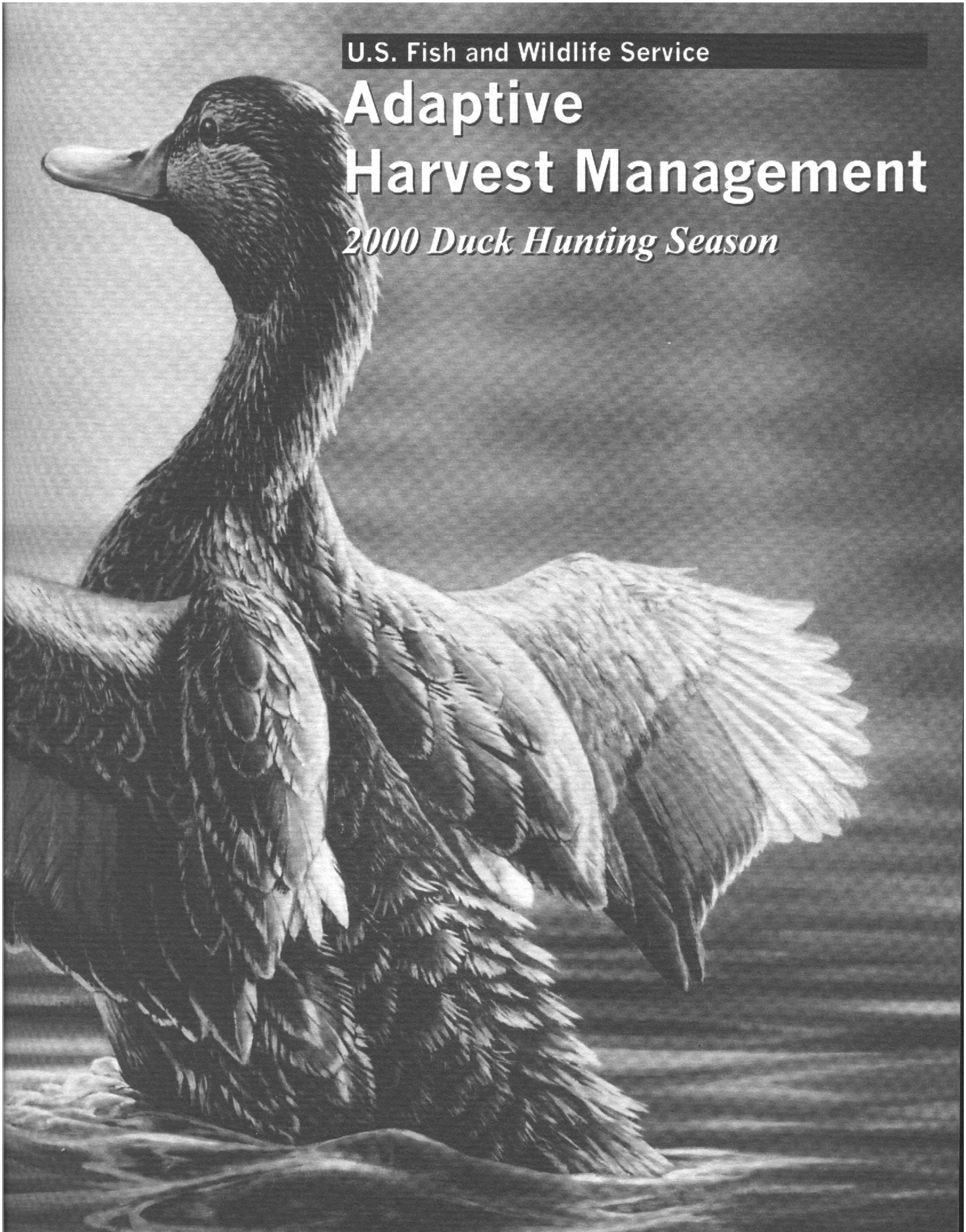
U.S. Fish and Wildlife Service

Adaptive Harvest Management

2000 Duck Hunting Season



Citation: U.S. Fish and Wildlife Service. 2000. Adaptive Harvest Management: 2000 Hunting Season. U.S. Dept. Interior, Washington, D.C. 40pp.

U. S. Fish & Wildlife Service

Adaptive Harvest Management

2000 Duck Hunting Season

PREFACE

The process of setting waterfowl hunting regulations is conducted annually in the United States. This process involves a number of meetings where the status of waterfowl is reviewed by the agencies responsible for setting hunting regulations. In addition, the U.S. Fish and Wildlife Service (USFWS) publishes proposed regulations in the *Federal Register* to allow public comment. This document is part of a series of reports intended to support development of harvest regulations for the 2000 hunting season. Specifically, this report is intended to provide waterfowl managers and the public with information about the use of adaptive harvest management for setting duck-hunting regulations in the United States. This report provides the most current data, analyses, and decision-making protocols. However, adaptive management is a dynamic process, and information presented herein may differ from that published previously.

ACKNOWLEDGEMENTS

A working group comprised of technical representatives from the USFWS, the four Flyway Councils, and the USGS Biological Resources Division (Appendix A) was established in 1992 to review the scientific basis for managing waterfowl harvests. The working group subsequently proposed a framework of adaptive harvest management (AHM), which was first implemented in 1995. The USFWS expresses its gratitude to the working group and other individuals, organizations, and agencies that have contributed to the development and implementation of AHM. We especially thank D. J. Case and Associates for help with information and education efforts.

This report was prepared by the USFWS Adaptive Management & Assessment Team, which is administered by the Divisions of Migratory Bird Management and North American Waterfowl and Wetlands. F. A. Johnson (USFWS) was the principal author, but significant contributions to the report were made by J. A. Dubovsky (USFWS), W. L. Kendall (USGS Patuxent Wildlife Research Center), and M. T. Moore (USFWS). J. P. Bladen (USFWS), D. J. Case (D.J. Case & Assoc.), J. R. Kelley (USFWS), E. M. Martin (USFWS), M. C. Otto (USFWS), P. I. Padding (USFWS), G. W. Smith (USFWS), and K. A. Wilkins (USFWS) provided information or otherwise assisted with report preparation. Comments regarding this document should be sent to Jon Andrew, Chief, Division of Migratory Bird Management - USFWS, Arlington Square, Room 634, 4401 North Fairfax Drive, Arlington, VA 22203

Cover art: Adam Grimm’s painting of a mottled duck, which was selected for the 2000 federal “duck stamp.”

TABLE OF CONTENTS

U.S. FISH & WILDLIFE SERVICE
DEPARTMENT OF THE INTERIOR

Annual reports and other information regarding adaptive harvest management are available on the Internet at:
www.migratorybirds.fws.gov/reports/reports.html

EXECUTIVE SUMMARY

In 1995, the U.S. Fish and Wildlife Service (USFWS) adopted the concept of adaptive resource management for regulating duck harvests in the United States. The adaptive approach explicitly recognizes that the consequences of hunting regulations cannot be predicted with certainty, and provides a framework for making objective decisions in the face of that uncertainty.

To date, adaptive harvest management (AHM) has been based midcontinent mallards, but efforts are being made to modify the decision-making protocol to account for mallards breeding eastward and westward of the midcontinent region The ability to regulate harvest on 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 is to vary hunting regulations among Flyways in a manner that recognizes each Flyway's unique breeding-ground derivation of mallards. This year, the USFWS intends to propose modifications to the current AHM protocol to account for eastern mallards. The USFWS has identified two basic alternatives in this report. The first involves a single, *joint optimization* for midcontinent and eastern mallards. The characteristic feature of this approach is that all regulatory choices, regardless of Flyway, would depend on the status of both midcontinent and eastern mallards (with the degree of dependence based on each harvest area's unique combination of the two mallard populations). The second alternative would entail two *separate optimizations*, in which the Atlantic Flyway regulation would be based exclusively on the status of eastern mallards, and the regulatory choice for the remainder of the country would be based exclusively on the status of midcontinent mallards.

