A Proposed Protocol for the Adaptive Harvest Management of Mallards Breeding in Western North America

March 7, 2007

Executive Summary

Recent efforts to develop Flyway-specific harvest strategies have focused on the large number of mallards (*Anas platyrhnychos*) found during the breeding season in the states of the Pacific Flyway (including Alaska), British Columbia, and the Yukon Territory. The distribution of these mallards during fall and winter is centered in the Pacific Flyway. This report describes a proposed protocol for the adaptive harvest management (AHM) of these mallards that could be implemented as early as the 2007 hunting season.

Although we define western mallards as those breeding in Alaska, Yukon, British Columbia, and the lower Pacific Flyway States, we were concerned about our ability to reliably determine changes in the overall population size based on the collection of surveys conducted independently by Pacific Flyway States and the Province of British Columbia. These surveys tend to vary in design and intensity, and in some cases lack measures of precision. Therefore, we reviewed extant surveys to determine their adequacy for supporting a western-mallard AHM protocol, and ultimately selected Alaska, California, and Oregon for modeling purposes. These three states likely harbor about 75% of the western-mallard breeding population. Nonetheless, this geographic delineation is considered temporary until surveys in other areas can be brought up to similar standards and an adequate record of population estimates is available for analysis.

For modeling purposes we treated Alaska mallards independently of those in California and Oregon because of differing population trajectories and distribution of band recoveries. We relied on a discrete logistic model, which combines reproduction and natural mortality into a single parameter r, the intrinsic rate of growth. The model assumes density-dependent growth, which is regulated by the ratio of population size, N, to the carrying capacity of the environment, K (i.e., population size in the absence of harvest). In the traditional formulation, harvest mortality is additive to other sources of mortality, but compensation for hunting losses can occur through subsequent increases in production. However, we parameterized the model in a way that also allows for compensation of harvest mortality between the hunting and breeding seasons.

We used Bayesian estimation methods in combination with a state-space model that accounts explicitly for both process and observation error in breeding population size. Breeding population estimates of mallards in Alaska are available since 1955, but we had to limit the time-series to 1990-2005 because of changes in survey methodology and insufficient band-recovery data. The logistic model and associated posterior parameter estimates provided a reasonable fit to the observed time-series of Alaska population estimates. The estimated carrying capacity was 1.2 million, the intrinsic rate of growth was 0.31, and harvest mortality acted in an additive fashion. Breeding population and harvest-rate data were available for California-Oregon mallards for the period 1992-2006. The logistic model also provided a reasonable fit to these data, suggesting a carrying capacity of 0.7 million, an intrinsic rate of growth 0.34, and harvest mortality that acted in a partially compensatory manner.

For the purpose of understanding general patterns in optimal harvest rates, we assumed perfect control over harvest and evaluated state-dependent harvest rates from 0.0 to 0.25 in increments of 0.05. We examined two different management objectives conditioned on this set of harvest rates: (1) maximize long-term cumulative harvest; and (2) attain approximately 90% of the maximum long-term cumulative harvest. For an objective to maximize long-term cumulative harvest, there were many combinations of stock sizes that had harvest-rate prescriptions of either 0 or 25 percent. Very few stock sizes had intermediate harvest-rate prescriptions. In contrast, an objective to attain 90% of the maximum yield produced an optimal strategy with a more even distribution of available harvest rates, and very few prescriptions for closed seasons.

Empirical estimates of harvest rates showed no obvious response to changes in regulations, based on extensive analyses using a variety of regulatory metrics, including season length, mallard bag limits, and framework opening and closing dates (singly and in combination). We were forced to conclude that changes in regulations in the Pacific

Flyway since 1980 have not resulted in significant changes in the harvest rates of western mallards. It appears that more extreme regulatory changes than those used in the past may be needed to effect substantive changes in harvest rates. To help understand the implications of this apparent lack of control over harvest rates, we assumed the most extreme case of two regulatory options: a closed season and an open season. We assumed that an open season would produce a harvest rate of 0.1259 (the mean of all our estimates) and that a closed season would produce a harvest rate of 0.0. We then conducted an optimization to determine the population thresholds for season closures assuming minimal control over harvest rates. Generally, as long as both stocks are above about 250k, then the optimal choice is an open season. Below that, the lower one stock is, the higher the other has to be to maintain an open season.

We believe that the models presented in this report provide a sufficient basis for developing an initial AHM protocol. Moreover, extant monitoring of mallard abundance and harvest rates in Alaska and California-Oregon will provide the necessary basis for updating model parameter estimates and their associated probabilities. Similarly, we believe that sufficient information is available to inform the choice of an objective function for western mallards. In particular, an objective to attain 90% of the maximum long-term cumulative harvest provides for levels of hunting opportunity that are similar to those now in effect for a wide range of stock sizes. On a more pessimistic note, we were unable to establish a viable set of regulatory alternatives with which to effect changes in harvest rate. Therefore, an essential task is consideration of hunting regulations beyond the realm of experience that might be expected to have a meaningful effect on harvest rates. Until such time this task is completed, however, we believe a derived strategy of optimal harvest rates can provide sufficient guidance for managing the western mallard population.

Ideally, the development of AHM protocols for mallards would consider how different breeding stocks distribute themselves among the four flyways so that Flyway-specific harvest strategies could account for the mixing of birds during the hunting season. At present, however, a joint optimization of western, mid-continent, and eastern stocks is not feasible. We are therefore proposing that the initial AHM protocol for western mallards be structured similarly to that used for eastern mallards, in which an optimal harvest strategy is based on the status of a single breeding stock and harvest regulations in a single flyway. Although the contribution of mid-continent mallards to the Pacific Flyway harvest is significant, we believe an independent harvest strategy for western mallards poses little short-term risk to the mid-continent stock. And over the longer term, we believe that the current hurdles to deriving joint harvest strategies can be overcome.

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Introduction

Significant numbers of breeding mallards occur from the northern U.S. through Canada and into Alaska. Geographic differences in the reproduction, mortality, and migrations of these mallards suggest that there may be corresponding differences in optimal levels of sport harvest. The ability to regulate harvests of mallards originating from various breeding areas is complicated, however, by the fact that a large degree of mixing occurs during the hunting season. The challenge for managers, then, is to vary hunting regulations among Flyways (or other agreed-upon harvest units) in a manner that recognizes each Flyway's unique breeding-ground derivation of mallards. Of course, no Flyway receives mallards exclusively from one breeding area, and so Flyway-specific harvest strategies ideally must account for multiple breeding stocks that are exposed to a common harvest.

The optimization procedures used in adaptive harvest management (AHM) can account for breeding populations of mallards beyond the mid-continent region, and for the manner in which these ducks distribute themselves among the Flyways during the hunting season. An optimal approach would allow for Flyway-specific regulatory strategies, which in a sense represent for each Flyway an average of the optimum harvest strategies for each contributing breeding stock, weighted by the relative size of each stock in the fall flight. This "joint optimization" of multiple mallard stocks requires:

(a) models of population dynamics for all recognized stocks of mallards;
(b) an objective function that accounts for harvest-management goals for all mallard stocks in the aggregate, as well as associated regulatory constraints; and
(c) decision rules allowing Flyway-specific regulatory choices.

Since 2000, AHM protocols have recognized a mid-continent and eastern stock of mallards. Optimal harvest strategies for these stocks currently are derived using a constrained approach, in which the Atlantic Flyway regulatory strategy is based exclusively on the status of eastern mallards, and the regulatory strategy for the remaining Flyways is based exclusively on the status of mid-continent mallards. This approach is not completely satisfactory, however, because it does not account for a large number of eastern mallards that winter in the Mississippi Flyway and for a small, but regionally important, component of mid-continent mallards that winters in the southern Atlantic Flyway. However, we have encountered a number of analytical, computational, and policy difficulties in developing a joint harvest strategy for eastern and mid-continent mallards; we will elaborate on these difficulties in a later section of this report.

Recent efforts to develop Flyway-specific harvest strategies have focused on the large number of mallards found in the states of the Pacific Flyway (including Alaska), British Columbia, and the Yukon Territory during the breeding season. The distribution of these mallards during fall and winter is centered in the

Pacific Flyway. Efforts to understand the population dynamics of these mallards have been underway for several years and the Pacific Flyway States, the U.S. Fish and Wildlife Service (USFWS), and the Canadian Wildlife Service (CWS) have collaborated extensively to improve survey and banding programs. Extensive research also has been conducted by the New York Cooperative Fish and Wildlife Research Unit and the University of Nevada Reno to help understand the harvest potential of western mallards through the development of population models.

The purpose of this report is to describe the development of a proposed AHM protocol for western mallards that could be implemented as early as the 2007-08 hunting season. We have organized this report into the following major sections:

(1) spatial delineation of western mallards
(2) population modeling and estimation
(3) implications of population models for harvest management
(4) regulating the harvest of western mallards
(5) a proposed AHM protocol for 2007

Acknowledgements.—Efforts to produce an AHM protocol for western mallards dates back to at least 1999. Production of this report thus depended on the work of many other scientists involved in those efforts, especially Drs. Sue Sheaffer, Rich Malecki, Mark Herzog, James Sedinger, and Mike Conroy. We also note that the valuable work of these scientists would not have been possible without funding provided by the USFWS, the CWS, the Pacific Flyway Council, the States of California and Oregon, the California Waterfowler's Association, and Ducks Unlimited, Inc. Finally, we are grateful for the guidance of the Adaptive Harvest Management Working Group, which is comprised of a large and diverse collection of federal, state, and provincial scientists and managers.

Delineation of Western Mallards

For our purposes we accepted Sheaffer and Malecki's (1999) and Herzog and Sedinger's (2004) spatial delineation of western mallards, which includes birds breeding in Alaska, Yukon, British Columbia, and the lower Pacific Flyway States. Although significant numbers of mallards wintering in the Pacific Flyway also originate from southern Alberta, we believed that including them in the definition of western mallards was not justified at this time because it would have required the simultaneous development of new population models for mid-continent mallards. Moreover, the population dynamics of Alberta mallards are likely more similar to those of other mallards in the Great Plains than those of the Pacific Coast. Thus, the potential for addition spatial heterogeneity in the population dynamics of western mallards was a concern from a modeling and estimation perspective.

Even within our limited spatial delineation of western mallards, extant data-collection programs necessary for understanding population dynamics are highly fragmented in both time and space. Monitoring programs also vary greatly in sampling design and statistical rigor. These facts make it difficult to aggregate population estimates in a way that can be used to reliably monitor and model the dynamics of western mallards and, thus, to establish criteria for regulatory decision-making under AHM.

In particular, we were concerned about our ability to reliably determine changes in the population size of western mallards based on a collection of surveys conducted independently by Pacific Flyway States and the Province of British Columbia. These surveys tend to vary in design and intensity, and in some cases lack measures of precision (i.e., sampling error). British Columbia is of particular concern because of its relatively large breeding population. Unfortunately, methods for estimating mallard abundance in British Columbia are still in the development and evaluation phase, and there are as yet unanswered questions about how mallard abundance will be determined there on an operational basis. On a more positive note, helicopters are currently being evaluated for use in surveys that eventually could cover the majority of key waterfowl habitats in British Columbia.

During 2005 we reviewed extant surveys to determine their adequacy for supporting a western-mallard AHM protocol. We were principally interested in whether the extant surveys: (a) estimate total birds (rather than breeding pairs); (b) have a sound sampling design (and SEs available); (c) consider imperfect detection of birds; and (d) require data augmentation (i.e., filling missing years). Based on these criteria, Alaska, California, and Oregon were selected for modeling purposes. These three states likely harbor about 75% of the western-mallard breeding population (Fig. 1). Nonetheless, this geographic definition is considered temporary until such time that surveys in other areas can be brought up to similar standards and an adequate record of population estimates is available for analysis.

