A Multi-stock Adaptive Harvest Management Protocol for Informing Annual Harvest Regulations in the Atlantic Flyway

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INTRODUCTION

Since 2000, the U.S. Fish and Wildlife Service (USFWS) has used an Adaptive Harvest Management (AHM) protocol based on the status of eastern mallards to establish the annual frameworks (i.e., season length and overall daily bag limit) for duck hunting seasons in the Atlantic Flyway. By 2010 it was apparent that all of the competing biological models used in the AHM protocol were performing poorly in terms of accurately predicting the following year's eastern mallard breeding population. This led the USFWS and the Atlantic Flyway Council (AFC) to conduct a comprehensive review of Eastern Mallard AHM, during which several questions arose. The questions focused on four general ideas: (1) Should we continue to set duck hunting regulations in the Atlantic Flyway using our current approach without any modifications?; (2) Should we continue using the Eastern Mallard AHM process, but work to improve the models used to support the process?; (3) Should we continue using the same process, but consider a new suite of models?; (4) Should we consider an alternative process, other than Eastern Mallard AHM, for setting duck hunting regulations in the Atlantic Flyway?

Through a double-loop learning process (Johnson et al. 2015) in 2012, the AFC determined that the current Eastern Mallard AHM decision framework did not adequately address the fundamental objectives for duck harvest management in the Atlantic Flyway. Specifically, the AFC concluded that eastern mallards do not adequately represent duck harvest dynamics throughout the entire flyway, they do not represent the breeding ecology and habitat requirements of other important Atlantic Flyway duck species because their breeding range does not overlap with that of other ducks that breed in the flyway, and their breeding and/or wintering habitat needs differ from many of the other duck species in the flyway. Thus, the status (i.e., abundance, population trend, and harvest) of eastern mallards does not necessarily reflect that of other Atlantic Flyway species. For example, mallards in eastern North America have declined at an annual rate of 1% since 1998. This constitutes a 19% overall decline in eastern mallards since 1998. Over the same time period all other species in eastern North America for which we have robust population estimates are stable or increasing.

The AFC determined that a decision framework based upon a suite of duck species that better represent the habitat needs and harvest distribution of ducks in the Atlantic Flyway was more desirable than the current Eastern Mallard AHM framework. Development of a multiple species (hereafter, multi-stock) framework also allows managers to base harvest decisions on species that provide a more complete representation of habitats important to waterfowl in the Atlantic Flyway. Although habitat management was not part of the objectives (see below), a multi-stock framework would provide a more complete suite of habitats for managers to target when attempting to integrate harvest and habitat management as suggested in the 2012 North American Waterfowl Management Plan Revision. Accordingly, the USFWS and the AFC began working to develop a multi-stock AHM protocol for setting annual duck hunting season frameworks for the Atlantic Flyway.

As we worked toward developing a multi-stock framework, we initially included mallard in the framework because it is one of the most abundant and most harvested duck species in the flyway. However, we found that even though the biological models we are using in the multi-stock framework are more basic than those used in Eastern Mallard AHM, the model set performed poorly with mallard included, likely due to the same underlying difficulties experienced with the Eastern Mallard AHM models. We concluded that mallards should not be part of a multi-stock decision framework for setting the general duck season in the Atlantic Flyway. The USFWS conducted a separate assessment of harvest potential to inform decisions about bag limits for eastern mallards (see Roberts et al. 2018)

This report describes the processes we undertook during the development of multi-stock AHM, the options considered for various elements of the harvest strategy, and the process used to select a specific strategy for implementation.

OBJECTIVES

The AFC used a structured decision-making process to identify two fundamental objectives of duck harvest management in the Atlantic Flyway:

1. Sustain Atlantic Flyway duck populations at levels that meet the legal mandates and demands for the recreational uses of this resource, and
2. Maximize hunter satisfaction with harvest opportunity and regulations.