A critical need for successful implementation of AHM is a set of regulatory alternatives that remain fixed for an extended period. For the 2000 season, the USFWS is maintaining the same regulatory alternatives as those used during1997-99. However, this year, the prediction of harvest rates associated with these regulatory alternatives must account for the possibility that the AHM protocol will be modified to allow a regulatory alternative in the Atlantic Flyway that is different from other Flyways. Therefore, it was necessary to predict harvest rates for each mallard population for the 25 combinations of regulatory alternatives (including the option of closed seasons) in the Atlantic Flyway and the remainder of the country. Based on this analysis, harvest rates of eastern mallards depend not only on the regulation in the Atlantic Flyway, but on the regulation in the remainder of the country. Harvest rates of midcontinent mallards depend almost completely on regulations in the three western Flyways.

Using current regulatory alternatives and associated harvest rates, both the joint-optimization and separate-optimization alternatives would be expected to greatly increase the frequency of liberal regulations in the Atlantic Flyway. Based on the joint optimization, however, there seems to be no discernible influence of midcontinent mallard status on optimal regulatory prescriptions for the Atlantic Flyway, nor does there seem to be any significant impact of eastern mallard status on optimal regulations in the remainder of the country. The notable exception is the case in which midcontinent population size is below goal and eastern population size is high; under these conditions the regulation in the three western Flyways would be slightly more liberal than it would be in the absence of a consideration of eastern mallard status. These results seem to follow from the high degree of spatial discrimination between the two mallard populations during the hunting season.

Optimal regulatory choices for the 2000 hunting season were calculated using: (1) objectives to maximize long-term cumulative harvest utility (i.e., harvest conditioned on a population goal) and harvest of midcontinent and eastern mallards, respectively; (2) all possible combinations of regulatory alternatives in the Atlantic Flyway and the remainder of the country; and (3) four alternative population models and their updated weights for midcontinent mallards, and eight alternative models of eastern mallards, equally weighted. Based on this year's breeding survey results of 10.5 million midcontinent mallards, 2.4 million ponds in Prairie Canada, and 890 thousand eastern mallards, the optimal regulatory choice for all Flyways is the liberal alternative (irrespective of whether the joint-optimization or separate-optimization alternative is applied).

A characteristic feature of AHM is the annual updating of model probabilities ("weights") based on a comparison of observed and predicted population sizes. This year, the weights associated with the midcontinent-mallard models reflect increased support for the hypothesis of strongly density-dependent reproduction. Model weights continue to suggest that hunting mortality is completely additive in midcontinent mallards. Weights associated with the models of eastern mallards will be updated for the first time next year.

BACKGROUND

The annual process of setting duck-hunting regulations in the United States is based on a system of resource monitoring, data analyses, and rule making (Blohm 1989). Each year, monitoring activities such as aerial surveys and hunter questionnaires provide information on harvest levels, population size, and habitat conditions. Data collected from this monitoring program are analyzed each year, and proposals for duck-hunting regulations are developed by the Flyway Councils, States, and U.S. Fish and Wildlife Service (USFWS). After extensive public review, the USFWS announces a regulatory framework within which States can set their hunting seasons.

In 1995, the USFWS adopted the concept of adaptive resource management (Walters 1986) for regulating duck harvests in the United States. The adaptive approach explicitly recognizes that the consequences of hunting regulations cannot be predicted with certainty, and provides a framework for making objective decisions in the face of that uncertainty (Williams and Johnson 1995). Inherent in the adaptive approach is an awareness that management performance can be maximized only if regulatory effects can be predicted reliably. Thus, adaptive management relies on an iterative cycle of monitoring, assessment, and decision making to clarify the relationships among hunting regulations, harvests, and waterfowl abundance.

In regulating waterfowl harvests, managers face four fundamental sources of uncertainty (Nichols et al. 1995*a*, Johnson et al. 1996, Williams et al. 1996):

(1) environmental variation - temporal and spatial variation in weather conditions and other key features of waterfowl habitat; an example is the annual change in the number of ponds in the Prairie Pothole Region, where water conditions influence duck reproductive success;

(2) partial controllability - the ability of managers to control harvest only within limits; the harvest resulting from a particular set of hunting regulations cannot be predicted with certainty because of variation in weather conditions, timing of migration, hunter effort, and other factors;

(3) partial observability - the ability to estimate key population variables (e.g., population size, reproductive rate, harvest) only within the precision afforded by existing monitoring programs; and

(4) structural uncertainty - an incomplete understanding of biological processes; a familiar example is the long-standing debate about whether harvest is additive to other sources of mortality or whether populations compensate for hunting losses through reduced natural mortality; structural uncertainty increases contentiousness in the decision-making process and decreases the extent to which managers can meet long-term conservation goals.

Adaptive harvest management (AHM) was developed as a systematic process for dealing objectively with these uncertainties. The key components of AHM (Johnson et al. 1993, Williams and Johnson 1995) include:

(1) a limited number of regulatory alternatives, which contain Flyway-specific season lengths, bag limits, and framework dates;

(2) a set of population models describing various hypotheses about the effects of harvest and environmental factors on waterfowl abundance;

(3) a measure of reliability (probability or "weight") for each population model; and

(4) a mathematical description of the objective(s) of harvest management (i.e., an "objective function"), by which harvest strategies can be evaluated.

These components are used in an optimization procedure to derive a harvest strategy, which specifies the appropriate regulatory choice for each possible combination of breeding population size, environmental conditions, and model weights (Johnson et al. 1997). The setting of annual hunting regulations then involves an iterative process:

(1) each year, an optimal regulatory alternative is identified based on resource and environmental conditions, and on

current model weights;

(2) after the regulatory decision is made, model-specific predictions for subsequent breeding population size are determined;

(3) when monitoring data become available, model weights are increased to the extent that observations of population size agree with predictions, and decreased to the extent that they disagree; and

(4) the new model weights are used to start another iteration of the process.

By iteratively updating model weights and optimizing regulatory choices, the process should eventually identify which model is most appropriate to describe the dynamics of the managed population. The process is optimal in the sense that it provides the regulatory choice each year necessary to maximize management performance. It is adaptive in the sense that the harvest strategy "evolves" to account for new knowledge generated by a comparison of predicted and observed population sizes.

MALLARD STOCKS AND FLYWAY MANAGEMENT

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 are also differences in optimal levels of sport harvest. The ability to regulate harvest on 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 is to vary hunting regulations among Flyways 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.

To date, AHM strategies have been based solely on the status of midcontinent mallards (Fig. 1). An optimal regulatory choice for midcontinent mallards has been based on breeding population size and prairie water conditions, and on the weights assigned to the alternative models of population dynamics. The same regulatory alternative has been applied in all four Flyways, although season lengths and bag limits always have been Flyway-specific. Efforts are underway, however, to extend the AHM process to account for mallards breeding westward and eastward of the midcontinent survey area. These mallard stocks make significant contributions to the total mallard harvest, particularly in the Atlantic and Pacific Flyways (Munro and Kimball 1982).