For modeling purposes we were hesitant to pool Alaska mallards with those in California and Oregon because of differing population trajectories (Fig. 2), and because we believed it likely that different environmental driving variables were at play during the breeding season in northern and southern latitudes. Mallards banded in Alaska and in California/Oregon also had different distributions of direct band recoveries, suggesting that these two groups of mallards may be subject to different mortality factors during the non-breeding season (Fig. 3).

Although we eventually accounted for potential differences in demography of the Alaskan and California/Oregon stocks, we had to make the simplifying assumption that the two stocks were closed to immigration and emigration. However, we did examine breeding-population surveys for circumstantial evidence of large-scale directional movement between mallard stocks. To our surprise, there appeared to be little in the way of directional movement between birds breeding in Alaska and those in the remainder of the range of mid-continent mallards (i.e., no suggestion of “over-flights” of mid-continent mallards to Alaska in dry years in the prairies and parklands) (Fig. 4a). However, there was a negative (albeit non-significant) relationship between changes in population size of Alaska and California/Oregon mallards (Fig. 4b) but it is unclear whether this was the result of simultaneous shifts in the distribution of these two stocks. Rather, it may have been a function of the Pacific Southern Oscillation, which whether at a peak (El Niño) or a trough (La Niña) tends to produce contrasting environmental conditions along the northern and southern Pacific Coasts (www.wrcc.dri.edu/enso/ensofaq.html). Finally, changes in population size of mallards in California/Oregon and the mid-continent region tended to be positively related (Fig. 4c), but this could be due to large-scale weather patterns that result in a positive correlation between the incidence of drought in the prairies and in California and Oregon. In any case, based on these patterns, we were comfortable with a closure assumption as a first approximation for modeling population dynamics.

Modeling and Estimation

The Discrete Logistic Growth Model

In contrast to earlier investigators, we did not model changes in population size of western mallards as an explicit function of survival and reproductive rate estimates (which in turn may be functions of harvest and environmental covariates). We believed this so-called “balance-equation approach” was not viable for western mallards because of insufficient banding in Alaska to estimate survival rates, and because of the difficulty in estimating stock-specific fall age ratios from a sample of wings derived from a mix of breeding stocks. We therefore relied on a discrete logistic model (Schaefer 1954), which combines reproduction and natural mortality into a single parameter r, the intrinsic rate of growth. The model assumes density-dependent growth, which is regulated by the ratio of population size, N, to the carrying capacity of the environment, K (i.e., population size in the absence of harvest). In the traditional formulation, harvest mortality is additive to other sources of mortality, but compensation for hunting losses can occur through subsequent increases in production. However, we parameterized the model in a way that also allows for compensation of harvest mortality between the hunting and breeding seasons. It is important to note that compensation modeled in this way is purely phenomenological, in the sense that there is no explicit ecological mechanism for compensation (e.g., density-dependent mortality after the hunting season).

The basic model for both the Alaska and California/Oregon stocks had the form:

$$N_{t+1} = \left[N_t + N_t r \left(1 - \frac{N_t}{K} \right) \right] \left(1 - \alpha_t \right)$$
$$where \quad \alpha_t = d \cdot h_t^{AM}$$

and where t = year, h^{AM} = the harvest rate of adult males, and d = a scaling factor. The scaling factor is used to account for a combination of unobservable effects, including un-retrieved harvest (i.e., crippling loss), differential harvest mortality of cohorts other than adult males, and for the possibility that some harvest mortality may not affect subsequent breeding-population size (i.e., the compensatory mortality hypothesis).

Estimation framework

We used Bayesian estimation methods in combination with a state-space model that accounts explicitly for both process and observation error in breeding population size. This combination of methods is becoming widely used in natural resource modeling, in part because it facilitates the fitting of non-linear models that may have non-normal errors (Meyer and Millar 1999). The Bayesian approach also provides a natural and intuitive way to portray uncertainty, allows one to incorporate prior information about model parameters, and permits the updating of parameter estimates as further information becomes available.

We first scaled N by K as recommended by Meyer and Millar (1999), and assumed that process errors e_t were log-normally distributed with mean 0 and variance σ^2. Thus, the process model had the form:

$$P_t = N_t / K_t$$

$$\log(P_t) = \log\{[P_{t-1} + P_{t-1} r (1 - P_{t-1})](1 - d \cdot h_{t-1}^{AM})\} + e_t$$

$$where \quad e_t \sim N(0, \sigma^2)$$

The observation model related the unknown population sizes ($P_t K$) to the population sizes (N_t) estimated from the breeding-population surveys in Alaska and California/Oregon. We assumed that the observation process yielded additive, normally distributed errors, which were represented by:

$$N_t = P_t K + \varepsilon_t^{BPOP} ,$$

$$where \quad \varepsilon_t^{BPOP} \sim N(0, \sigma_{BPOP}^2) .$$

Use of the observation model allowed us to account for the sampling error in population estimates, while permitting us to estimate the process error, which reflects the inability of the model to completely describe changes in population size. The process error reflects the combined effect of misspecification of an appropriate model form, as well as any un-modeled environmental drivers. We initially examined a number of possible environmental covariates, including the Palmer Drought Index in California and Oregon, spring temperature in Alaska, and the El Niño Southern Oscillation Index (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/mei.html). While the estimated effects of these covariates on r or K were generally what one would expect, they were never of sufficient magnitude to have a meaningful effect on optimal harvest strategies. We therefore chose not to further pursue an investigation of environmental covariates, and posited that the process error was a sufficient surrogate for these un-modeled effects.

Parameterization of the models also required measures of harvest rate. Beginning in 2002, harvest rates of adult males were estimated directly from the recovery of reward bands. Prior to 1993, we used direct recoveries of standard bands, corrected for band-reporting rates provided by Nichols et al. (1995). We also used the band-reporting rates provided by Nichols et al. (1995) for estimating harvest rates in 1994 and 1995, except that we inflated the reporting rates of full-address and toll-free bands based on an unpublished analysis by Clint Moore and Jim Nichols (Patuxent Wildlife Research Center). We were unwilling to estimate harvest rates for the years 1996-2001 because of suspected, but unknown, increases in the reporting rates of all bands. For simplicity, harvest rate estimates were treated as known values in our analysis, although future analyses might benefit from an appropriate observation model for these data.

In a Bayesian analysis, one is interested in making probabilistic statements about the model parameters (θ), conditioned on the observed data. Thus, we are interested in evaluating P(θ|data), which requires the specification of prior distributions for all model parameters and unobserved system states (θ) and the sampling distribution (likelihood) of the observed data P(data| θ). Using Bayes theorem, we can represent the posterior probability distribution of model parameters, conditioned on the data, as:

$$P(\theta \mid data) \propto P(\theta) \times P(data \mid \theta) .$$

Accordingly, we specified prior distributions for model parameters r, K, d, and P_0, which is the initial population size relative to carrying capacity. For both stocks, we specified the following prior distributions for r, d, and σ^2:

$$r \sim Log-normal(-1.0397, 1.4427)$$

$$d \sim Uniform(0, 2)$$

$$\sigma^2 \sim Inverse-gamma(0.001, 0.001)$$

The prior distribution for r is centered at 0.35, which we believe to be a reasonable value for mallards based on life-history characteristics and estimates for other avian species. Yet the distribution also admits considerable uncertainty as to the value of r within what we believe to be realistic biological bounds (Fig. 5). As for the harvest-rate scalar, we would expect $d \geq 1$ under the additive hypothesis and $d < 1$ under the compensatory hypothesis. As we had no data to specify an informative prior distribution, we specified a vague prior in which d could take on a wide range of values with equal probability. We used a traditional, uninformative prior distribution for σ^2. Prior distributions for K and P_0 were stock-specific and are described in the following sections.

We used the public-domain software WinBUGS (http://www.mrc-bsu.cam.ac.uk/bugs/) to derive samples from the joint posterior distribution of model parameters via Markov-Chain Monte Carlo (MCMC) simulations. We obtained 510,000 samples from the joint posterior distribution, discarded the first 10,000, and then thinned the remainder by 50, resulting in a final sample of 10,000. The data and the WinBUGS code to fit the logistic model for both the Alaska and California-Oregon stock are provided in the Appendix.

Alaska mallards

Data selection.--Breeding population estimates of mallards in Alaska (and the Old Crow Flats in Yukon) are available since 1955 in federal survey strata 1-12 (Smith 1995). However, a change in survey aircraft in 1977 instantaneously increased the detectability of waterfowl, and thus population estimates (Hodges et al. 1996). Moreover, there was a rapid increase in average annual temperature in Alaska at the same time, apparently tied to changes in the frequency and intensity of El Niño events (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/mei.html). This confounding of changes in climate and survey methods led us to truncate the years 1955-1977 from the time series of population estimates.

Modeling of the Alaska stock also depended on the availability of harvest-rate estimates derived from band-recovery data. Unfortunately, sufficient numbers of mallards were not banded in Alaska prior to 1990. A search for covariates that would have allowed us to make harvest-rate predictions for years in which band-recovery data were not available was not fruitful, and we were thus forced to further restrict the time-series to 1990-2005. Even so, harvest rate estimates were not available for the years 1996-2001 because of unknown changes in band-reporting rates. Because available estimates of harvest rate showed no apparent trend over time, we simply used the mean and standard deviation of the available estimates and generated independent samples of predictions for the missing years based on a logit transformation and an assumption of normality:

$$\ln\left(\frac{h_t}{1-h_t}\right) \sim Normal(-2.3227, 0.0931) \quad for\ t = 1996 - 2001$$

Prior distributions for K and P_0.—We believed that sufficient information was available to use mildly informative priors for K and P_0. In recent years the Alaska stock has contained approximately 0.8 million mallards. If harvest rates have been comparable to that necessary to achieve maximum sustained yield (MSY) under the logistic model (i.e., $r/2$), then we would expect $K \approx 1.6$ million. On the other hand, if harvest rates have been less than those associated with MSY, then we would expect $K < 1.6$ million. Because we believed it was not likely that harvest rates were $>r/2$, we believed the likely range of K to be 0.8 – 1.6 million. We therefore specified a prior distribution that had a mean of 1.4 million, but had a sufficiently large variance to admit a wide range of possible values (Fig. 6):

$$K \sim Log-normal(0.13035, 0.41224)$$

Extending this line of reasoning, we specified a prior distribution that assumed the estimated population size of approximately 0.4 million at the start of the time-series (i.e., 1990) was 20-60% of K. Thus on a log scale:

$$P_o \sim Uniform(-1.6094, -0.5108)$$

Parameter estimates.—The logistic model and associated posterior parameter estimates provided a reasonable fit to the observed time-series of population estimates (Fig. 7). The posterior means of K and r were similar to their priors, although their variances were considerably smaller (albeit still large) (Table 1). However, the posterior distribution of d was essentially the same as its prior, reflecting the absence of information in the data necessary to reliably estimate this parameter.

Table 1. Estimates of model parameters resulting from fitting a discrete logistic model with MCMC to a time-series of estimated population sizes and harvest rates of mallards breeding in Alaska, 1990-2005.