Next, they identified means objectives, that is, objectives that, if reached, would result in achievement of the fundamental objectives. For each means objective they identified performance metrics that would allow them to evaluate predicted performance of competing multi-stock harvest strategies. Means objectives associated with fundamental objective 1 were:

1. Do not allow any species to fall below the population level required for sustainability,
2. Make annual harvest management decisions based on representative species and habitats,
3. Maintain a desired level of abundance for important species, and
4. Determine and reach a duck carrying capacity objective for the Atlantic Flyway.

Means objectives associated with fundamental objective 2 were:

1. No closed seasons,
2. Maximize the percentage of satisfied hunters,
3. Simple regulations,
4. Hunters see lots of ducks, and
5. Minimize year to year changes in regulations.

The AFC selected a single performance metric to evaluate the performance of competing harvest strategies relative to sustaining Atlantic Flyway duck populations (fundamental objective 1): maximizing the predicted equilibrium breeding population size of each of the representative species used in the multi-stock framework. They developed four performance metrics to evaluate the performance of competing multi-stock harvest strategies relative to fundamental objective 2, maximizing hunter satisfaction with harvest opportunity and regulations:

1. Maximize predicted mean season length,
2. Minimize predicted frequency of annual regulatory changes,
3. Maximize predicted mean harvest, and
4. Maximize predicted fall flight (index to seeing ducks and having an opportunity to harvest them).

Finally, they went through a process of ranking and weighting the fundamental objectives and associated performance metrics, which affirmed to them that a duck harvest strategy was needed that takes into account those species that are important in the Atlantic Flyway, that represents the suite of habitats managers are trying to conserve and enhance, and that recognizes that within the bounds of sustainable harvest, harvest management strategies should be geared towards providing maximum satisfaction to the majority of the Atlantic Flyway waterfowl hunter constituency.

METHODS

Selection of Representative Species

We selected a suite of four species that we felt represented the dynamics of duck harvest in the Atlantic Flyway and the various habitat types used by waterfowl throughout the Atlantic Flyway: green-winged teal (*Anas crecca*), common goldeneye (*Bucephala clangula*; hereafter, goldeneye), ring-necked duck (*Aythya collaris*), and wood duck (*Aix sponsa*). These species comprise >40% of the Atlantic Flyway's total duck harvest, and they reflect regional variation in harvest composition; during the 2015 and 2016 hunting seasons, 87% of the goldeneye harvest occurred in northern states (New England, NY, PA and WV) and 91% of the ring-necked duck harvest occurred in southern states (NC, SC, GA and FL), whereas wood ducks and green-winged teal were important components of duck harvest throughout the flyway (Raftovich et al. 2017). The selected species represent upland nesters in boreal and southern Canada (green-winged teal), over-water nesters in boreal Canada (ring-necked duck), cavity nesters in the U.S. and southern Canada (wood duck), and cavity nesters in boreal Canada (goldeneye). The most important winter waterfowl habitats in the Atlantic Flyway (salt marsh, freshwater marsh, tidal waters, freshwater ponds and lakes, rivers and streams) are important to at least one of these four species. Species selection was also influenced by our need for sufficient time series of estimates of annual abundance and estimates of harvest rate or annual harvest.

Models and Data Sources

Population Modeling. We modeled the population dynamics for green-winged teal and wood duck (i.e., species with enough banding data to estimate harvest rate) assuming logistic growth, with harvest occurring after population growth, as:

$$N_{t+1} = N_t \left(1 + r\left(1 - \frac{N_t}{K}\right)\right)(1 - h),$$

where N = population size, r = the maximum intrinsic rate of population growth , K = carrying capacity, t = year, and h = harvest rate. The derivation of equilibrium dynamics for this model is provided in Koneff et al. 2017:S1. We used a similar model based on total harvest (H) for ring-necked duck and goldeneye:

$$N_{t+1} = N_t \left(1 + r\left(1 - \frac{N_t}{K}\right)\right) - H.$$

Derivation of the equilibrium dynamics for this model is described in Runge et al. (2004).