The optimization procedures currently employed in AHM can be extended to account for the population dynamics of eastern and western mallards, and for the manner in which these ducks distribute themselves among the Flyways during the hunting season. A globally optimal approach would allow for Flyway-specific regulatory strategies, which for each Flyway would represent an average of the optimal 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 involves:

(1) augmentation of the current decision criteria to include population and environmental variables relevant to eastern and western mallards (as based on models of population dynamics);

(2) revision of the objective function to account for harvest-management goals for mallards breeding outside the midcontinent region; and

(3) modification of the decision rules to allow independent regulatory choices among the Flyways.

Joint optimization of multiple stocks presents many challenges in terms of modeling, parameter estimation, and computation of harvest strategies. These challenges cannot always be overcome due to limitations in monitoring and assessment programs, and in access to sufficiently powerful computing resources. In these situations, however, it may be appropriate to impose constraints or simplifying assumptions that reduce the dimensionality of the problem. Although sub-optimal by definition, these constrained harvest strategies may perform nearly as well as those that are globally optimal, particularly in cases where breeding stocks differ little in their ability to support harvest, where Flyways don't receive significant numbers of birds from more than one breeding stock, or where management outcomes are highly uncertain due to poor ability to observe stock status,

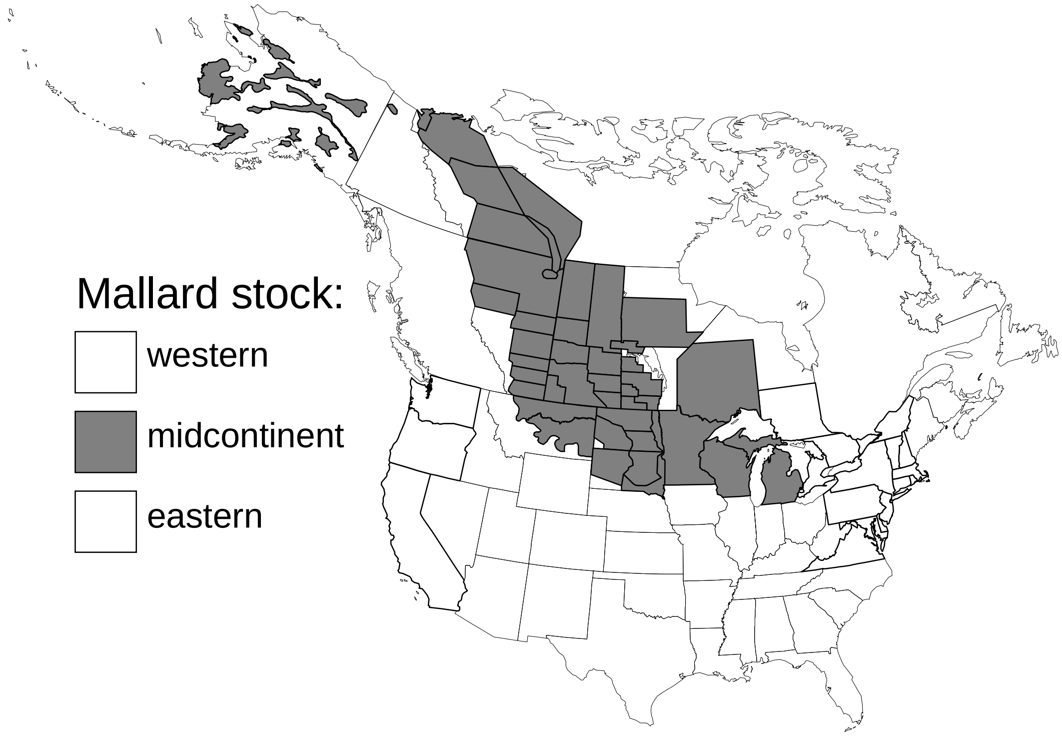


Fig. 1. Survey areas currently assigned to the western, midcontinent, and eastern stocks of mallards for the purpose of harvest management. Delineation of the western stock is preliminary pending additional information from British Columbia and other western areas with significant numbers of breeding mallards.

environmental variation, partial control of harvests, or limited understanding of stock dynamics.

MALLARD POPULATION DYNAMICS

Midcontinent Mallards

Midcontinent mallards are defined as those breeding in federal survey strata 1-18, 20-50, and 75-77, and in Minnesota, Wisconsin, and Michigan. Estimates of the entire midcontinent population are available only since 1992. Since then, the number of midcontinent mallards has grown by an average of 7.1 percent (SE = 1.2) per annum (Table 1).

The dynamics of midcontinent mallards are described by four alternative models, which result from combining two mortality and two reproductive hypotheses. Collectively, the models express uncertainty (or disagreement) about whether harvest is an additive or compensatory form of mortality (Burnham et al. 1984), and whether the reproductive process is weakly or strongly density dependent (i.e., the degree to which habitat availability limits reproductive success). The model with additive hunting mortality and weakly density-dependent recruitment (S_AR_W) leads to the most conservative harvest strategy, whereas the model with compensatory hunting mortality and strongly density-dependent recruitment leads to the most liberal strategy (S_CR_S). The other two models (S_AR_S and S_CR_W) lead to strategies that are intermediate between these extremes.

Table 1. Estimates[a] of midcontinent mallards breeding in the federal survey area (strata 1-18, 20-50, and 75-77) and the states of Minnesota, Wisconsin, and Michigan.

	Federal surveys		State surveys		Total	
Year	N	SE	N	SE	N	SE
1992	5976.1	241.0	977.9	118.7	6954.0	268.6
1993	5708.3	208.9	863.5	100.5	6571.8	231.8
1994	6980.1	282.8	1103.0	138.8	8083.1	315.0
1995	8269.4	287.5	1052.2	130.6	9321.6	304.5
1996	7941.3	262.9	945.7	81.0	8887.0	275.1
1997	9939.7	308.5	1026.1	91.2	10965.8	321.7
1998	9640.4	301.6	979.6	88.4	10620.0	314.3
1999	10805.7	344.5	957.5	100.6	11763.1	358.9
2000	9470.2	290.2	1031.1	85.3	10501.3	302.5

[a] In thousands.

Two other sources of uncertainty in mallard harvest management are acknowledged. Uncertainty about future environmental conditions is characterized by random variation in annual precipitation, which affects the number of ponds available during May in Canada. There is also an accounting for partial controllability, in which the link between regulations and harvest rates is imperfect due to uncontrollable factors (e.g., weather, timing of migration) that affect mallard harvest. A detailed description of the population dynamics of midcontinent mallards and associated sources of uncertainty are provided by Johnson et al. (1997) and in Appendix B.

A key component of the AHM process for midcontinent mallards is the annual updating of model weights (Appendix C). These weights describe the relative ability of the alternative models to predict changes in population size, and they ultimately influence the nature of the optimal harvest strategy. Model weights are based on a comparison of predicted and observed population sizes, with the updating leading to higher weights for models that prove to be good predictors (i.e., models with relatively small differences between predicted and observed population sizes) (Fig. 2). These comparisons account for sampling error (i.e., partial observability) in population size and pond counts, as well as for partial observability and controllability of harvest rates.

When the AHM process was initiated in 1995, the four alternative models of population dynamics were considered equally likely, reflecting a high degree of uncertainty (or disagreement) about harvest and environmental impacts on mallard abundance. This year, the updated weights reflect increased support for the hypothesis of strongly density-dependent reproduction (Table 2). Model weights continue to suggest that hunting mortality is completely additive in midcontinent mallards.

