreasing	E: LC, EU27: VU
Garganey *Spatula querquedula*	E, EU27: decreasing	E: LC, EU27: VU
Northern shoveler *Spatula clypeata*	E, EU27: stable	E, EU27: LC
Gadwall *Mareca strepera*	E, EU27: increasing	E, EU27: LC
Common pochard *Aythya ferina*	E, EU27: decreasing	E, EU27: VU
Common goldeneye *Bucephala clangula*	E: stable EU27: decreasing	E, EU27: LC
Tufted duck *Aythya fuligula*	E: stable EU27: decreasing	E, EU27: LC

Adding breeding parameters (annual numbers of breeding pairs and measures of brood production) would significantly improve the models, but such data are hard to collect, and therefore simply not always available for modelling (Niel and Lebreton 2005, Johnson et al. 2012).

Secondly, the species' conservation status needs to be considered (Table 1). One should be cautious about using AM for endangered species, due to high uncertainty and risks (i.e. high probability of a poor choice resulting in dramatic errors, especially during the early phases of the learning process, when uncertainty is still relatively large; but see Runge 2011). Critically endangered species could benefit from different structured management actions other than AM, such as scenario planning (Allen and Gunderson 2011). In addition, the harvest regulation based on population development of an endangered or rare species would provide poor information in relation to generating estimates of hunting bags for other species. Here, we do not evaluate the best management practises for endangered species, but focus on developing models that have the ability to be generalised for several species (i.e. in North America the model produced for mallard with the best quality data has been used to also help managing other species where sufficient data were not available).

Thirdly, to increase generality, and hence transferability and applicability to other species, a model species should be a generalist in terms of habitat use. Thus, any species with a too narrow habitat niche is rejected as an appropriate model species.

After rejecting mallard, and using the criteria outlined above, we exclude species lacking sufficient population and hunting bag data. The bulk of the northern pintail population winters outside Europe, in sub-Saharan African regions (Scott and Rose 1996), making total population size difficult to estimate. Garganey *Spatula querquedula* is also a special case, because it is a trans-Saharan migrant, and circumstances outside the general European flyway seem to have a major modifying effect on its population dynamics (Pöysä and Väänänen 2014). In addition, northern pintail, garganey and common pochard *Aythya ferina* are classified as vulnerable in the EU and are thus not ideal model species. Gadwall *Mareca strepera* is a southern species with a limited boreal breeding population (BirdLife International 2004) and it is a rare quarry species in Denmark, resulting in a low annual numbers of wing samples. The lack of adequate breeding and harvest data also makes the gadwall currently unsuitable as a model species. However, in the future it may be possible to use it as a model species for southern dabbling ducks. Among the remaining species, tufted duck *Aythya fuligula* and northern shoveler prefer very eutrophic lakes for breeding (Kauppinen 1993), and thus do not meet the habitat generalist criterion.

Model species

The three most common remaining freshwater duck species in Europe are two dabbling ducks teal and wigeon, in addition to one diving duck common goldeneye *Bucephala clangula* (hereafter goldeneye). They all fulfil the four requirements laid out here and thus represent the best candidates as model species to launch AM of ducks in northwestern Europe. We have robust estimates of their population numbers and trends based on winter surveys, and currently all three species are classified as having rather stable or slightly decreasing population levels in Europe (but note that data quality for wintering population estimates can be highly variable; BirdLife International 2015, Nagy et al. 2015). All three range widely as breeders in different kinds of habitats from oligotrophic to eutrophic lakes (Kauppinen 1993). The main part of the European breeding populations of these three species (i.e. excluding Russian breeding pairs) occurs in the European boreal (BirdLife International 2004, 2015). Thus, Finnish breeding data can potentially provide reliable and representative estimates of their reproduction trends. While the overall number of breeding teal and goldeneye pairs seem to be stable, the numbers of breeding wigeon have shown a long-term decline (Lehikoinen et al. 2016, Rintala et al. 2016).