We used a state-space approach for estimation and to fit the parameters of the logistic model using Bayesian methods in program runjags (Denwood 20016), similar to those used for western mallard adaptive harvest management (USFWS 2017). Specifically, we used

Markov Chain Monte Carlo simulations to estimate the posterior distributions of r, K, and process error ($\sigma 2$) for the model. In addition, we scaled parameters in the discrete logistic model by K to improve convergence (Myer and Millar 1999). For K, we used a uniform prior between current population size (i.e., current harvest levels are completely compensatory) and double the current population size (i.e., populations are currently being harvested at maximum sustainable yield [MSY] and are at ½ K). Further, we extended the uniform prior 20% less and 20% greater than these end points (i.e., 20% less than the current mean population and 20% greater than 2 times the mean population size) to incorporate uncertainty associated with annual variability in the observed data. We used the demographic invariant method (Niel and Lebreton 2005) with survival rate estimates based on an allometric relationship between species mass and survival in captive birds (Johnson et al. 2012) to develop informed log normal priors for r. We used a non-informative inverse gamma prior for estimating process variation. We ran five chains for 20,000 iterations after a 100,000 iteration burn-in for each species. We assessed convergence by inspecting history plots and calculating Gelman-Rubin statistics (R-hat; Gelman and Hill 2007), and assumed R-hat values <1.1 indicated adequate convergence.

Population Estimates. We used population size estimates from the eastern portion of the Waterfowl Breeding Population and Habitat Survey (Fig. 1; Zimmerman et al. 2012) for ring-necked ducks, goldeneyes, and green-winged teal. This survey has been conducted consistently by the USFWS and Canadian Wildlife Service (CWS) since 1998. Population estimates were derived from integrating survey data from USFWS and CWS surveys into a single estimate. We integrated data from the Atlantic Flyway Breeding Waterfowl Plot Survey (Heusmann and Sauer 2000, Sauer et al. 2014) and the U.S. Geological Survey's Breeding Bird Survey to derive a population estimate for wood ducks from Florida north to Maine (Zimmerman et al. 2015).