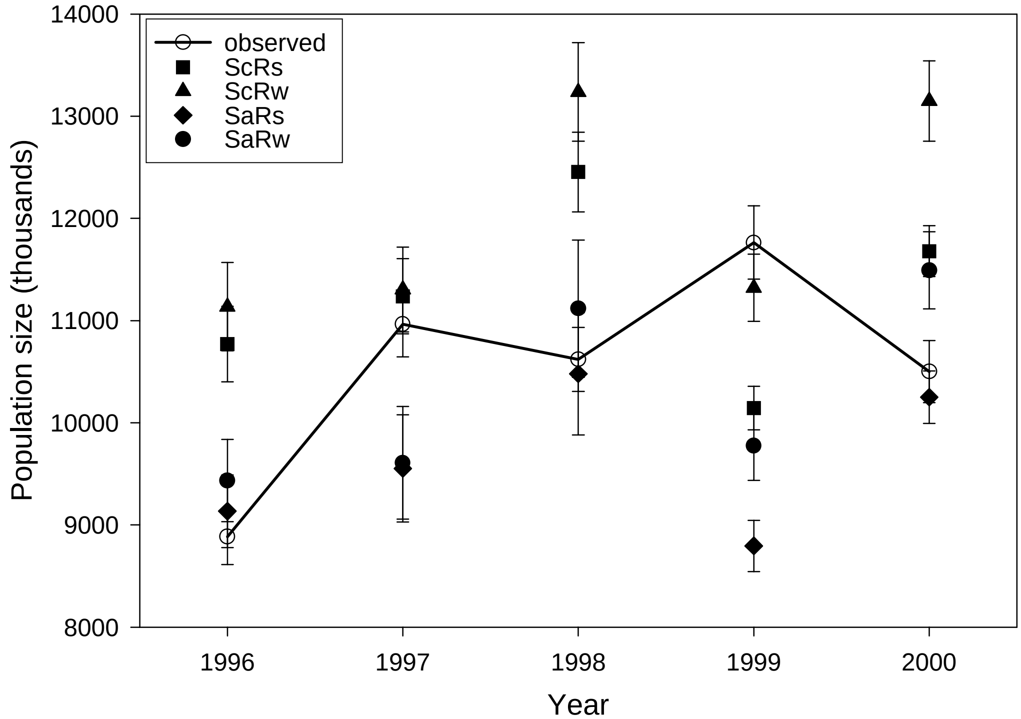


Fig. 2. Estimates of observed mallard population size (line with open circles) compared with predictions from four alternative models of population dynamics (ScRs = compensatory mortality and strongly density-dependent reproduction; ScRw = compensatory mortality and weakly density-dependent reproduction; SaRs = additive mortality and strongly density-dependent reproduction; SaRw = additive mortality and weakly density-dependent reproduction). Vertical bars represent one standard deviation on either side of the estimated population size.

Table 2. Temporal changes in probabilities ("weights") for alternative hypotheses of midcontinent mallard population dynamics.

		Model weights					
Mortality hypothesis	Reproductive hypothesis	1995	1996	1997	1998	1999	2000
Additive	Strong density dependence	0.25000	0.65479	0.53015	0.61311	0.60883	0.92176
Additive	Weak density dependence	0.25000	0.34514	0.46872	0.38687	0.38416	0.07822
Compensatory	Strong density dependence	0.25000	0.00006	0.00112	0.00001	0.00001	0.00001
Compensatory	Weak density dependence	0.25000	0.00001	0.00001	0.00001	0.00700	0.00001

Eastern Mallards

Eastern mallards are defined as those breeding in survey strata 51-54 and 56, and in New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, New York, Pennsylvania, New Jersey, Delaware, Maryland, and Virginia (Fig. 1). Midwinter counts and the Breeding Bird Survey provide evidence of rapid growth in the eastern mallard population during the 1970s and 1980s. Since 1990, however, the mallard population in the fixed-wing (strata 51-54 and 56) and northeastern plot (New Hampshire south through Virginia) surveys (Table 3) grew at an average rate of only 1.3 percent (SE = 0.8) per annum (Table 3).

Table 3. Estimates[a] of mallards breeding in the northeastern U.S. (plot survey from New Hampshire to Virginia) and eastern Canada (fixed-wing survey strata 51-54 and 56).

	Plot survey		Fixed-wing survey		Total	
Year	N	SE	N	SE	N	SE
1990	665.1	78.3	190.7	47.2	855.8	91.4
1991	779.2	88.3	152.8	33.7	932.0	94.5
1992	562.2	47.9	320.3	53.0	882.5	71.5
1993	683.1	49.7	292.1	48.2	975.2	69.3
1994	853.1	62.7	219.5	28.2	1072.5	68.7
1995	862.8	70.2	184.4	40.0	1047.2	80.9
1996	848.4	61.1	283.1	55.7	1131.5	82.6
1997	795.1	49.6	212.1	39.6	1007.2	63.4
1998	775.1	49.7	263.8	67.2	1038.9	83.6
1999	879.7	60.2	212.5	36.9	1092.2	70.6
2000	757.8	48.5	132.3	26.4	890.0	55.2

[a] In thousands.

The population dynamics of eastern mallards were studied extensively by Sheaffer and Malecki (1996), but the USFWS has not yet adopted a set of alternative models. A proposed model set for eastern mallards includes eight alternatives based on key uncertainties in reproductive and survival processes. This model set captures uncertainty about the relationship between fall age ratios (i.e., young/adult) and the Breeding Bird Survey (BBS) index, between the BBS index and actual population size as measured by aerial and ground surveys, and between the BBS index and natural-mortality rates of females. Each of the models is considered equally plausible given available data. In constructing this model set we chose to focus on the nature of density-dependent population regulation because of its pivotal role in determining sustainable harvest strategies. There continues to be a need for a more comprehensive examination of environmental variables (e.g., precipitation) that might influence survival and reproductive rates irrespective of population size. Mathematical details of the alternative models for eastern mallards are provided in Appendix B and in “Adaptive Harvest Management for Eastern Mallards: Progress Report - January 13, 2000" (available on the Internet at www.migratorybirds.fws.gov/reports/reports.html).

The proposed model set suggests that in the absence of harvest the eastern mallard population would stop growing (i.e., reach carrying capacity) somewhere between 1.23 and 3.49 million birds. All eight models suggest fairly liberal harvest strategies, at least by historical standards. For a population size >1 million, seven of the eight models suggest an allowable harvest rate in excess of that achieved under the most liberal regulatory alternative. All eight models suggest that hunting should be curtailed when the breeding-population size is <400 thousand.

Western Mallards

For purposes of this report, western mallards are defined as those breeding in the states of California, Oregon, and Washington. This definition may be modified if monitoring and assessment information becomes available for other important breeding areas of western mallards, such as British Columbia. A major effort to model the population dynamics of western mallards was completed in 1999. Estimated natural mortality rates of western mallards were similar to those of midcontinent mallards. As with midcontinent mallards, the relationship between harvest rates and annual survival rates was equivocal. Reproductive rates appear to be related to the size of the breeding population and to the amount of winter precipitation in California, Oregon, and Washington. A final set of population models, which describe how western mallards respond to harvest and uncontrolled environmental factors, as well as key uncertainties associated with those relationships, may be proposed next year.

HARVEST MANAGEMENT OBJECTIVES

Midcontinent Mallards

The basic harvest management objective for midcontinent mallards is to maximize cumulative harvest over the long term, which inherently requires conservation of a viable mallard population. Moreover, this objective is constrained to avoid regulatory decisions that could be expected to result in a subsequent population size below the goal of the North American Waterfowl Management Plan (NAWMP) (Fig. 3). According to this constraint, the value of harvest opportunity decreases proportionally as the difference between the goal and expected population size increases. This balance of harvest and population objectives results in a harvest strategy that is more conservative than that for maximizing long-term harvest, but more liberal than a strategy to attain the NAWMP goal regardless of effects on hunting opportunity. The current objective uses a population goal of 8.7 million mallards, which is based on the NAWMP goal of 8.1 million for the federal survey area and a goal 0.6 million for the combined states of Minnesota, Wisconsin, and Michigan.