Parameter	Mean	SD	95% credibility interval
K	1.217	0.319	0.765 – 1.782
P_0	0.315	0.088	0.209 – 0.491
d	1.002	0.541	0.138 – 1.874
r	0.312	0.126	0.126 – 0.530
σ^2	0.021	0.014	0.006 – 0.047

California-Oregon mallards

Data selection.—Breeding-population estimates of mallards in California are available starting in 1992, but not until 1994 in Oregon. Also, Oregon did not conduct a survey in 2001. In order to avoid truncating the time-series, we used the admittedly weak relationship (P = 0.19) between California and Oregon population estimates to predict population sizes in Oregon in 1992, 1993, and 2001. The fitted linear model was:

$$\ln\left(N_t^{OR}\right) = 8.03 + 0.28 \cdot \ln\left(N_t^{CA}\right).$$

To derive realistic standard errors, we assumed that the predictions had the same mean coefficient of variation as the years when surveys were conducted (n = 11, CV = 0.115). The estimated sizes and variances of the California-Oregon stock were calculated by simply summing the state-specific estimates.

We pooled banding and recovery data for California and Oregon and estimated harvest rates in the same manner as that for Alaska mallards. Although banded sample sizes were sufficient in all years, harvest rates could not be estimated for the years 1996-2001 because of unknown changes in band-reporting rates. As with Alaska, available estimates of harvest rate showed no apparent trend over time, and we simply used the mean and standard deviation of the available estimates and generated independent samples of predictions for the missing years based on a logit transformation and an assumption of normality:

$$\ln\left(\frac{h_t}{1-h_t}\right) \sim Normal\left(-1.9518,\ 0.0373\right) \quad for\ t = 1996 - 2001$$

Prior distributions for K and P_0.— Unlike the Alaska stock, the California-Oregon population has been relatively stable with a mean of 0.48 million mallards. We believed K should be in the range 0.48 – 0.96 million, assuming the logistic model and that harvest rates were $\leq r/2$. We therefore specified a prior distribution on K that had a mean of 0.7 million, but with a variance sufficiently large to admit a wide range of possible values (Fig. 8):

$$K \sim Log - normal(-0.5628, 0.41224)$$

The estimated size of the California-Oregon stock was 0.48 million at the start of the time-series (i.e., 1992). We used a similar line of reasoning as that for Alaska for specifying a prior distribution P_0, positing that initial population size was 40-100% of *K*. Thus on a log scale:

$$P_o \sim Uniform(-0.9163, 0.0)$$

Parameter estimates.—The logistic model and associated posterior parameter estimates provided a reasonable fit to the observed time-series of population estimates (Fig. 9). The posterior means of *K* and *r* were similar to their priors, although the variances were considerably smaller (albeit still large) (Table 1). Interestingly, the posterior mean of *d* was <1, suggestive of a compensatory response to harvest; however the standard deviation of the estimate was large, with the upper 95% credibility limit >1.

Table 1. Estimates of model parameters resulting from fitting a discrete logistic model with MCMC to a time-series of estimated population sizes and harvest rates of mallards breeding in California and Oregon, 1990-2006.

Parameter	Mean	SD	95% credibility interval
K	0.676	0.180	0.451 – 1.137
P_0	0.725	0.161	0.427 – 0.985
d	0.624	0.423	0.041 – 1.651
r	0.336	0.218	0.068 – 0.874
σ^2	0.015	0.014	0.001 – 0.051

Model Implications

Equilibrium Analysis

We calculated equilibrium population sizes and harvest utilities for the Alaska and California-Oregon stocks for a range of constant harvest rates. Because the two stocks are subject to a joint harvest, we treated the harvest rate of California-Oregon mallards as the control variable, and then predicted the harvest rate of Alaska mallards based on the mean ratio of Alaska to California-Oregon harvest rates (μ = 0.75). We fixed model parameters at their posterior medians (we used medians rather than means because the posterior distributions tended to be skewed), and then simulated a constant harvest rate through time until an equilibrium had been reached. The resulting yield curve has three dimensions instead of the usual two, but otherwise has a familiar shape (Fig. 10). Based on this analysis, the California-Oregon population can sustain harvest rates that are sufficiently high to drive the Alaska stock extinct. This result can be traced back to an estimated mean value of $d < 1$ for the California-Oregon stock, a result that is consistent with (but does not necessarily imply) a compensatory mortality process.

Dynamic Analysis

We derived an optimal, state-dependent harvest policy using stochastic dynamic program, which we implemented using the public-domain software SDP (Lubow 1995). We accounted for uncertainty in model parameters *K*, *r*, and *d* by discretizing the joint posterior distribution for each stock. We first formed the cut-off points of three bins for each parameter by using their 30^{th} and 70^{th} percentiles from the 10,000 MCMC samples of the joint posterior distribution. Then for each MCMC sample, we classified the collection of parameter estimates as falling in one of 27 bins (3 possible frequency classes for each of 3 model parameters = 3^3). Next we tallied the frequency with which the MCMC samples occurred in each of the 27 bins, and used these as probability masses associated with the joint set of parameter values. The discrete values used for each parameter were their 15th , 50th, and 85th percentiles, which represented the values that divided the probability mass of each of the three frequency bins (i.e., 0-30%, 30-70%, 70-100%) into two equal pieces (Table 3). This rather elaborate process was necessary to preserve the correlation structure of the parameter estimates (e.g., MCMC samples in which the estimate of *r* was high and that of *d* was low were rare because the combination was not well supported by the data). We also accounted for uncertainty in the ratio of Alaska to California-Oregon harvest rates using an empirical frequency distribution with five random outcomes (Fig. 11). Therefore, there were 27 × 27 × 5 = 3,645 possible outcomes for each state-dependent harvest rate being evaluated. This means there were effectively 3,645 alternative models used in the optimization, with each being weighted based on its relative ability to describe the record of observed population sizes. For all optimizations, we set the process error for each stock at its mean of zero.

Table 3. Percentile points of logistic-model parameter estimates that were used in deriving optimal harvest policies for mallards breeding in Alaska and California-Oregon.

	Alaska				California-Oregon			
Percentile	*K*	*r*	*d*	σ^2	*K*	*r*	*d*	σ^2
15th	0.881	0.181	0.360		0.510	0.137	0.193	
50th	1.180	0.303	1.003	0.017	0.628	0.286	0.548	0.012
85th	1.560	0.442	1.646		0.860	0.542	1.081	

For the purpose of understanding general patterns in optimal harvest rates, we assumed perfect control over harvest and evaluated state-dependent harvest rates from 0.0 to 0.25 in increments of 0.05. We examined two different management objectives conditioned on this set of harvest rates: (1) maximize long-term cumulative harvest; and (2) attain approximately 90% of the maximum long-term cumulative harvest. We included the second objective because an objective to maximize harvest tends to produce harvest strategies that are knife-edged, meaning that very small changes in population size can precipitate relatively large changes in optimal harvest rates. However, where something less than maximum yield is satisfactory, the optimal harvest strategy tends to be less knife-edged and prescribes fewer closed seasons. The "cost" of these improvements is typically a lower range of population sizes that have relatively liberal-season prescriptions.

These features can be discerned in the optimal, state-dependent harvest strategies for western mallards (Fig. 12). For an objective to maximize long-term cumulative harvest (Fig. 12a), there are many combinations of stock sizes that have harvest-rate prescriptions of either 0 or 25 percent. Very few stock sizes have intermediate harvest-rate prescriptions. In contrast, an objective to attain 90% of the maximum yield produces an optimal strategy with a more even distribution of available harvest rates, and very few prescriptions for closed seasons.

Harvest Control

Because managers do not control harvest rates directly, we were interested in evaluating the relationship between harvest rates and hunting regulations in the Pacific Flyway. As in the previous optimizations, the harvest rate of California-Oregon adult males was treated as the control variable. Unfortunately, the harvest rate estimates we used in fitting the logistic model showed no obvious relationship with any major feature of regulations (season length, bag limit, length of the framework), perhaps because of the small sample size. Therefore, we extended the time series of harvest rate estimates by assuming that the band-reporting rates reported by Nichols et al. (1995) were applicable back to 1980. Given that Nichols et al.

(1991) found essentially no difference in overall mallard reporting rates from those reported by Henny and Burnham (1976), we believed the assumption of constancy of reporting rates was reasonable.

The resulting estimates of harvest rates still showed no obvious response to changes in regulations, however (Fig. 13). We confirmed this result with more rigorous analyses involving linear regression and analysis of variance using a variety of regulatory metrics, including season length, mallard bag limits, and framework opening and closing dates (singly and in combination) as independent variables. We also examined various ordinal and non-ordinal classifications of regulations to no avail. There were also no apparent patterns using cohorts of mallards other than adult males.

An examination of Fig. 13 suggests that the harvest rate estimates derived from reward banding (2002-2005) may be lower on average than those derived from a combination of standard bands and estimated reporting rates. We cannot presently explain the reason for this difference, especially in light of the very liberal regulations in effect during 2002-2005. Therefore, we ignored these estimates and instead examined mean harvest rates during three periods of relatively stable regulations: 1980-84 (liberal); 1985-87 (moderate); and 1988-93 (restrictive). The harvest-rate means for the three periods were indistinguishable, even when band-reporting rate was assumed to be measured without error (Table 4).

Table 4. Estimated harvest rates of adult male mallards banded in California and Oregon, based on recoveries of standard bands and the reporting rates provided by Nichols et al. (1995). The standard deviations account only for banded sample sizes and not for the uncertainty associated with estimated band-reporting rates.

Period	$\bar{h}_t$	$sd(\bar{h}_t)$	Season length (days)
1980-84	0.1334	0.0117	93
1985-87	0.1242	0.0300	79
1988-93	0.1203	0.0178	59

We were forced to conclude that changes in regulations in the Pacific Flyway since 1980 have not resulted in significant changes in the harvest rates of mallards banded in California-Oregon. It appears that more extreme regulatory changes than those used in the past may be needed to effect substantive changes in harvest rates.

To help understand the implications of this apparent lack of control over harvest rates, we assumed the most extreme case of two regulatory options: a closed season and an open season. We assumed that an open season would produce a harvest rate of 0.1259 (the mean of all our estimates) and that a closed season would produce a harvest rate of 0.0. We then determined the optimal choice for each possible combination of population size in Alaska and California-Oregon. We conducted this optimization to determine the population thresholds for season closures, assuming minimal control over harvest rates. We wish to emphasize that failure to close the season below these population thresholds in no way implies that the open-season harvest rate is not sustainable, only that it is not optimum for maximizing long-term cumulative yield.

Generally, as long as both stocks are above about 250-300 thousand, then the optimal choice is an open season (Fig. 14). Below that, the lower one stock is, the higher the other has to be to maintain an open season. It's also interesting to note that open seasons can be optimum even when one stock is extinct, as long as the remaining stock can support the open season.

A Proposed AHM Protocol

The establishment of an AHM protocol for western mallards requires agreement on the following elements:

(1) models that describe system dynamics and the effects of harvest, and which explicitly account for uncertainty in those dynamics and effects;
(2) a set of alternative management actions, including any constraints on their use;
(3) an objective function describing one or more unambiguous harvest-management objectives; and
(4) a monitoring program for assessing system status, and for updating estimates of model parameters.

We believe that the models presented in this report provide a sufficient basis for developing an initial AHM protocol. Moreover, extant monitoring of mallard abundance and harvest rates in Alaska and California-Oregon will provide the necessary basis for updating model parameter estimates and their associated probabilities. Finally, the Bayesian estimation framework is sufficiently flexible to permit the use of new sources of information that may become available concerning population dynamics. Even changes in the spatial delineation of western mallards would not be problematic given that minimum data requirements were met.

Similarly, we believe that sufficient information is available to inform the choice of an objective function for western mallards. In particular, an objective to attain 90% of the maximum long-term cumulative harvest provides for levels of hunting opportunity that are similar to those now in effect for a wide range of stock sizes. In the end, however, the specification of an objective function is a value-based decision that will require consensus among key stakeholders.