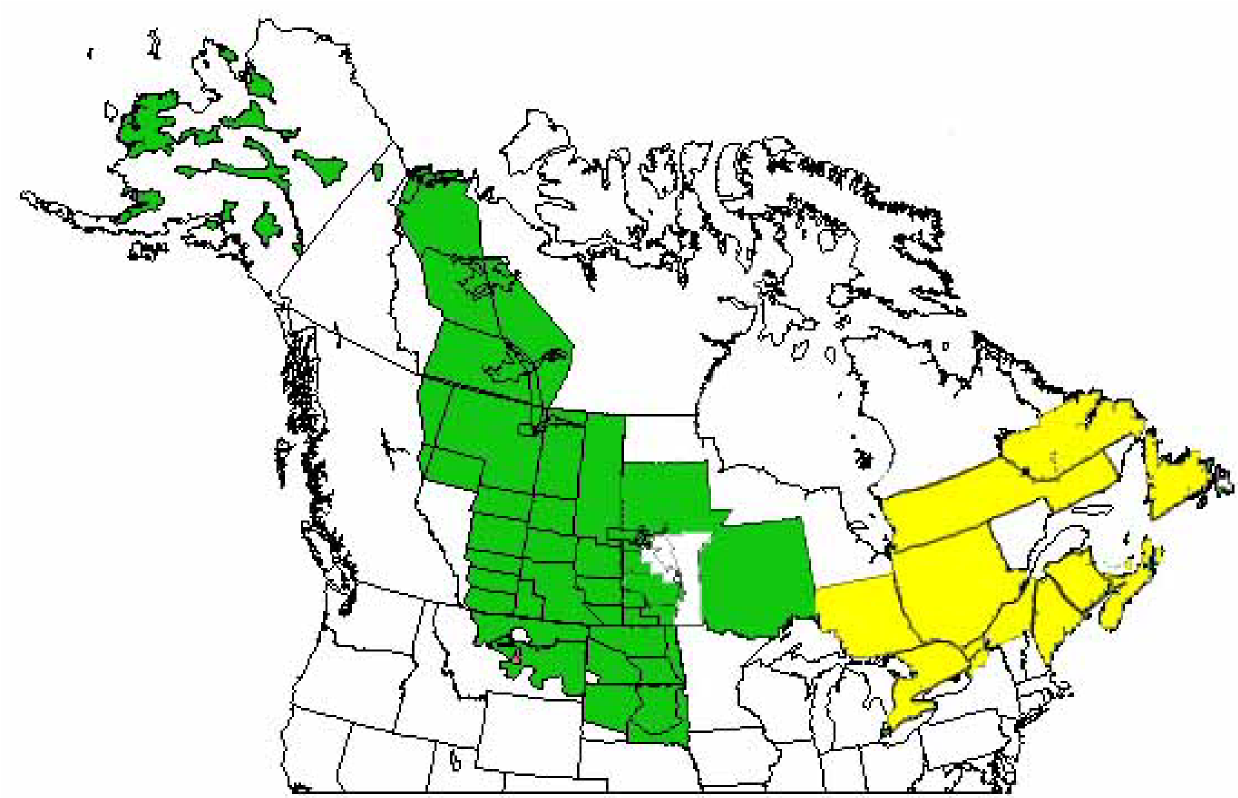

Figure 1. Coverage of the Waterfowl Breeding Population and Habitat Survey. The eastern portion of the survey is shown in yellow.

***Estimating Expected Species Harvest Rate Under Current Conditions*.** Duck hunting regulations have been liberal (i.e., 60-day season and a 6-bird daily bag limit) in the Atlantic Flyway since 1997. We estimated expected harvest rates and their associated variances for green-winged teal and wood ducks for the Atlantic Flyway's liberal regulatory alternative using birds banded in eastern Canada and the Atlantic Flyway (banding reference areas 8, 15, 16; the states of North Carolina, South Carolina, Georgia, and Florida; eastern Quebec; and the provinces of New Brunswick, Nova Scotia, Newfoundland and Labrador, and Prince Edward Island) during 1998-2014. We used these bands and their direct recoveries in binomial models to estimate direct recovery probabilities and then adjusted those recovery probabilities with regional reporting rates (birds banded in these areas were recovered in eastern Canada, the Atlantic Flyway, and Mississippi Flyway; Boomer et al. 2013) to estimate harvest rates (USFWS 2017). We pooled age and sex classes for this estimation because the discrete logistic model used for this assessment does not incorporate age structure. We used Bayesian methods and Markov chain Monte Carlo (MCMC) to estimate annual recovery probabilities and adjusted the recovery probabilities within the MCMC to obtain variances and incorporate uncertainty in the estimates of reporting rates. We used program JAGS (Plummer 2003) to analyze the band recovery data. We ran three chains for 60,000 iterations and used the first 50,000 iterations as a burn-in. We used the last 10,000 iterations to summarize means, variances, and quantiles for the parameters of interest (recovery and harvest rates). We assumed non-informative beta priors (i.e., dbeta[1,1]) for the recovery probabilities and calculated expected harvest rates as the mean of the annual estimates.

Banding and recovery data were insufficient for estimating the expected ring-necked duck and goldeneye harvest rates, so we used annual estimates of harvest (H) and population size instead. We estimated the annual fall population size (N_F) from direct estimates of the breeding population size (Runge et al. 2004), and then estimated the expected harvest rate as H/N_F. Therefore, the estimates of harvest rate for ring-necked duck and goldeneye were both calculated as a derived parameter in the discrete logistic model used to estimate r and K for the population. We used program JAGS (Plummer 2003) to fit the model and ran three chains for 1,000,000 (goldeneye) or 6,000,000 (ring-necked duck) iterations in an MCMC framework. We used the first 999,000 (goldeneye) or 5,999,000 (ring-necked duck) iterations as a burn-in. We estimated the variance for harvest rate as the standard deviation of the MCMC iterations saved after the burn-in period. Breeding population estimates for ring-necked ducks and goldeneyes in eastern North America were available beginning in 1998, therefore we estimated the expected harvest rate for both species based on 1998-2014 harvest and population estimates.