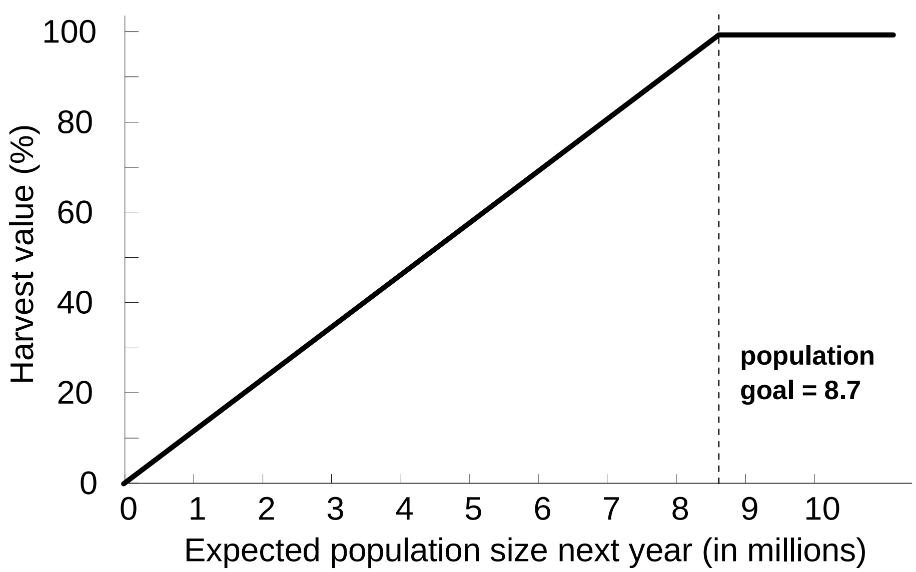


Fig. 3. The relative value of midcontinent mallard harvest, expressed as a function of breeding-population size expected in the subsequent year.

Eastern Mallards

The preliminary management objective for eastern mallards is to maximize long-term cumulative harvest. This objective is subject to change once the implications for average population size, variability in annual regulations, and other performance characteristics are better understood.

REGULATORY ALTERNATIVES

Evolution of Alternatives

When AHM was first implemented in 1995, three regulatory alternatives characterized as liberal, moderate, and restrictive were defined based on regulations used during 1979-84, 1985-87, and 1988-93, respectively (Appendix F, Table F-1). These regulatory alternatives also were considered for the 1996 hunting season. In 1997, the regulatory alternatives were modified to include: (1) the addition of a very restrictive alternative; (2) additional days and a higher duck bag-limit in the moderate and liberal alternatives; and (3) an increase in the bag limit of hen mallards in the moderate and liberal alternatives. The basic structure of the regulatory alternatives has remain unchanged since 1997, although in 1998 the U.S. Congress intervened to allow the option of extended framework dates and shorter seasons in some southern Mississippi Flyway States (Table 4).

Predictions of Mallard Harvest Rates

Since 1995, harvest rates of adult male mallards associated with the AHM regulatory alternatives have been predicted using harvest-rate estimates from 1979-84, which have been adjusted to reflect current specification of season lengths and bag limits, and for contemporary numbers of hunters. The prediction of mallard harvest rates is complicated this year by the possibility that modification of the AHM protocol to account for eastern mallards could allow for a regulatory alternative in the Atlantic Flyway that is different from the other Flyways. Therefore, it was necessary to predict harvest rates for midcontinent and eastern mallards for the 25 combinations of regulatory alternatives (including the option of closed seasons) in the Atlantic Flyway and the remainder of the country (Tables 5 and 6). As usual, these predictions are based only in part on band-recovery data, and rely heavily on models of hunting effort and success derived from hunter surveys (Appendix D). As such, these predictions have large sampling variances, and their accuracy is uncertain. Moreover, these predictions rely implicitly on an assumption that the historic relationship between hunting regulations (and harvest rates) in the U.S. and Canada will remain unchanged in the future. Currently, we have no way to judge whether this is a reasonable assumption. As a conservative measure, we assumed that when hunting seasons are closed in the U.S., then rates of harvest in Canada would be similar to those observed during 1988-93, which is the most recent period for which reliable estimates are available. Fortunately, optimal harvest strategies do not appear to be very sensitive to what we believe to be a realistic range of harvest-rate values associated with closed seasons in the U.S.

Adult female mallards tend to be less vulnerable to harvest than adult males, while young are more vulnerable (Table 7). Estimates of the relative vulnerability of adult females and young in the eastern mallard population tend to be higher and more variable than in the midcontinent population.

Table 4. Regulatory alternatives considered for the 2000 duck-hunting season.

	Flyway			
Regulation	Atlantic[a]	Mississippi[b]	Central[c]	Pacific[d]
Shooting hours	one-half hour before sunrise to sunset for all Flyways			
Framework dates	Oct 1 - Jan 20	Saturday closest to October 1 and Sunday closest to January 20		
Season length (days)				
Very restrictive	20	20	25	38
Restrictive	30	30	39	60
Moderate	45	45	60	86
Liberal	60	60	74	107
Bag limit (total / mallard / female mallard)				
Very restrictive	3 / 3 / 1	3 / 2 / 1	3 / 3 / 1	4 / 3 / 1
Restrictive	3 / 3 / 1	3 / 2 / 1	3 / 3 / 1	4 / 3 / 1
Moderate	6 / 4 / 2	6 / 4 / 1	6 / 5 / 1	7 / 5 / 2
Liberal	6 / 4 / 2	6 / 4 / 2	6 / 5 / 2	7 / 7 / 2

[a] The states of Maine, Massachusetts, Connecticut, Pennsylvania, New Jersey, Maryland, Delaware, West Virginia, Virginia, and North Carolina are permitted to exclude Sundays, which are closed to hunting, from their total allotment of season days.

[b] In the states of Alabama, Mississippi, and Tennessee, in the moderate and liberal alternatives, there is an option for a framework closing date of January 31 and a season length of 38 days and 51 days, respectively.

[c] The High Plains Mallard Management Unit is allowed 8, 12, 23, and 23 extra days under the very restrictive, restrictive, moderate, and liberal alternatives, respectively.

[d] The Columbia Basin Mallard Management Unit is allowed seven extra days under the very restrictive, restrictive, and moderate alternatives.

Table 5. Predicted harvest rates of adult male <u>midcontinent</u> mallards under the current regulatory alternatives, and allowing for a regulatory choice in the Atlantic Flyway that could differ from the remaining Flyways.

Regulatory alternative in the three western Flyways	Regulatory alternative in the Atlantic Flyway	Harvest rate	SE
Closed	Closed	0.0088	0.0030
Closed	Very restrictive	0.0193	0.0052
Closed	Restrictive	0.0197	0.0052
Closed	Moderate	0.0203	0.0052
Closed	Liberal	0.0207	0.0053
Very restrictive	Closed	0.0521	0.0103
Very restrictive	Very restrictive	0.0526	0.0106
Very restrictive	Restrictive	0.0530	0.0107
Very restrictive	Moderate	0.0536	0.0108
Very restrictive	Liberal	0.0540	0.0109
Restrictive	Closed	0.0658	0.0136
Restrictive	Very restrictive	0.0662	0.0142
Restrictive	Restrictive	0.0665	0.0142
Restrictive	Moderate	0.0672	0.0143
Restrictive	Liberal	0.0676	0.0144
Moderate	Closed	0.1094	0.0250
Moderate	Very restrictive	0.1104	0.0264
Moderate	Restrictive	0.1108	0.0264
Moderate	Moderate	0.1114	0.0266
Moderate	Liberal	0.1118	0.0266
Liberal	Closed	0.1282	0.0304
Liberal	Very restrictive	0.1291	0.0320
Liberal	Restrictive	0.1295	0.0321
Liberal	Moderate	0.1301	0.0322
Liberal	Liberal	0.1305	0.0323

Table 6. Predicted harvest rates of adult male <u>eastern</u> mallards under the current regulatory alternatives, and allowing for a regulatory choice in the Atlantic Flyway that could differ from the remaining Flyways.