All three species are commonly hunted in Europe; the teal is the second most hunted species after mallard, while the goldeneye has the third and wigeon the fourth largest harvest bag (Mooij 2005, see also Guillemain et al. 2016). All species are well represented also in the Danish wing sample data; in the 2015/2016 sample set 1673 wings were from wigeon (ca 13% of the total number), 2771 from teal (ca 21%), and 305 from goldeneye (ca 2%) (Aarhus University 2017). Flyway-scale harvest analyses investigating age-dependent survival rates have been carried out so far for teal (covering France, Denmark and Finland, Guillemain et al. 2010) and wigeon (Denmark and Finland, Guillemain et al. 2013b).

Even though these three species seem to be the best potential model species for northwestern European AM, many parameters needed for the further development of AM for these species are not yet available. For example, at present it is not possible to generate estimates of annual European-level reproduction as well as age- and sex-specific survival rates. There might also be a gradient within these species regarding density-dependent processes; in teal (Elmberg et al. 2003, Nummi et al. 2015) and wigeon (Pöysä and Pesonen 2003) breeding success seems not to be density dependent, while the breeding success of goldeneye shows strong density dependence (Pöysä and Pöysä 2002, Nummi et al. 2015). Understanding the causalities of density dependence in population dynamics is important for hunting management, but currently poorly understood in Europe (Gunnarsson et al. 2013, Madsen et al. 2015b). However, learning is an integral part of the AM process. In the North American AHM for ducks, four models combining strong or weak density-dependent feedback on breeding output and additive or compensatory effects of harvest on natural mortality were initially considered. Similarly in Europe, the implementation of AM should gradually provide a better understanding of the drivers of duck population dynamics.

Discussion

Resource managers are facing complex problems including urgent needs to conserve biological diversity and ecosystems which are subject to large-scale environmental changes. Consumptive use of natural resources in ways which are sustainable over long time periods under these circumstances requires acquisition of information and knowledge (Williams and Brown 2014). Harvesting can become sustainable if the yield is determined wisely based on the reproductive surplus (Hilborn et al. 1995). Accordingly, sustainable duck hunting requires knowledge-based harvest regulation (Cooch et al. 2014).

Focusing on northwestern Europe, we argue that, based on our current limited knowledge, the most suitable candidate species for introducing duck AM are teal, wigeon and goldeneye due to their wide distribution, hunting status and the availability of breeding and harvest data. The goldeneye has a more limited overall distribution across Europe compared to the other two species (Cramp and Simmons 1977), which limits its spatial coverage as a model species. Furthermore, being a cavity nesting species, the goldeneye may respond to and therefore need other, different management actions (e.g. nest box programmes and changed forestry practices; Pöysä and Pöysä 2002) compared to ground nesting ducks. Teal exhibits highly variable population dynamics reflecting environmental variation and has been studied considerably during both the wintering and the breeding stages (Guillemain et al. 2010, Guillemain and Elmberg 2014, Holopainen et al. 2014, 2015).

Duck populations vary naturally in size in response to environmental variation (Pöysä et al. 2016), generating uncertainty for their management (Johnson et al. 1997). The AM framework with data gathering planned for geese by the AEWA EGMP (AEWA 2016) could be extended to also include and benefit ducks. The framework should be targeting to secure the population sizes over the long-term by relying on population and habitat monitoring and providing a resource for sustainable harvest at a significant level (Fig. 1).

While hunting regulations have been liberal in Europe, harvest may not be the main reason for the declining trends among some waterfowl, as there are examples of non-hunted species that show declines (Pöysä et al. 2013), and hunted species that increase (Nagy et al. 2015). However, because

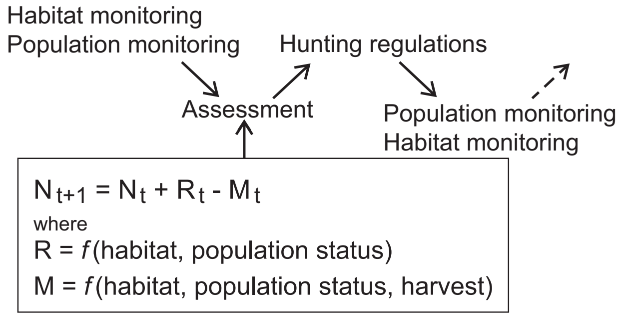

Figure 1. Possible adaptive management scene in Europe including both adaptive harvest management and habitat monitoring. Modified from Williams et al. 1999.