On a more pessimistic note, we were unable to establish a viable set of regulatory alternatives with which to effect changes in harvest rate. Therefore, an essential task is consideration of hunting regulations beyond the realm of experience that might be expected to have a meaningful effect on harvest rates. Such changes might include delayed opening dates or substantial reductions in season length and/or bag limit. We encourage the Pacific Flyway Council to begin considering such regulatory alternatives should a substantive change in harvest rate of western mallards become necessary. Until such time this task is completed, however, we believe a derived strategy of optimal harvest rates can provide sufficient guidance for managing the western mallard population.

As was discussed at the beginning of this report, the development of AHM protocols for mallards ideally would consider how different breeding stocks distribute themselves among the four flyways. At present, however, a joint optimization of western, mid-continent, and eastern stocks is not feasible because:

(1) we cannot yet predict stock-specific harvest rates as a function of Flyway-specific regulations (due to the difficulty of extrapolating beyond our range of experience in which all flyways have either restricted or liberalized in concert);
(2) we have insufficient policy guidance concerning how stock-specific management objectives should be combined into a joint objective for all mallard stocks (although forthcoming recommendations from the AHM-NAWMP Joint Task Group may help in this regard); and
(3) we have been unable to overcome (at least in a way that is practical) the computational hurdles associated the simultaneous consideration of more than two mallard stocks and two harvest areas (although computation limitations continue to decrease as faster processors become available).

We are therefore proposing that the initial AHM protocol for western mallards be structured similarly to that used for eastern mallards, in which an optimal harvest strategy is based on the status of a single breeding stock and harvest regulations in a single flyway. Based on band-recovery data, we estimate that only about 5% of the fall flight of mid-continent mallards winters in the Pacific Flyway, while 70% and 98% of the Alaska and California-Oregon stocks, respectively, do so. However, the size of the mid-continent stock is roughly six times as large as that in Alaska and California-Oregon, so the contribution of mid-continent mallards to the Pacific Flyway harvest is still significant. Nonetheless, we believe an independent harvest strategy for western mallards poses little short-term risk to the mid-continent stock. And over the longer term, we believe that the current hurdles to deriving joint harvest strategies can be overcome.

Literature Cited

Henny, C. J., amd K. P. Burnham. 1976. A reward band study of mallards to estimate band reporting rates. Journal of Wildlife Management 40:1-14.

Herzog, M., and J. Sedinger. 2004. Western mallard population model: Report to the Wildlife Management Institute and the Pacific Flyway Study Committee. Dept. of Natural Resources and Environmental Science, University of Reno, Nevada. 78pp.

Hodges, J. L., J. G. King, B. Conant, and H. A. Hanson. 1996. Aerial surveys of waterbirds in Alaska 1975-94: population trends and observer variability. Information and Technology Report 4, National Biological Service, U.S. Dept. of the Interior, Washington, D.C. 25pp.

Lubow, B. C. 1995. SDP: Generalized software for solving stochastic dynamic optimization problems. Wildlife Society Bulletin 23:738-742.

Nichols, J. D., R. J. Blohm, R. E. Reynolds, R. E. Trost, J. E. Hines, and J. P. Bladen. 1991. Band reporting rates for mallards with reward bands of different dollar values. Journal of Wildlife Management 55:119-126.

Nichols, J. D., R. E. Reynolds, R. J. Blohm, R. E. Trost, J. E. Hines, and J. P. Bladen. 1995. Geographic variation in band reporting rates for mallards based on reward banding. Journal of Wildlife Management 59:697-708.

Meyer, R., and R. B. Millar. 1999. BUGS in Bayesian stock assessments. Canadian Journal of Fisheries and Aquatic Sciences 56:1078-1086.

Schaefer, M. B. 1954. Some aspects of the dynamics of populations important to the management of commercial marine fisheries. Bulletin of the Inter-American Tropical Tuna Commission 1:25-56.

Sheaffer, S. E., and R. A. Malecki. 1999. Models for adaptive harvest management of western mallards. New York Cooperative Fish and Wildlife Research Unit, Cornell University, Ithaca, New York. 59pp.

Smith, G. W. 1995. A critical review of the aerial and ground surveys of breeding waterfowl in North America. Biological Science Report 5, National Biological Service, U.S. Dept. of the Interior, Washington, D.C. 252pp.

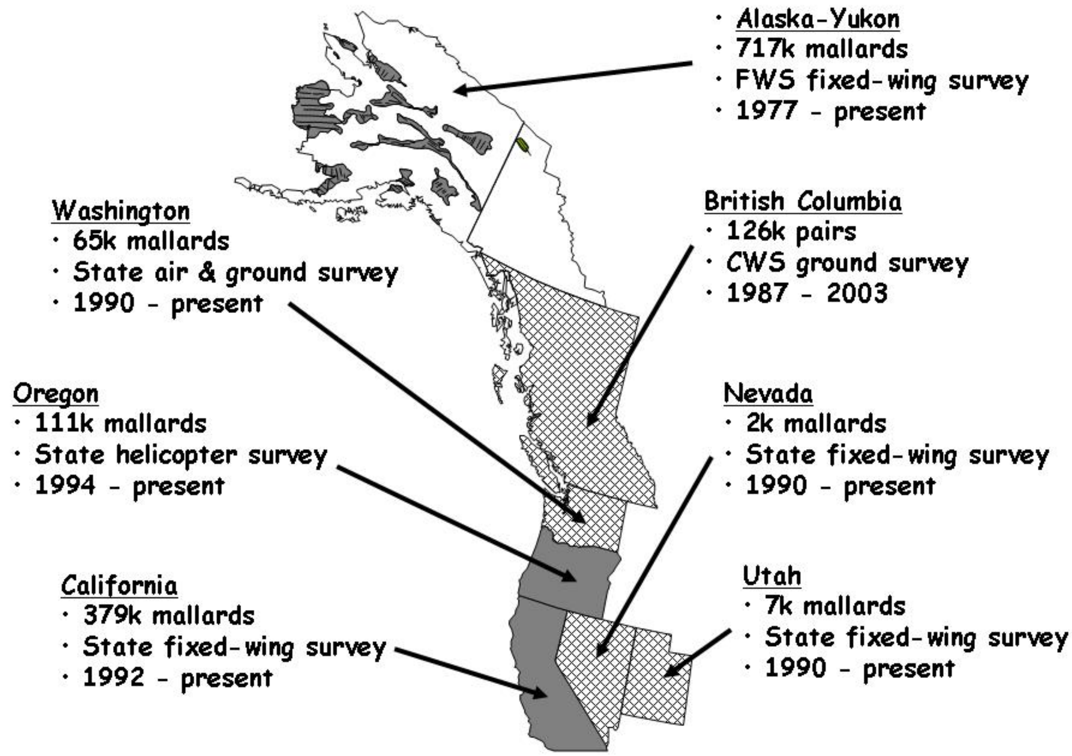


Fig. 1. Status of population surveys in the range of western mallards. States with solid shading represent those that were used to model western-mallard population dynamics.

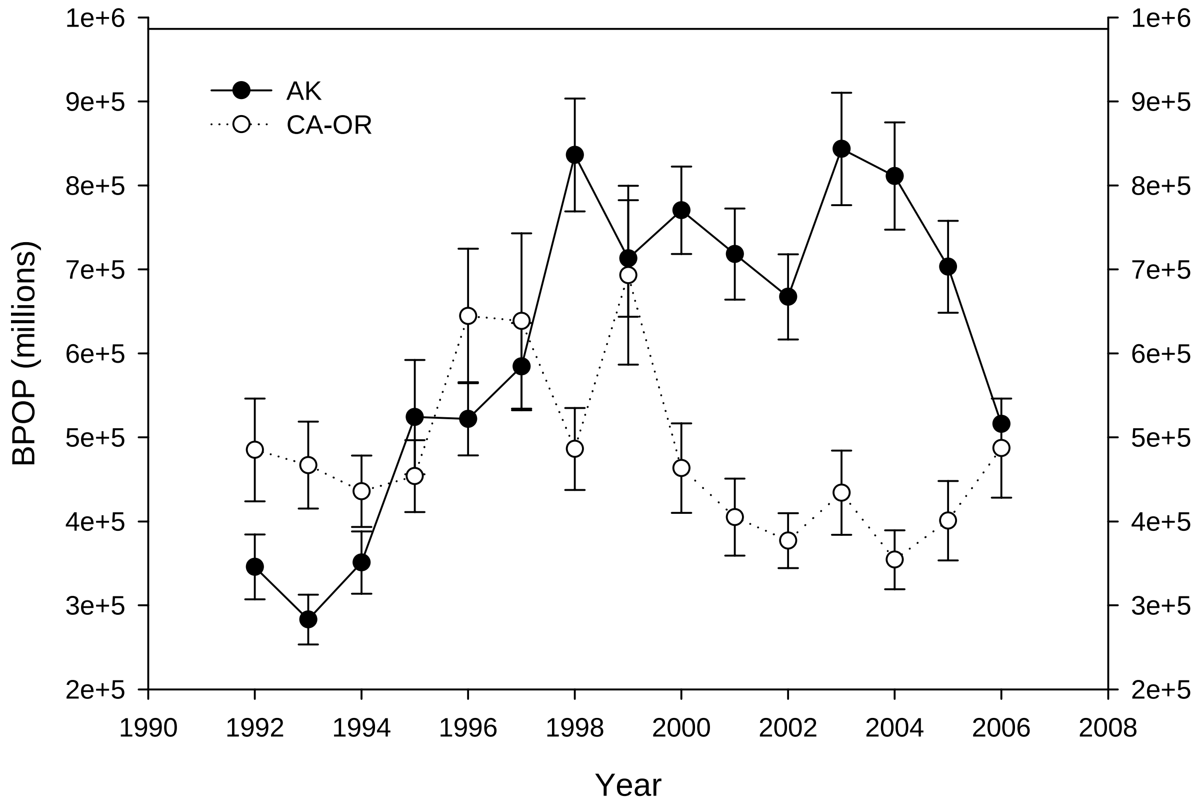


Fig. 2. Estimated abundances of mallards breeding in Alaska and California-Oregon as derived from federal and state surveys, respectively. Error bars represent one standard deviation.