Regulatory alternative in the Atlantic Flyway	Regulatory alternative in the three western Flyways	Harvest rate	SE
Closed	Closed	0.0248	0.0050
Closed	Very restrictive	0.0927	0.0142
Closed	Restrictive	0.0959	0.0138
Closed	Moderate	0.1062	0.0131
Closed	Liberal	0.1110	0.0130
Very restrictive	Closed	0.1130	0.0211
Very restrictive	Very restrictive	0.1212	0.0205
Very restrictive	Restrictive	0.1245	0.0203
Very restrictive	Moderate	0.1348	0.0201
Very restrictive	Liberal	0.1395	0.0202
Restrictive	Closed	0.1237	0.0025
Restrictive	Very restrictive	0.1320	0.0220
Restrictive	Restrictive	0.1352	0.0219
Restrictive	Moderate	0.1455	0.0218
Restrictive	Liberal	0.1502	0.0219
Moderate	Closed	0.1407	0.0257
Moderate	Very restrictive	0.1473	0.0252
Moderate	Restrictive	0.1522	0.0253
Moderate	Moderate	0.1625	0.0254
Moderate	Liberal	0.1672	0.0255
Liberal	Closed	0.1506	0.0282
Liberal	Very restrictive	0.1588	0.0279
Liberal	Restrictive	0.1621	0.0279
Liberal	Moderate	0.1724	0.0280
Liberal	Liberal	0.1771	0.0282

Table 7. Mean harvest vulnerability (SE) of adult female and young mallards, relative to adult males, based on band-recovery data, 1979-95.

Mallard population	Age and sex		
	Adult females	Young females	Young males
Midcontinent	0.748 (0.108)	1.188 (0.138)	1.361 (0.144)
Eastern	0.985 (0.145)	1.320 (0.264)	1.449 (0.211)

OPTIMAL HARVEST STRATEGIES

Joint Optimization of Midcontinent and Eastern Mallards

We derived an optimal regulatory strategy for the Flyways based on a joint optimization of the midcontinent and eastern mallards. We specified the following conditions to derive this strategy:

(1) an objective function that maximizes the long-term cumulative sum of eastern-mallard harvest and midcontinent-mallard harvest utility (where harvest utility is a function of both harvest and population size; see Fig.3);

(2) all possible combinations of current regulatory alternatives in the Atlantic Flyway and the remainder of the country (Tables 5 and 6), and a simplifying assumption of perfect controllability (i.e., deterministic harvest rates); and

(3) current population models and associated weights for midcontinent mallards, and the eight alternative models of eastern mallards, equally weighted.

The optimal regulatory choice for the Atlantic Flyway rarely diverges from the liberal alternative, even when the status of midcontinent mallards is poor (Table 8). The status of eastern mallards has more effect on the optimal regulatory choice in the remainder of the country, but the effect is minimal and observed only when midcontinent mallards fall below the population goal. These results are consistent with the high degree of spatial discrimination between the two populations during the hunting season.

Table 8. A Flyway-specific regulatory strategy, based on a joint optimization of midcontinent and eastern mallards. The objective function, models of population dynamics, and harvest rates associated with the regulatory alternatives are described elsewhere in this report.

Midcontinent mallard population (millions)	Ponds in Prairie Canada (millions)	Eastern mallard population (millions)	Regulation in the three western Flyways	Regulation in the Atlantic Flyway
3	1-5	0.5-1.5		L
3	6	0.5		M
3	6	0.6-1.5		L
3	7	0.5		M
3	7	0.6-1.5		L
4	1-6	0.5-1.5		L

Midcontinent mallard population (millions)	Ponds in Prairie Canada (millions)	Eastern mallard population (millions)	Regulation in the three western Flyways	Regulation in the Atlantic Flyway
4	7	0.5		M
4	7	0.6-1.5		L
5	1-5	0.5-1.5		L
5	6	0.5		L
5	6	0.6-1.5	VR	L
5	7	0.5-0.6	VR	L
5	7	0.7-1.5	R	L
6	1-2	0.5-1.5		L
6	3	0.5-1.5	VR	L
6	4	0.5-0.6	VR	L
6	4	0.7-1.5	R	L
6	5	0.5-0.9	R	L
6	5	1.0-1.5	R	L
6	6	0.5	M	M
6	6	0.6-1.5	M	L
6	7	0.5	M	M
6	7	0.6-1.5	M	L
7	1	0.5-0.7	VR	L
7	1	0.8-1.5	R	L
7	2	0.5-1.5	R	L
7	3	0.5-0.7	R	L
7	3	0.8-1.5	M	L
7	4	0.5	M	M
7	4	0.6-1.5	M	L
7	5	0.5	L	M
7	5	0.6-1.5	L	L
7	6-7	0.5-1.5	L	L
8	1	0.5-1.5	M	L
8	2	0.5-1.0	M	L
8	2	1.1-1.3	L	L
8	2	1.4-1.5	M	L

Midcontinent mallard population (millions)	Ponds in Prairie Canada (millions)	Eastern mallard population (millions)	Regulation in the three western Flyways	Regulation in the Atlantic Flyway
8	3	0.5	M	L
8	3	0.6-1.5	L	L
8	4-7	0.5-1.5	L	L
9	1	0.5	L	M
9	1	0.6-1.5	L	L
9	2	0.5	L	M
9	2	0.6-1.5	L	L
9	3-7	0.5-1.5	L	L
10	1	0.5	L	M
10	1	0.6-1.5	L	L
10	2-7	0.5-1.5	L	L
11-12	1-7	0.5-1.5	L	L

Blank cells in Table 8 (and in other harvest strategies in this report) represent combinations of population size and environmental conditions that are insufficient to support an open season, given current regulatory alternatives. In the case of midcontinent mallards, the prescriptions for closed seasons largely are a result of the harvest-management objective, which emphasizes population growth at the expense of hunting opportunity when mallard numbers are below the NAWMP goal. However, limited harvests at low population levels would not be expected to impact long-term population viability. Therefore, the decision to actually close the hunting season would depend on both biological and sociological considerations.

Based on the harvest strategy in Table 8, the benefits of a joint optimization of midcontinent and eastern mallards appear to be negligible (at least in terms of currently specified objectives) because regulations within each harvest area are affected principally by a single stock of mallards. However, the computational costs associated with the joint optimization of midcontinent and eastern mallards is considerable. We experienced severe limitations in our ability to fully explore the implications of all sources of uncertainty (e.g., partial control of harvests), for all possible system states, even when using state-of-the-art Pentium workstations.

Stock-specific Optimization

An alternative, constrained approach is to conduct two separate optimizations, in which the Atlantic Flyway regulation is based exclusively on the status of eastern mallards, and the regulatory choice for the remainder of the country is based exclusively on the status of midcontinent mallards. From the perspectives of hunting opportunity and resource conservation, there is little apparent difference between the joint optimization and this constrained approach. Moreover, the advantage of the stock-specific optimization is that it would make more computing resources available for use in joint optimizations of mallards and other species important to recreational hunting (e.g., wood ducks, black ducks).