of inadequate bag statistics, our knowledge of the importance of hunting pressure in determining the population dynamics of European ducks is very limited. Waterfowl trends may therefore be responding to larger habitat changes in wetland ecosystems. These include eutrophication of breeding sites (Pöysä et al. 2013, 2017, Fox et al. 2016b, Lehikoinen et al. 2016), habitat loss (Amezaga et al. 2002, European Environment Agency 2010), increased abundance and distribution of alien predators (Väänänen et al. 2007, 2016, European Environment Agency 2012) and changes in physical and chemical qualities (Schindler 1998, Sala et al. 2000, Tománková et al. 2013), which may be driven by land use changes (Arzel et al. 2015). All of these factors threaten duck populations, and affect the possible hunting harvest (Fox et al. 2015). Climate change is one such large-scale threat having a strong influence on migratory ducks and challenging their management (Nichols et al. 2011, Guillemain et al. 2013a). Without flyway-level knowledge of population dynamics and key drivers of overall abundance and distribution, it is impossible to specify the mechanisms of the population declines, their magnitude and in which part of the flyway they will occur.

As encapsulated within AEWA, attention needs to be drawn to the sustainable use of the ecological systems that support ducks. Following climate change and subsequent changes in migratory patterns, we also need to be able to adapt reserve networks to match changing distributions of ducks (Lehikoinen et al. 2013, Elmberg et al. 2014, Pavón-Jordán et al. 2015, Guillemain and Hearn 2017). The protection of known key wintering and staging sites is important due to high densities of ducks aggregating in these limited areas. In breeding areas, many common duck species occur at very low densities (Scott and Rose 1996), making it less realistic to increase protection through site-safeguard mechanisms.

Our recommendations to develop a preliminary mechanism for the more effective management of the three duck species is based on the best available knowledge, but has been largely confined to considering the many and complex technical aspects of setting up such a system. We remain fully aware that the process towards the sustainable management of migratory ducks in Europe should and will also be based on incorporating the views of politicians, decision makers, managers and sociologists. However, this review article represents the beginning of the debate about how best to manage these natural resources. For this reason, we respect the fact that multiple views will be needed to be taken into account when considering the nature of and the ultimate species composition of ducks that are finally managed under any future AM schemes.

Conclusions

At the flyway level, European duck management lacks comprehensive monitoring, habitat management and hunting regulation (Elmberg et al. 2006, Madsen et al. 2015a). Despite this, European duck management could be substantially improved over and above the current situation just by better utilising existing knowledge, for instance by adopting ideas from AM, which is a highly effective management model also for application to inadequately known systems (Madsen et al. 2015b). We suggest that, as in North America, a model is initially developed for one or a few duck species and only later applied to others. This would be cost-efficient and serve to initiate flyway-level duck management in Europe. Establishing an AM for ducks in Europe requires that the trade-off between hunting opportunities and regulatory complexity is critically evaluated. Species-specific AM or corresponding plans for all the 28 native European duck species (BirdLife International 2004) does not constitute the most optimal formulation, as it would lead to redundant actions, duplication and extremely complicated regulations. As shown in North America, plans to implement AHM for several species has created its own difficulties caused by complex and expensive regulation, while the application of a model derived from only one species has its own weaknesses, e.g. reaching species-specific sustainability due to species-specific heterogeneity in terms of harvest potential (Johnson 2011, Johnson et al. 2015).

As suggested by Williams (1997) and Williams et al. (1999) for North America, European waterfowl management would also benefit from more coordinated and carefully prioritized conservation efforts, together with broader partnerships between researchers and managers. We need to improve our understanding of the linkages between waterfowl habitats and biological as well as sociological processes. If adaptive duck management were to be adopted in Europe, following the development and capacity building of the EGMP or some other corresponding platform, both harvest and conservation methods would need to be integrated to provide the most coherent and effective management actions at the flyway level. This seems essential if we are to truly enable the sustainable management of our currently relatively common duck species and their environments under the heavy anthropogenic influence in Europe.

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