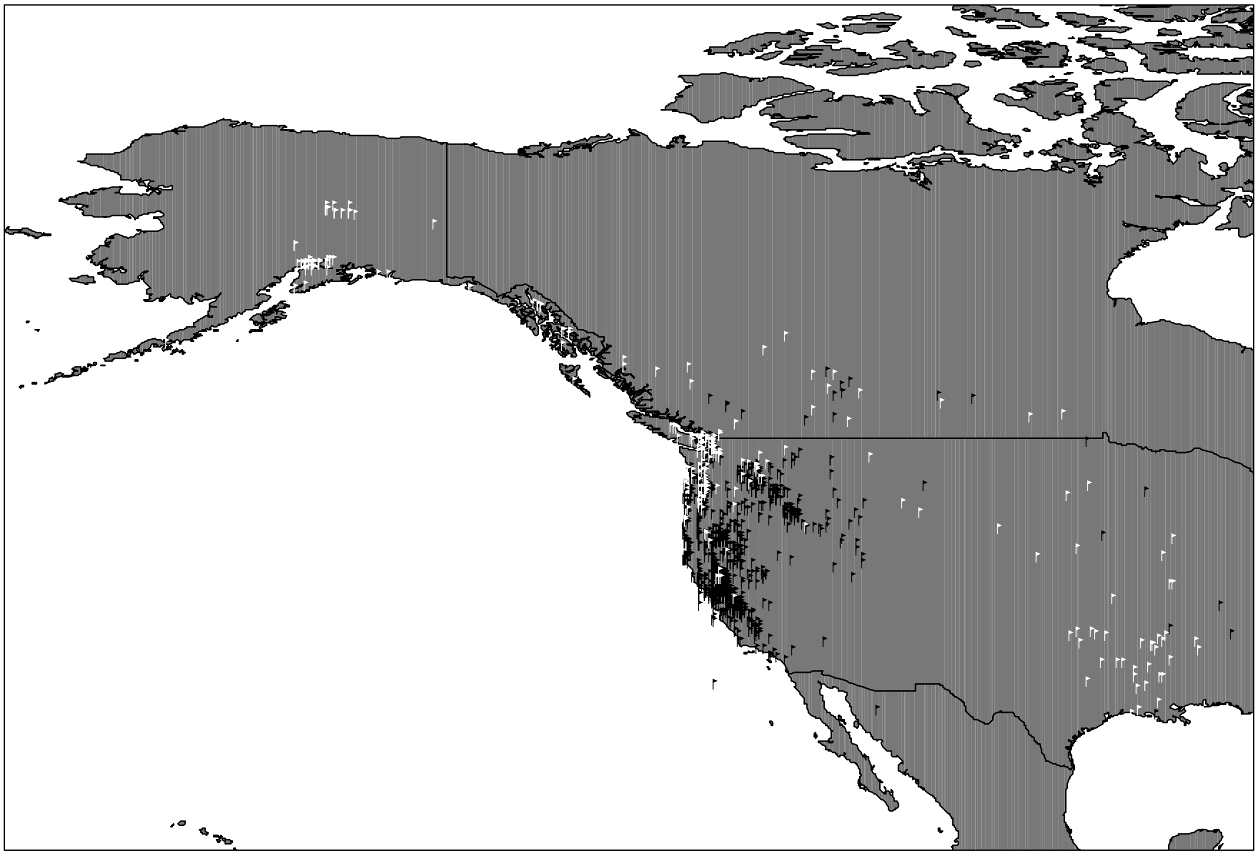


Fig. 3. Location of direct recoveries of mallards banded in Alaska (white flags) and in California-Oregon (black flags).

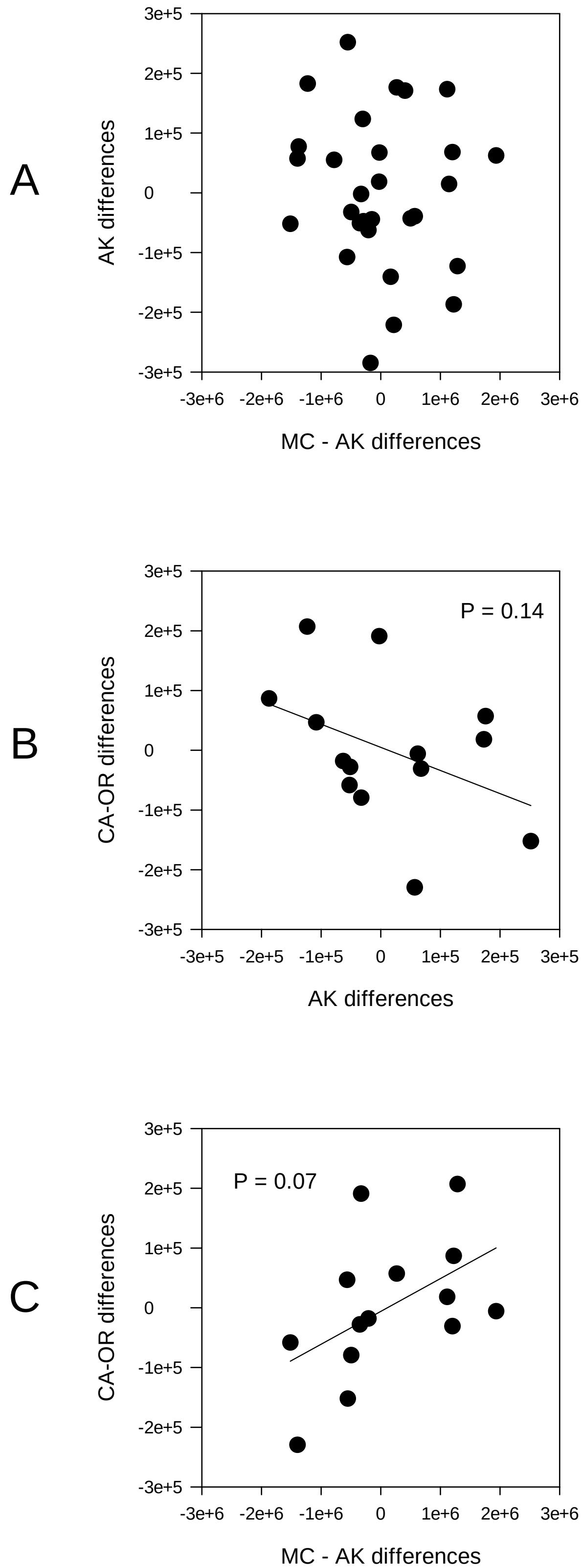


Fig. 4. Comparisons of first-order differences in stock sizes of western (AK and CA-OR) and mid-continent (MC-AK; I,e, the traditional mid-continent population minus the Alaska component) mallards.

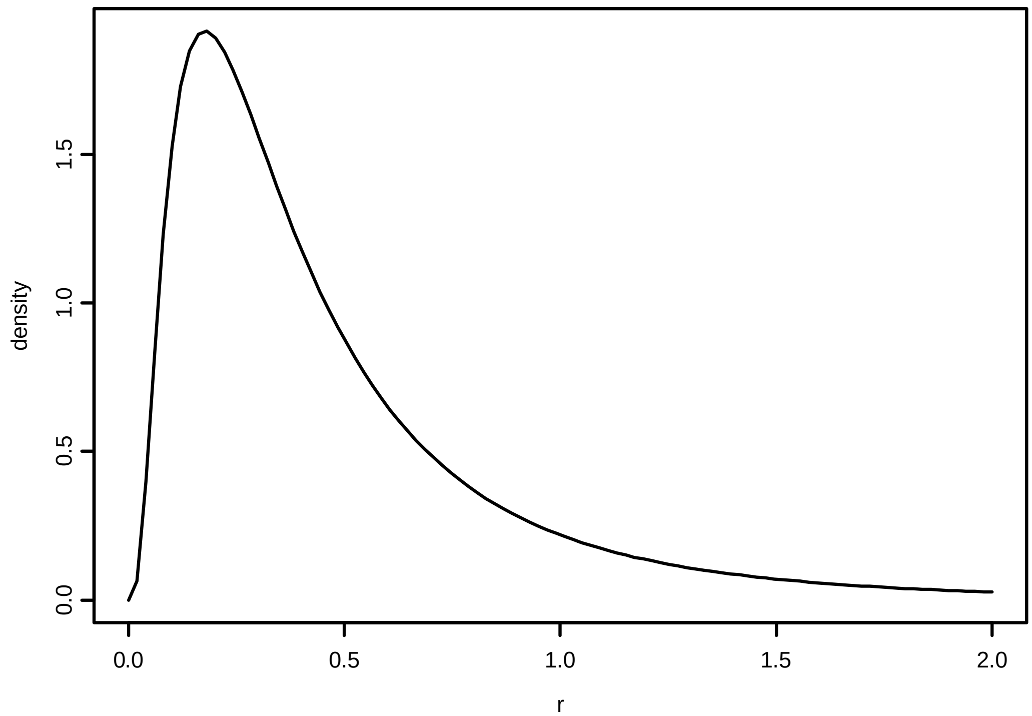


Fig. 5. Prior distribution of *r* in the logistic model for both Alaska and California-Oregon mallards.

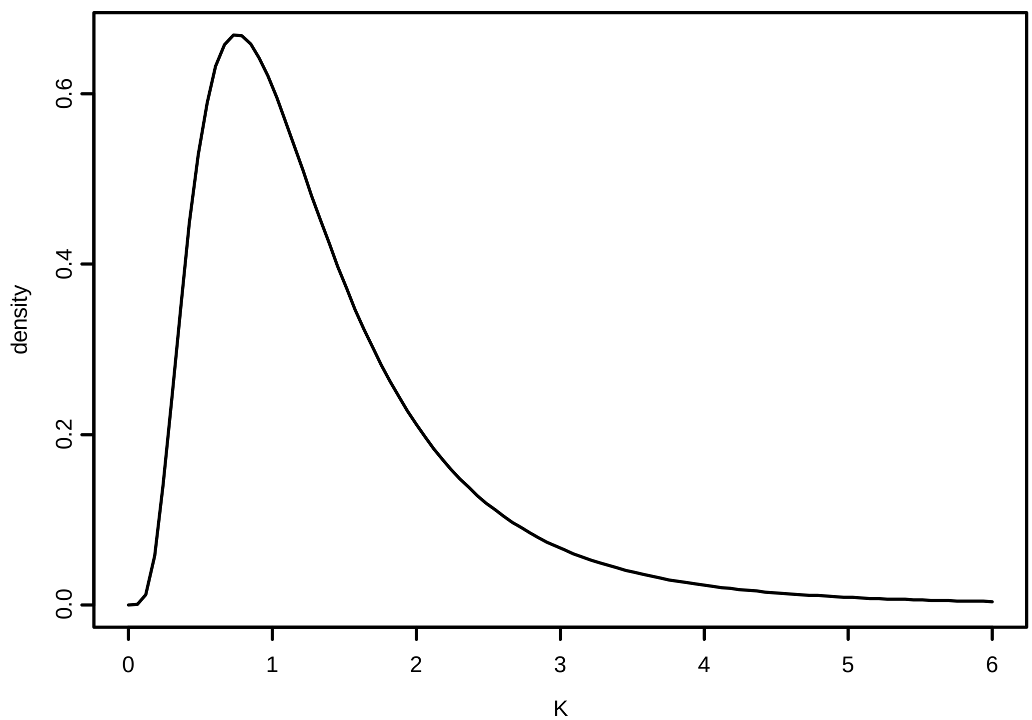


Fig. 6. Prior distribution of K (in millions) in the logistic model for Alaska mallards.

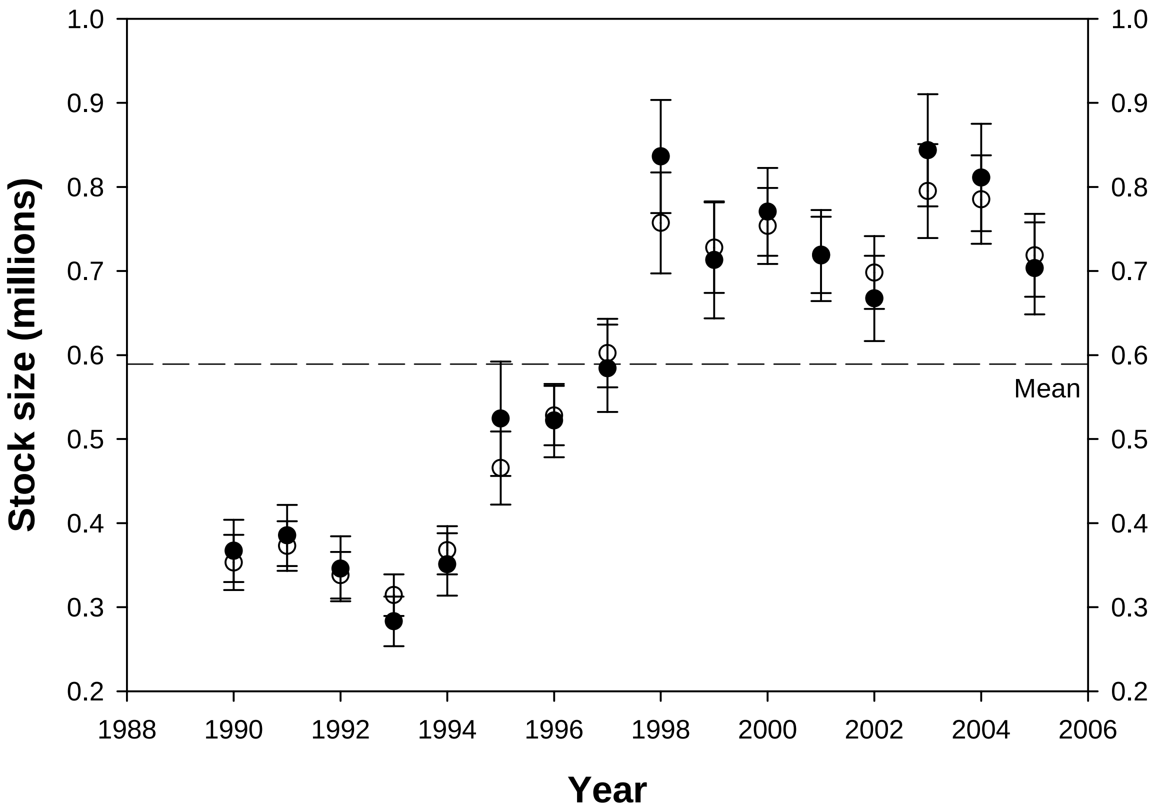


Fig. 7. Observed population sizes (filled circles) in Alaska compared with those predicted (open circles) from the logistic model described in this report. Error bars represent one standard deviation.