Estimating Species Harvest Rates under Alternative Season Lengths. The Atlantic Flyway has not experienced more restrictive duck hunting regulations (e.g., 30-day season and a 3-bird limit) since the early 1990s. Furthermore, pre-season duck banding efforts in eastern North America were limited until the 1990s. Therefore, we relied on data collected through the annual USFWS's Parts Collection Survey (PCS) to estimate expected harvest rates during seasons of <60 days and/or bag limits of <6 birds. The PCS asks participating hunters to send in a wing from every duck they shoot throughout the entire hunting season, and to report the state in which the duck was harvested and the date it was shot (Martin and Carney 1977). The species of a duck can be identified from its wing plumage (Carney 1992); thus, the PCS provides species-specific data on both the spatial and temporal distribution of the annual duck harvest and on bag size frequencies. We estimated the effect of reduced season length separately from the effect of bag limit reduction.

We used harvest date, number of wings received and species composition data from 2004-2013 (n = 60,427 individual hunts in the Atlantic Flyway during which at least one duck was harvested) to estimate the expected reduction in harvest during seasons shorter than 60 days. Atlantic Flyway states employ both zones and split seasons (Federal Register Vol. 80 No. 151 p. 47394) to maximize the hunting opportunity afforded by a given season length. Consequently, the temporal distribution of annual PCS wing receipts was never confined to 60 consecutive days in any state, and simply subtracting the wings from birds shot during a given period was insufficient for estimating expected harvest for a specified season length. Instead, we truncated the state- and year-specific temporal distributions to, for example, 1/2 of the total number of actual hunting days to represent a 30-day season, by removing the consecutive days with the least amount of harvest. Then we calculated the expected reduction for each species (season length effect) as the number of wings from birds shot during the removed days divided by total wings received for that species. Because the harvest of the four species varied geographically due to differences in migration patterns and winter distributions among the species (Baldassarre 2014), we stratified the states into northern (New England, NY, PA and WV), mid-Atlantic (NJ, MD, DE and VA), and southern regions (NC, SC, GA and FL). The expected reduction for each region was then weighted by the proportion of total flyway harvest of that species that occurred in the region. We summed the weighted regional reductions to estimate the expected flyway-wide reduction in harvest of each species.

Estimating Species Harvest Rates under Alternative Season Length and Bag Limits. We used daily bag composition data from the PCS to estimate the proportional reduction in harvest of each species that was expected to result from smaller bag limits under the moderate and restrictive regulatory alternatives (bag limit effect), following methods described by Martin and Carney (1977) and Balkcom et al. (2010). For each of the four species, we then summed the expected flyway-wide reductions due to reduced season lengths and the expected reduction due to a smaller bag limits to estimate total expected reductions (er) as proportions of the harvest under the liberal regulatory alternative. We estimated the expected harvest rate (h_e) under the moderate and restrictive alternatives from the estimates of er and estimates of mean harvest rate under the liberal regulatory alternative (h), as

$$h_e = h\,(1-er).$$

We were unable to the estimate the variances of er estimates directly, so we used the CV estimates for h to develop the probability distributions for the estimates of h_e.

These methods assume that (1) all PCS participants send in a wing from every duck they shoot throughout the hunting season; (2) effects of reduced season length and bag limit reduction are additive; (3) hunters do not adjust to shorter seasons by hunting the same number of days they do during longer seasons; and (4) the number of active duck hunters does not change when seasons and bag limits are reduced.