We used the the separate-optimization approach to optimize regulatory choices for the Atlantic Flyway and the remainder of the country based on the status of eastern and midcontinent mallards, respectively. Subject to this constraint, the optimal regulatory strategy for the western three Flyways was derived using: (1) current regulatory alternatives; (2) the four alternative models and associated weights for midcontinent mallards; and (3) the dual objectives to maximize long-term cumulative harvest and achieve a population goal of 8.7 million midcontinent mallards. We assumed that the regulatory choice in the Atlantic Flyway would have no discernable effect on the overall harvest rate of midcontinent mallards or, if an effect existed, that it was accounted for by the range of variation associated with harvest rates when regulatory choices are not Flyway-specific. The resulting harvest strategy (Table 9) is substantially more liberal than that for midcontinent mallards in 1999, due to the increase in probability associated with the hypothesis of strongly density-dependent reproduction. The optimal harvest strategies based on midcontinent mallards for the 1995-99 seasons are provided in Appendix F (Tables F-2 to F-6) so that the reader can assess how the harvest strategy has "evolved" over time.

Table 9. Optimal regulatory choices[a] in the three western Flyways during the 2000 hunting season. This strategy is based on current regulatory alternatives, on current midcontinent-mallard models and weights, and on the dual objectives of maximizing long-term cumulative harvest and achieving a population goal of 8.7 million midcontinent mallards.

	Ponds[b]									
Mallards[c]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
<4.5										
4.5										VR
5.0						VR	VR	VR	R	R
5.5	VR	VR	VR	VR	VR	R	R	R	M	M
6.0	VR	R	R	R	R	M	M	M	L	L
6.5	R	R	M	M	M	M	L	L	L	L
7.0	M	M	M	M	L	L	L	L	L	L
7.5	M	M	L	L	L	L	L	L	L	L
8.0	L	L	L	L	L	L	L	L	L	L
>8.0	L	L	L	L	L	L	L	L	L	L

[a] VR = very restrictive, R = restrictive, M = moderate, and L = liberal.
[b] Estimated number of ponds in Prairie Canada in May, in millions.
[c] Estimated number of midcontinent mallards during May, in millions.

We simulated the use of the harvest strategy in Table 9 with the four population models and current weights to determine expected performance characteristics. Assuming that regulatory choices adhered to this strategy, the annual harvest and breeding population size would average 1.29 (SE = 0.42) million and 8.05 (SE = 1.00) million, respectively.

Based on a midcontinent population size of 10.5 million mallards and 2.4 million ponds in Prairie Canada, the optimal regulatory choice for the Pacific, Central, and Mississippi Flyways in 2000 is the liberal alternative.

We optimized the regulatory choice for the Atlantic Flyway based on: (1) current regulatory alternatives; (2) the eight alternative models of population dynamics, equally weighted; and (3) an objective to maximize long-term cumulative harvest. Unlike the situation with midcontinent mallards, however, the regulatory choice in the three western Flyways has a discernable effect on the harvest rate of eastern mallards (see Table 6). Therefore, the optimal regulatory choice for the Atlantic Flyway depends on the regulatory choice in the other Flyways. To avoid making the regulatory choice in the Atlantic Flyway conditional on regulations elsewhere, we estimated the expected harvest rates of eastern mallards when managers lack *a priori* knowledge of the chosen regulation in the western three Flyways. We did this by taking a weighted average of the estimated harvest rates associated with each of the possible regulatory alternatives in the western Flyways, for each possible regulatory alternative in the Atlantic Flyway (see Table 6). The weights were derived using simulations of the midcontinent-mallard strategy described above to determine the expected frequency of regulatory choices in the western Flyways. We estimated the variances associated with each regulatory alternative in the Atlantic Flyway using Monte Carlo simulations, based on the variances in Table 6 and their associated weights. The resulting regulatory strategy (Table 10) is very liberal (at least by historical standards), and is characterized by a lack of intermediate regulations. The strategy exhibits this behavior largely because of the small differences in harvest rate among regulatory alternatives.

Table 10. Optimal regulatory choices[a] for the Atlantic Flyway during the 2000 hunting season. This strategy is based on current regulatory alternatives, on eight alternative models of eastern mallards (equally weighted), and on an objective to maximize long-term cumulative harvest.

Mallards[b]	Regulation
<500	
500	R
550	L
>550	L

[a] VR = very restrictive, R = restrictive, M = moderate, and L = liberal.
[b] Estimated number of eastern mallards in the combined fixed-wing and northeastern plot surveys, in thousands.

We simulated the use of the harvest strategy in Table 10 to determine expected performance characteristics. Assuming that harvest management adhered to this strategy, the annual harvest and breeding population size would average 387 (SE = 99) thousand and 1.06 (SE = 0.2) million, respectively.

Based on a breeding population size of 890 thousand mallards, the optimal regulatory choice for the Atlantic Flyway in 2000 is the liberal alternative.

CURRENT AHM PRIORITIES

Midcontinent Mallards

The current AHM specifications for midcontinent mallards have been in place since 1995. Therefore, the AHM technical working group is reviewing all aspects of these specifications to determine if revisions are warranted. This review is focusing principally on the set of models describing population dynamics, and on the method by which the weights associated with alternative models are updated. Unfortunately, efforts to develop mechanistic models of density-dependent survival have been stymied by programming problems and a lack of demographic and environmental data at the appropriate scales. Patuxent Wildlife Research Center has recently acquired additional staff to help address the problems. On a more promising note, it appears that some of the variability in reproductive success can be explained by the distribution of ponds in the Prairie Pothole Region. The AHM working group is exploring the implications of this spatial effect, as well as alternative forms of the relationships among reproductive success and important environmental factors. With respect to the updating of model weights, there is an agreed-upon need to account for all sources of variation in the updating procedure, whether or not the variation is explained by the models. This will be more straightforward once the model set for mallards has been revised. The inclusion of additional variance components in the updating procedure likely will slow the movement of model weights, and perhaps be more reflective of actual rates of learning.

The ability to accurately determine model performance also is influenced by our ability to estimate actual harvest rates. Since 1994 there has been a systematic effort to increase the rate at which hunters report band recoveries, and this effort has made it temporarily difficult to estimate the harvest rate of mallards. A large-scale study to evaluate recent changes in band-reporting rate is in the planning stage, with implementation to occur in 2001 or 2002. As part of that planning effort, a pilot study was conducted in southern Saskatchewan in 1998 and again in 1999 to obtain a preliminary estimate of band-reporting rates for adult male mallards. Results of preliminary analyses suggested a constant reporting rate of 0.84 (SE = 0.05) for the 1998 and 1999 hunting seasons. The pilot study will continue for the 2000 hunting season.

Eastern Mallards

There are many possible approaches to modifying the AHM protocol to account for eastern mallards, but we have identified two basic alternatives in this report. The first involves a single, joint optimization for midcontinent and eastern mallards. This approach would result in optimal regulatory choices for the Atlantic Flyway and for the remainder of the country, for each possible combination of midcontinent population size, pond numbers in Canada, and eastern mallard population size. The characteristic feature of this approach is that all regulatory choices, regardless of Flyway, would depend on the status of both midcontinent and eastern mallards (with the degree of dependence based on each harvest area's unique combination of the two mallard populations). This joint-optimization approach is globally optimal, in the sense that it would be expected to outperform all other alternatives in terms of harvest-management objectives for midcontinent and eastern mallards. The second alternative would entail two separate optimizations, in which the Atlantic Flyway regulation would be based exclusively on the status of eastern mallards, and the regulatory choice for the remainder of the country would be based exclusively on the status of midcontinent mallards. This approach is sub-optimal by definition because neither the Atlantic Flyway nor the three western Flyways (as a unit) derive their harvest exclusively from one mallard population. However, the joint-optimization alternative appears to provide little advantage over the separate-optimization alternative in terms of meeting harvest-management objectives for mallards. This result follows from the high degree of spatial discrimination between the two mallard populations during the hunting season.