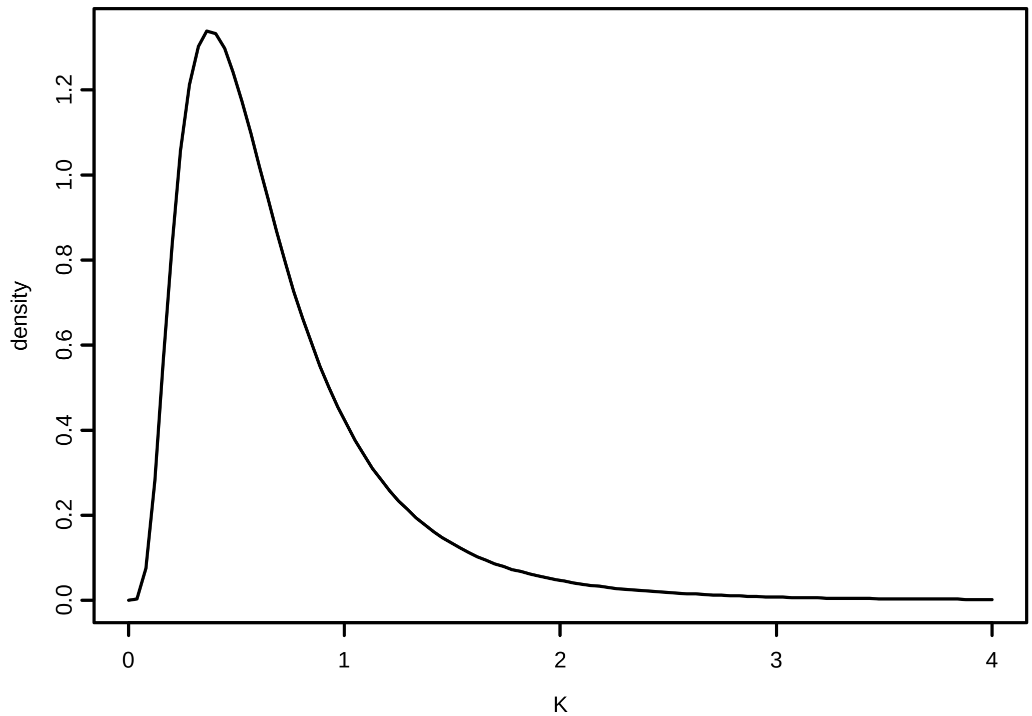


Fig. 8. Prior distribution of *K* (in millions) in the logistic model for California-Oregon mallards.

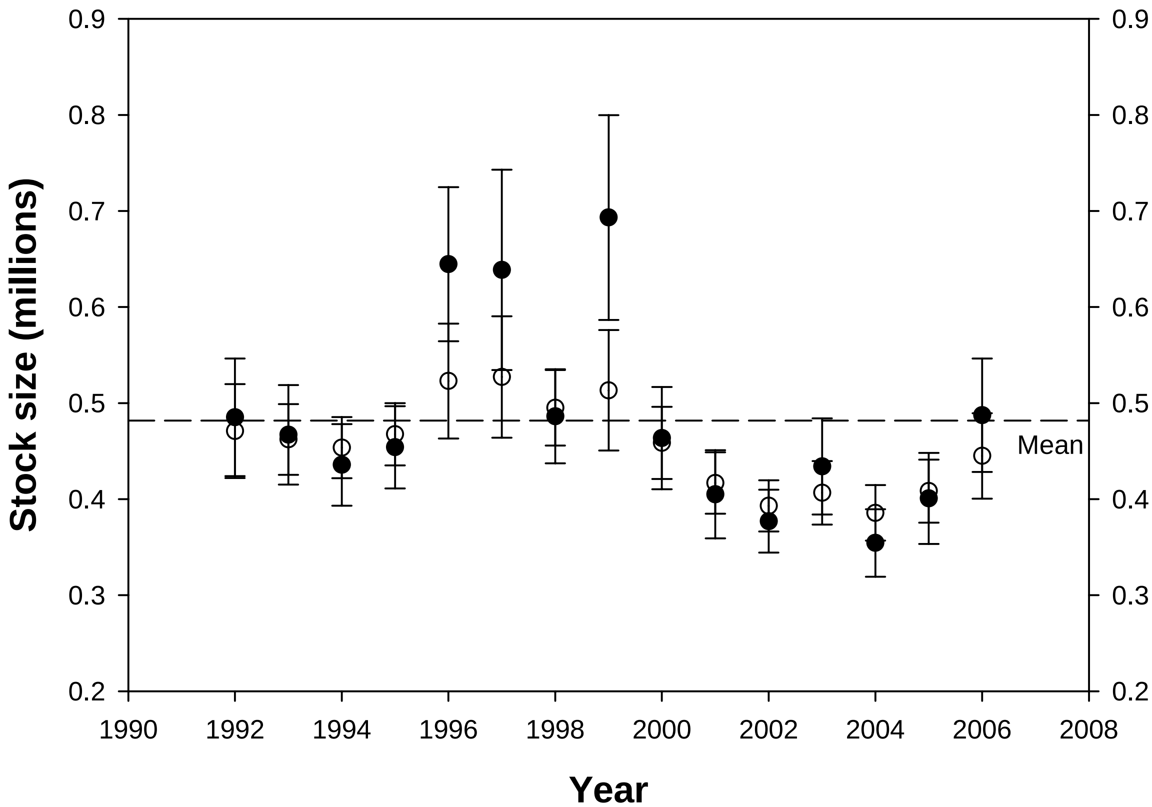


Fig. 9. Observed population sizes (filled circles) in California-Oregon compared with those predicted (open circles) from the logistic model described in this report. Error bars represent one standard error.

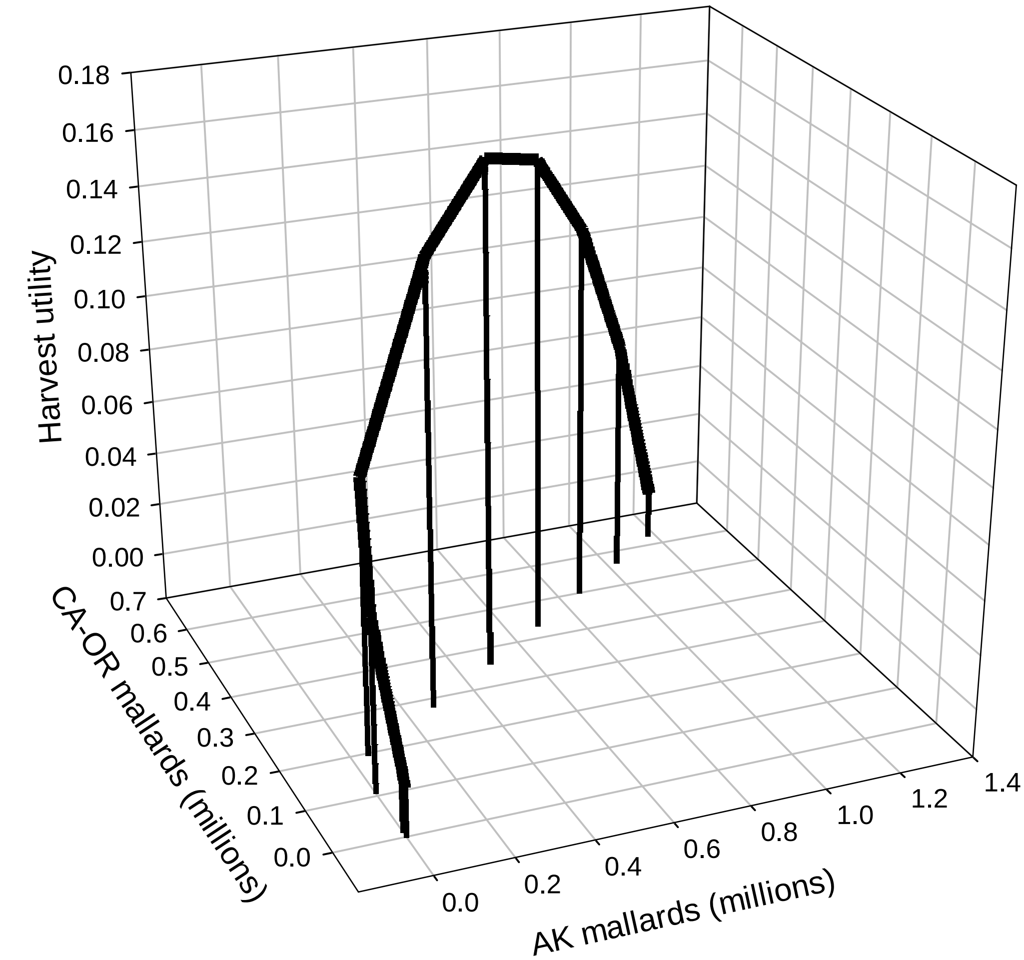


Fig. 9. Equilibrium yield curve for the joint harvesting of Alaska and California-Oregon mallards as based on the models described in this report. Vertical lines represent harvest rates from 0.0 to 0.45 in increments of 0.05.