In 2016 the AFC recommended to the USFWS that the ending framework date for the general duck season be changed from the last Sunday in January to a fixed date of January 31, during years when the optimal regulatory alternative is either a liberal or a moderate season. In order to incorporate this request, we relied on the observed effect of a 16-day framework date extension implemented in 2002 that increased the mallard harvest rate by 0.0052 (USFWS 2016, Appendix G). We estimated a mean additional extension of 3 days for the January 31 fixed ending date, and assumed that the effect per day would be the same as the observed per day effect of the previous extension. The resulting predicted increase in harvest rate (3/16 X 0.0052 = 0.000975) was added to the estimates of h_e for the liberal and moderate alternatives.

Optimization and Simulation

We used stochastic dynamic programming (Chadès et al. 2014) to calculate an optimal regulatory policy that would achieve the duck harvest objective over an infinite time horizon. The optimal policy is derived 1 year (*t*) prior to the start of the hunting season (*t+1*). The resulting policy is state dependent relative to the most recently observed population size (N_t) and most recently implemented regulatory package (*t-1*) (Johnson et al. 2016). The optimal policies were calculated for a coarse grid of potential population sizes to help overcome the computational "curse of dimensionality" (Walters 1986). Previous analyses with fewer species suggested that the reduction in performance of an optimal policy based on a coarse rather than a fine grid of population sizes is minimal. The only stochasticity explicitly considered was the species-specific process errors for the logistic models, and we assumed these were independent. To calculate an optimal policy we used the publicly available software MDPSOLVE (https://sites.google.com/site/mdpsolve/home), which is a set of software tools, written in the MATLAB programming language, for solving dynamic optimization problems.

An optimal policy is a large table showing the appropriate harvest regulation for all possible combinations of the coarse grid species-specific population sizes that might be observed prior to a regulatory decision. Because the table is difficult to visualize effectively, we fit a classification tree (Ripley 2016) to the policy. A classification tree is a dichotomous key that captures the key features of the optimal policy by highlighting important patterns. We stress that a classification tree is not the optimal policy itself, but a simplified version (model) of the optimal policy.

We simulated (actual) optimal policies using the R program language (R Core Team 2016). We were principally interested in harvest statistics in the aggregate and for individual species, as well as expected species-specific population sizes. Also of interest were statistics describing use of the various regulatory frameworks under consideration. We simulated harvests and population sizes for 50 years, discarding the first 25 years to avoid the influence of initial conditions, and conducted 1,000 replications of the aggregate policies.

Harvest Strategy Development

Finalizing a harvest strategy required decisions about three important elements: a harvest objective function used in the optimization routine, the relative importance of each of the four species in the Atlantic Flyway harvest process, and the regulatory alternatives that will be used in the strategy. We examined and compared the consequences of scenarios consisting of each of these elements in a multi-criteria decision analysis. We considered three options for a harvest objective function that would apply to each of the four species: MSY, 98% of MSY, and 95% of MSY. The MSY option was quickly rejected and we proceeded with the remaining two objective functions. Options considered for relative species importance were: (1) equal importance (i.e., a weight of 0.25 for each of the four species), (2) importance weights based on each species' relative contribution to the total duck harvest in the Atlantic Flyway, 1999 - 2015, and (3) weights based on regional estimates of hunter effort (i.e., hunter days) and then weighted by species harvest proportion in that region, to account for regional differences in how important each species is to hunters. Finally, the AFC selected three sets of regulatory alternatives for examination: (1) a "liberal" alternative with a season length of 60 days and a daily bag limit of 6 ducks (60 and 6), a 45 and 6 "moderate" season alternative, a 30 and 3 "restrictive" season alternative, and a closed season in the U.S.; (2) liberal, moderate, and restrictive season alternatives of 60 and 4, 45 and 4, and 30 and 3, respectively, along with a closed season alternative; and (3) a "standard" season alternative of 50 and 5, a 30 and 3 restrictive alternative, and a closed season alternative.