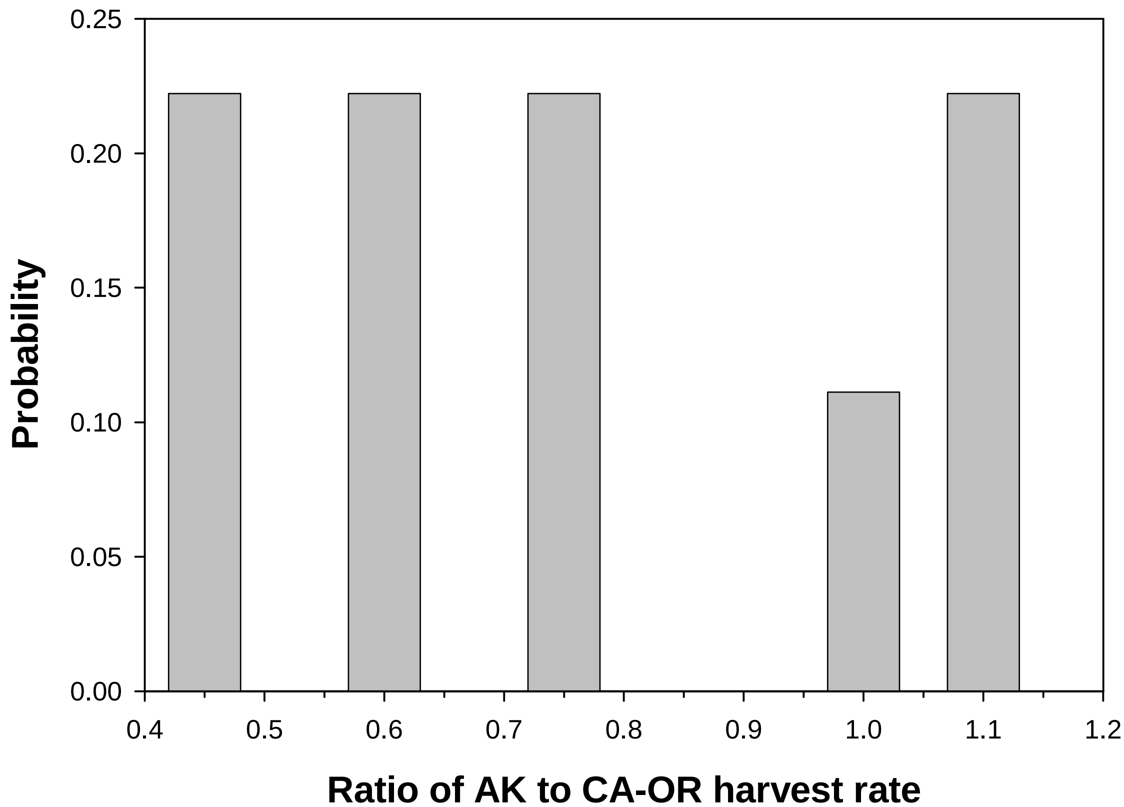
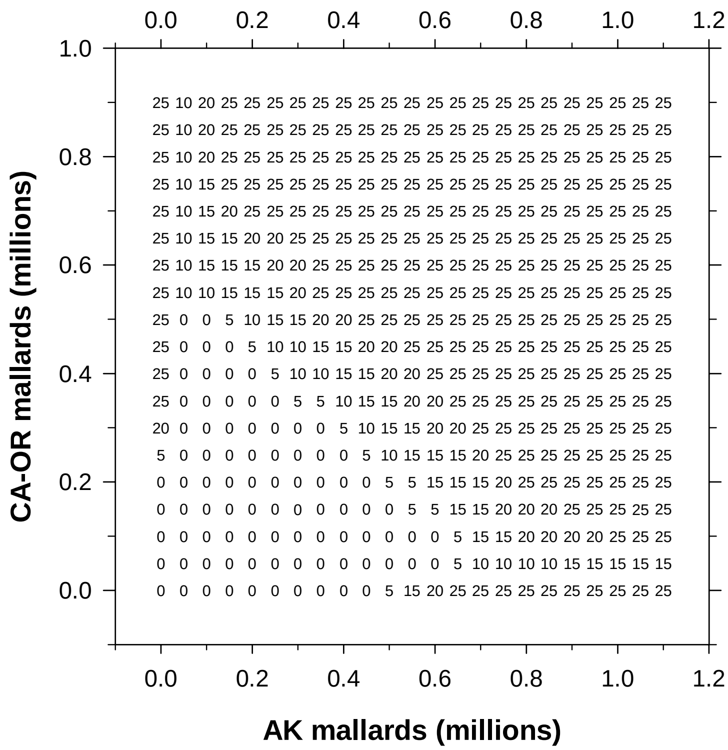


Fig. 11. Empirically-based probabilities assigned to random outcomes of the ratio of Alaska to California-Oregon adult-male mallard harvest rates.



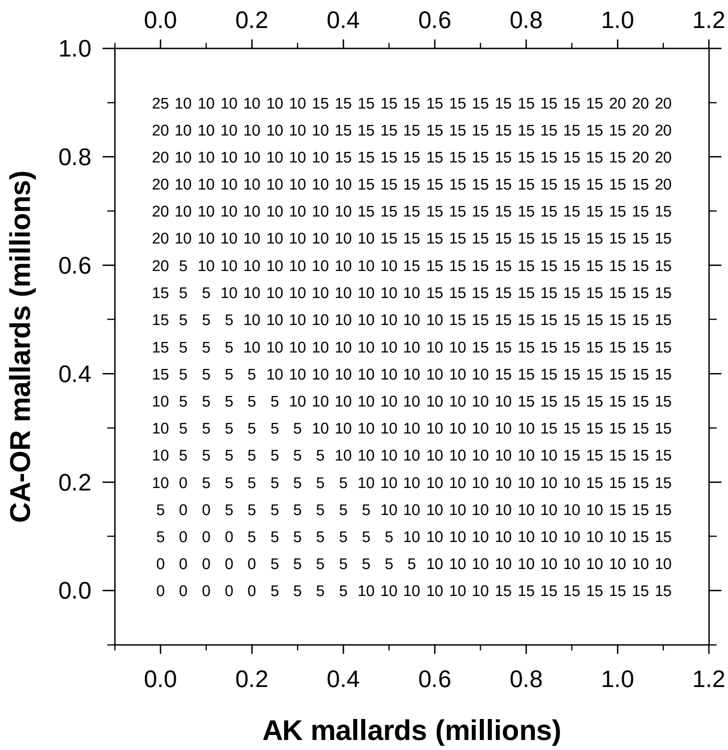


Fig. 12. Optimal harvest rates (in percent) for adult-male western mallards, conditioned on harvest rates from 0-25% in increments of 5%, and the models presented in this report. The top strategy is designed to maximize long-term cumulative harvest and the bottom strategy is designed to attain 90% of the maximum long-term harvest.

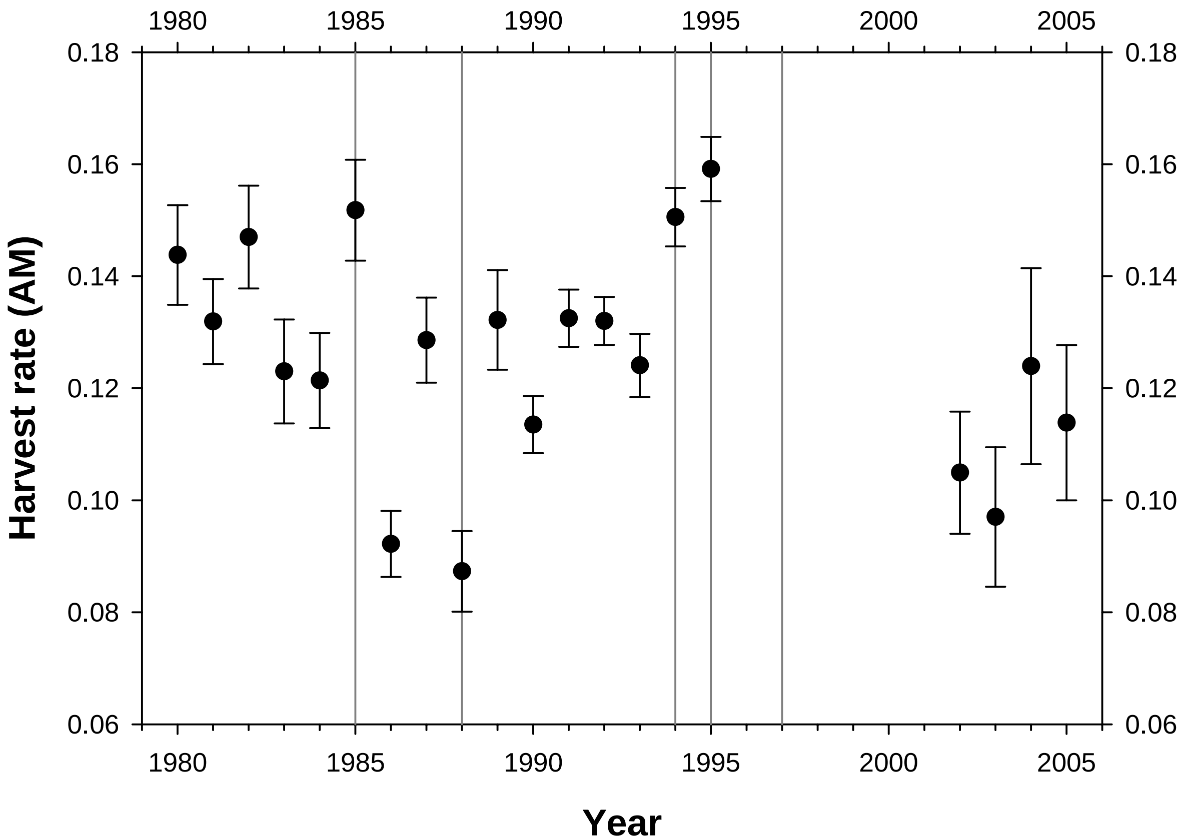


Fig. 13. Estimated harvest rates of adult-male mallards banded in California and Oregon. Vertical lines depict years in which major regulatory changes occurred. Error bars represent one standard error.

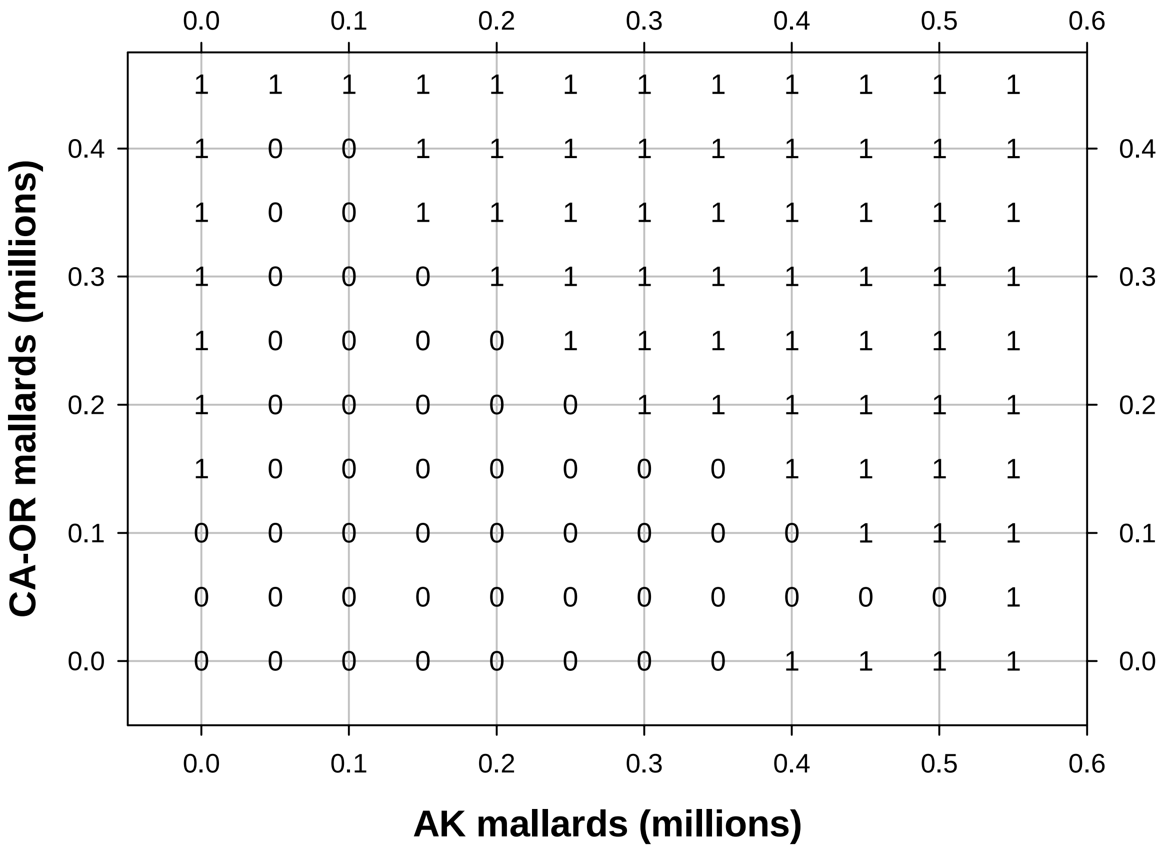


Fig. 14. Stock sizes in which the optimal decision would be a closed season ("0") or an open season ("1") for western mallards, given an objective to maximize long-term cumulative harvest and only two regulatory choices: a closed season where the harvest rate = 0.0 and an open season where the harvest rate = 0.1259.