Swing Weighting and Multi-criteria Trade-off Analysis

We used the results of the simulations to calculate the five performance metrics for each of the 18 competing scenarios. The nine scenarios that included the 95% of MSY objective function performed poorly across all four hunting opportunity metrics and were discarded from subsequent evaluation. The estimated equilibrium population size (in the aggregate) exhibited very little variation among the competing scenarios. Due to that limited variation this metric was not useful for discriminating among competing scenarios (i.e., it was a non-informative performance metric) and was discarded from subsequent deliberations. We conducted a swing weighting exercise (Goodwin and Wright 2004) based on the four hunting opportunity metrics to determine the importance of each metric to the AFC. We applied the resulting weights to the nine competing scenarios (all consisting of a 98% of MSY objective function) in a multi-criteria trade-off analysis to rank the alternatives and facilitate negotiation among AFC members to select an agreed-upon final harvest strategy consisting of (1) a harvest objective function, (2) species weights, and (3) regulatory alternatives.

RESULTS

Multi-Stock AHM Model Development

Expected harvest rates under the regulatory alternatives that we considered are shown in Table 1. We initially simulated optimal policies for multi-stock frameworks that included mallard as a fifth species. The AFC examined the resulting performance metrics for each scenario and selected the scenario with a harvest objective of 98% of MSY, regulatory alternatives of 60 and 6, 45 and 6, 30 and 3, and a closed season, and species weighting based on regional hunter effort. However, we subsequently decided to remove mallards from the multi-stock frameworks, so we repeated the simulations with mallards excluded. The AFC had clearly preferred 98% of MSY as their harvest objective previously; therefore, we only repeated the simulations and re-estimated performance metrics for the scenarios with that harvest objective (Table 2). The AFC again selected the scenario with a harvest objective of 98% of MSY, regulatory alternatives of 60 and 6, 45 and 6, 30 and 3, and a closed season, and species weighting based on regional hunter effort. At its meeting on March 27, 2018, the AFC recommended that the USFWS adopt that scenario as the framework for the Atlantic Flyway's multi-stock AHM strategy, and implement the strategy to set the 2019-20 duck hunting regulations for the Atlantic Flyway.

Table 1. Expected harvest rates (SE) of green-winged teal, wood ducks, ring-necked ducks, and common goldeneyes under various combinations of season length and duck bag limit in the Atlantic Flyway. The wood duck bag limit remains at three for duck bag limits >3.

		Species			
Season length	Daily bag limit	Green-winged teal	Wood duck	Ring-necked duck	Common goldeneye
60	6	0.117 (0.019)	0.124 (0.015)	0.130 (0.014)	0.029 (0.0018)
60	4	0.114 (0.019)	0.124 (0.015)	0.121 (0.013)	0.028 (0.0017)
50	5	0.106 (0.018)	0.112 (0.014)	0.117 (0.013)	0.025 (0.0015)
45	6	0.089 (0.015)	0.091 (0.011)	0.097 (0.011)	0.015 (0.0009)
45	4	0.086 (0.014)	0.091 (0.011)	0.088 (0.010)	0.015 (0.0009)
30	3	0.057 (0.009)	0.075 (0.009)	0.058 (0.006)	0.008 (0.0005)
0	0	0.017 (0.003)	0.006 (0.007)	0.025 (0.003)	0.005 (0.0003)

Table 2. Expected performance of nine potential multi-stock harvest management frameworks based on four performance metrics that reflect harvest management objectives that are important in the Atlantic Flyway.

Scenario descriptions		Performance metrics (means)			
Species weights	Regulatory alternatives	Years between regulatory change	Season length (days)	Bird index (millions)	Annual harvest
Equal	Current	2.56	57.06	4.51	591,800
Equal	Reduced bag	3.15	57.65	4.53	588,400
Equal	Standard	4.99	48.10	4.72	564,100
Days hunted	Current	2.63	57.21	4.50	592,600
Days hunted	Reduced bag	3.28	57.78	4.52	589,000
Days hunted	Standard	6.64	48.60	4.69	567,800
Harvest	Current	4.87	57.09	4.50	592,300
Harvest	Reduced bag	6.66	57.93	4.51	590,300
Harvest	Standard	5.34	48.20	4.71	564,700

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