Appendix

Data (population size in millions, $\hat{N}$, and harvest rate of adult males, h^{AM}) and the WinBUGS code we used to fit discrete logistic growth models for mallards breeding in Alaska and California-Oregon.

Data:

	Alaska			California-Oregon		
Year	$\hat{N}$	$se(\hat{N})$	$\hat{h}^{AM}$	$\hat{N}$	$se(\hat{N})$	$\hat{h}^{AM}$
1990	0.3669	0.0370	0.0689			
1991	0.3853	0.0363	0.1443			
1992	0.3457	0.0387	0.0977	0.4851	0.0612	0.1320
1993	0.2830	0.0295	0.0755	0.4669	0.0518	0.1241
1994	0.3509	0.0371	0.0742	0.4357	0.0425	0.1506
1995	0.5242	0.0680	0.0590	0.4539	0.0428	0.1592
1996	0.5220	0.0436		0.6445	0.0802	
1997	0.5842	0.0520		0.6386	0.1043	
1998	0.8362	0.0673		0.4862	0.0489	
1999	0.7131	0.0696		0.6931	0.1066	
2000	0.7703	0.0522		0.4635	0.0532	
2001	0.7183	0.0541		0.4050	0.0459	
2002	0.6673	0.0507	0.1121	0.3770	0.0327	0.1049
2003	0.8435	0.0668	0.1000	0.4340	0.0501	0.0970
2004	0.8111	0.0639	0.0968	0.3543	0.0352	0.1239
2005	0.7031	0.0547		0.4008	0.0474	0.1139
2006				0.4873	0.0590	

Alaska model fitting in WinBUGS:

```
#---------------------------------------------------------------------------
#   BUGS MODEL: akv5_M0
#---------------------------------------------------------------------------
#   Created By:  F Johnson & S Boomer
#   Created: 9 November 2005
#   Data: BPOP, SE_BPOP, harvest rates, PF days
#   Model: Standard logistic with harvest rates
#-----------------------------------------------------------------------------------------------------
#  Updates:
#  18 Nov 2005: added explicit scaling factors for adult male harvest rates;
#                      calculates hstar (r/2) in terms of adult-male harvest rate
#  09 Jan 2006:  incorporated model to impute missing harvest rates based on PF days
#  27 Feb 2006:  Version 2 - reparameterizes harvest bt applying h to post production;
#                      also uses d to scale adult male harvest rate to entire population
#  25 Sep 2006:  Version 4 cuts the time frame to 1990-2005 and uses estimated hrates;
#                                                  also uses a simple scaler for h (no explicit crippling loss)
#  22 Jan 2007:  Version 5 uses a logit-normal distribution of harvest rates for 1996-2001;
#                       harvest rates based on Nichols et al (1995) for 1990-92, Moore's adj
#                       for 1993-95, and reward bands 2002-2004
#-----------------------------------------------------------------------------------------------------
# PARAMETER DEFINITIONS
#       N = constant for number of years 1990-2005
#       BPOP = data vector for survey Bpop sizes
#       s = data vector for survey Bpop standard errors
#       h = data vector for estimated harvest rates with 0's for missing years
#       i = data vector for index values for observed harvest rate presence/absence
#       H = vector to store predicted harvest rates
#       hr = appropriate harvest rate (observed or predicted value) to use in population model
#       POP = vector for calculated BPOP "means"
#       P = vector for "population" (i.e., BPOP/K) state
#       Pmed = vector for "population" state "means"
#       r = intrinsic rate of increase
#       K = carrying capacity
#       sigma2 = process variance
#       isigma2 = prior on sigma (process variance)
#      d = adult male harvest rate scaler
#---------------------------------------------------------------------------

model;
{
            #harvest-rate scalar
            d~dunif(0,2);

            #prior for carrying capacity K: lognormal
            K ~dlnorm(0.13035,2.42574);# mu=1.4, sd=1

            #prior for rate of increase r: lognormal
            r ~dlnorm(-1.039721,1.442695);# mu=0.5, sd=0.5

            #prior for process variance sigma2: IG
            isigma2~dgamma(0.001,0.001);
            sigma2<-1/isigma2;

#---------------------------------------------------------------------------
# PROCESS MODEL :
#---------------------------------------------------------------------------

  # conditional prior for P's (state equations)

   Pmed[1]~dunif(-1.6094,-0.5108); #U(0.2,0.6)
```

```
  P[1]~dlnorm(Pmed[1],isigma2);

 # generate predicted harvest rates from a logit-normal distribution
  for(t in 1:N)
  {
    z[t]~dnorm(-2.3227,10.7408);
    H[t]<-pow((1+exp(-1*z[t])),-1);
  }

  # population model, which uses observed or fitted harvest rates as appropriate
   for(t in 2:N)
   {
    hr[t-1]<-i[t-1]*h[t-1] + (1-i[t-1])*H[t-1];
          Pmed[t]<-log(max(P[t-1]*(1+r*(1-P[t-1]))*(1-hr[t-1]*d), 0.000001));
    P[t]~dlnorm(Pmed[t],isigma2);
   }

#-----------------------------------------------------------------------------
# OBSERVATION MODEL :
#-----------------------------------------------------------------------------

   for (t in 1:N)
   {
       POP[t]<-(P[t]*K);
       taupop2[t]<-1/pow(s[t],2);
       BPOP[t]~dnorm(POP[t],taupop2[t]);
            }

#-----------------------------------------------------------------------------
# Calc derived population parameters
#-----------------------------------------------------------------------------
 #   MSY <- r*K/4;
  #  PopMSY <-K/2;
  # kstar<-r/2;
  #  hstaram <- (r/2)/d;
   Kinitp <- exp(Pmed[1]);

}# end model

list(N=16,
BPOP=c(0.366933,0.385319,0.345708,0.282983,0.350875,0.524200,
0.522006,0.584247,0.836216,0.713054,0.770333,0.718286,0.667339,
0.843497,0.811135,0.703140),
s=c(0.037017,0.036279,0.038708,0.029533,0.037142,0.067975,
0.043552,0.051997,0.067284,0.069568,0.052159,0.054127,0.050687,
0.066823,0.063878,0.054748),
h=c(0.0689,0.1443,0.0977,0.0755,0.0742,0.0590,0,0,0,
0,0,0,0.1121,0.1000,0.0968,0),
i=c(1,1,1,1,1,1,0,0,0,0,0,0,1,1,1,0))
list(isigma2=1000,d=1.0)
```

California-Oregon model fitting in WinBUGS:

```
#-------------------------------------------------------------------------------
#   BUGS MODEL: cov5_M0_mod
#-------------------------------------------------------------------------------
#   Created By:  F Johnson
#   Created: 10 November 2005
#   Data: BPOP, SE_BPOP
#   Model: Standard logistic
#-----------------------------------------------------------------
#   Updates:
#  21 Nov 2005: added explicit scaling factors for adult male harvest rates;
#                      calculates hstar (r/2) in terms of adult-male harvest rate
#  11 Jan 2006: incorporated models to impute missing harvest rates
#  04 Mar 2006: Version 1.5 - reparameterizes harvest by applying h to post production;
#                       also uses d to scale adult male harvest rate to entire population;
# 08 Sep 2006: cov1.5_M0_dat(2) includes 2006 and uses bpop-weighted harvest rates
#  22 Jan 2007:  Version 5 uses a logit-normal distribution of harvest rates for 1996-2001;
#                        harvest rates based on Nichols et al (1995) for 1990-92, Moore's adj
#                        for 1993-95, and reward bands 2002-2004
#-----------------------------------------------------------------
# PARAMETER DEFINITIONS
#      N = constant for number of years 1992-2006
#      BPOP = data vector for observed survey BPOP
#      s = se(BPOP)
#      h = data vector for observed harvest rates with 0's for missing years
#      i = data vector for index values for observed harvest rate presence/absence
#      H = vector to store predicted harvest rates
#      hr = appropriate harvest rate (observed vs predicted) to use in pop. model
#       POP = vector for back-transformed Bpop "means"
#       P = vector for population state
#       Pmed = vector for population state "means"
#       r = intrinsic rate of increase
#       K = carrying capacity
#       sigma2 = process variance
#       isigma2 = prior on sigma (process variance)
#       d = adult male harvest rate scaler
#-------------------------------------------------------------------------------

model;
{
            #harvest-rate scalar
            d~dunif(0,2);

    #prior for carrying capacity K: lognormal
            K ~dlnorm(-0.562797,2.425743); #mu=0.7,sd=0.5

    #prior for rate of increase r: lognormal
            r ~dlnorm(-1.039721,1.442695);# mu=0.5, sd=0.5

    #prior for process variance sigma2: IG
    isigma2~dgamma(0.001,0.001);
    sigma2<-1/isigma2;

#-------------------------------------------------------------------------------
# PROCESS MODEL :
#-------------------------------------------------------------------------------

    # conditional prior for P's (state equations)

   Pmed[1]~dunif(-0.91629,0.0); #U(0.4,1.0)
   P[1]~dlnorm(Pmed[1],isigma2);
```

```
 # generate predicted harvest rates from a logit-normal distribution
  for(t in 1:N)
  {
    z[t]~dnorm(-1.9815,25.71429);
    H[t]<-pow((1+exp(-1*z[t])),-1);
  }

  # population model, which uses observed or fitted harvest rates as appropriate
   for(t in 2:N)
   {
    hr[t-1]<-i[t-1]*h[t-1] + (1-i[t-1])*H[t-1];
          Pmed[t]<-log(max(P[t-1]*(1+r*(1-P[t-1]))*(1-hr[t-1]*d), 0.000001));
    P[t]~dlnorm(Pmed[t],isigma2);
   }#end for loop

#----------------------------------------------------------------------------
# OBSERVATION MODEL :
#----------------------------------------------------------------------------

   for (t in 1:N)
   {
      POP[t]<-(P[t]*K);
      taupop2[t]<-1/pow(s[t],2);
      BPOP[t]~dnorm(POP[t],taupop2[t]);
   }

#----------------------------------------------------------------------------
# Calc derived population parameters
#----------------------------------------------------------------------------
 #   MSY <- r*K/4;
 #  PopMSY <-K/2;
 #   kstar<-r/2;
 #  hstaram <- (r/2)/d;
   Kinitp <- exp(Pmed[1]);

}# end model


list(N=15,
BPOP=c(0.485084,0.466863,0.435742,0.453851,0.644534,0.638613,0.486189,0.693118,
0.463477,0.405009,0.376988,0.434002,0.354309,0.400825,0.487255),
s=c(0.061184,0.051769,0.042531,0.042813,0.080152,0.104332,0.048896,0.106603,
0.053242,0.045918,0.032657,0.050139,0.035168,0.047362,0.059027),
h=c(0.1320,0.1241,0.1506,0.1592,0,0,0,0,0,0,0.1049,0.0970,0.1239,0.1139,0),
i=c(1,1,1,1,0,0,0,0,0,0,1,1,1,1,0))
list(isigma2=1000, d=1.0)
```