The USFWS intends to make appropriate modifications to the existing AHM protocol to account for eastern mallards. However, the USFWS seeks a discussion and review of the relevant issues among the Flyway Councils and States prior to any changes. The USFWS will propose modifications to the current AHM protocol when late-season regulatory frameworks are proposed in August 2000.

Western Mallards

The Study Committee of the Pacific Flyway Council has assumed responsibility for recommending a set of alternative models for western mallards. These models will be based on the assessment prepared by the New York Cooperative Fish and Wildlife Research Unit, but also must satisfactorily address several modeling issues raised by the AHM technical working group (see the latest report from the working group on the Internet at www.migratorybirds.fws.gov/reports/reports.html). The USFWS will assume responsibility for proposing modifications to AHM protocols once a final model set is agreed upon.

Pintails

The Study Committee of the Pacific Flyway Council and Patuxent Wildlife Research Center are exploring alternative population models for pintails, based on a recent assessment by the New York Cooperative Fish and Wildlife Research Unit. As with western mallards, however, a number of critical modeling issues must be addressed before AHM can be implemented for pintails. Also, additional analyses will be required to model the relationship between hunting regulations and pintail harvests. While these analyses are being conducted, the management community should begin discussion about whether to: (a) optimize the selection of a regulatory alternative based on the joint status of pintails and mallards; (b) set hunting regulations for pintails independent of mallards; or (c) set pintail bag limits (or other regulatory tools) conditioned on the choice of regulatory alternatives prescribed for mallards.

Information and Education Needs

There is growing concern that the technical complexity of AHM is preventing some waterfowl managers from fully participating in the development of AHM protocols. The AHM technical working group will take the following actions to help address this concern: (a) a "refresher" workshop on AHM will be held in December 2000; the workshop will be conducted principally for members of the AHM working group, although other technical personnel may be invited; and (b) the AHM working group will develop 1-day and 2-hour team-taught courses, which could be offered on short notice throughout the country; course work and applications also may be presented on the Internet.

AHM and Considerations of Hunter Preferences

In spite of significant progress in defining harvest-management objectives, there continue to be unresolved disagreements among stakeholders about how to value harvest benefits and how those benefits should be shared. Resolution of these disagreements might be facilitated by a better understanding of how regulations affect hunter satisfaction. Most Flyway Council members have expressed an interested in coordinated, nationwide hunter surveys to monitor the opinions of waterfowl hunters. Despite agreement on the need for better data, however, the specific use and application of these data in the AHM process remain unclear. Therefore, the AHM working group has suggested that managers engage in a dialogue to better define "hunter satisfaction," and how it might be affected by variation in hunting regulations. To facilitate this dialogue, the AHM working will: (a) investigate regional differences in harvest and other metrics of hunter activity and success; and (b) consider facilitated focus groups among technicians and administrators to explore expectations related to the effect of regulations on hunter satisfaction.

Revision of the Set of Regulatory Alternatives

There currently are no guidelines describing when changes to the set of regulatory alternatives might be considered. Therefore, the AHM working group is considering the development of a schedule for making periodic revisions, as well as criteria governing the nature of any changes. The AHM working group currently is soliciting input from the Flyway Councils, and will address the issue during their meeting in April 2001.

LITERATURE CITED

Anderson, D. R., and C. J. Henny. 1972. Population ecology of the mallard. I. A review of previous studies and the distribution and migration from breeding areas. U. S. Fish and Wildl. Serv. Resour. Pub. 105. 166pp.

Blohm, R. J. 1989. Introduction to harvest - understanding surveys and season setting. Proc. Inter. Waterfowl Symp. 6:118-133.

Burnham, K. P., G. C. White, and D. R. Anderson. 1984. Estimating the effect of hunting on annual survival rates of adult mallards. J. Wildl. Manage. 48:350-361 .

Johnson, F.A., C. T. Moore, W. L. Kendall, J. A. Dubovsky, D. F. Caithamer, J. R. Kelley, Jr., and B. K. Williams. 1997. Uncertainty and the management of mallard harvests. J. Wildl. Manage. 61:202-216.

_____, B. K. Williams, J. D. Nichols, J. E. Hines, W. L. Kendall, G. W. Smith, and D. F. Caithamer. 1993. Developing an adaptive management strategy for harvesting waterfowl in North America. Trans. North Am. Wildl. Nat. Resour. Conf. 58:565-583.

_____, _____, and P. R. Schmidt. 1996. Adaptive decision-making in waterfowl harvest and habitat management. Proc. Inter. Waterfowl Symp. 7:26-33.

Munro, R. E., and C. F. Kimball. 1982. Population ecology of the mallard. VII. Distribution and derivation of the harvest. U.S. Fish and Wildl. Serv. Resour. Pub. 147. 127pp.

Nichols, J. D., F. A. Johnson, and B. K. Williams. 1995*a*. Managing North American waterfowl in the face of uncertainty. Ann. Rev. Ecol. Syst. 26:177-199.

Sheaffer, S. E., and R. A. Malecki. 1996. Quantitative models for adaptive harvest management of mallards in eastern North America. New York Coop. Fish and Wildl. Res. Unit, Cornell Univ., Ithaca, unpubl. rep. 116pp.

Walters, C. J. 1986. Adaptive management of renewable resources. MacMillan Publ. Co., New York, N.Y. 374pp.

Williams, B. K., and F. A. Johnson. 1995. Adaptive management and the regulation of waterfowl harvests. Wildl. Soc. Bull. 23:430-436.

_____, _____, and K. Wilkins. 1996. Uncertainty and the adaptive management of waterfowl harvests. J. Wildl. Manage. 60:223-232.

APPENDIX A: AHM Working Group

Bob Blohm
U.S. Fish and Wildlife Service
Arlington Square, Room 634
4401 North Fairfax Drive,
Arlington, VA 22203
phone: 703-358-1966
fax: 703-358-2272
e-mail: robert_blohm@fws.gov

Scott Baker
Dept. of Wildlife, Fisheries, & Parks
P.O. Box 378
Redwood, MS 39156
phone: 601-661-0294
fax: 601-364-2209
e-mail: mahannah1@aol.com

Brad Bortner
U.S. Fish and Wildlife Service
911 NE 11th Ave.
Portland, OR 97232-4181
phone: 503-231-6164
fax: 503-231-2364
e-mail: brad_bortner@fws.gov

Frank Bowers
U.S. Fish and Wildlife Service
1875 Century Blvd., Suite 345
Atlanta, GA 30345
phone: 404-679-7188
fax: 404-679-7285
e-mail: frank_bowers@fws.gov

Dave Case
D.J. Case & Associates
607 Lincolnway West
Mishawaka, IN 46544
phone: 219-258-0100
fax: 219-258-0189
e-mail: djcase@csi.com

Dale Caswell
Canadian Wildlife Service
123 Main St. Suite 150
Winnepeg, Manitoba, CANADA R3C 4W2
phone: 204-983-5260
fax: 204-983-5248
e-mail: dale.caswell@ec.gc.ca

John Cornely
U.S. Fish and Wildlife Service
P.O. Box 25486, DFC
Denver, CO 80225
phone: 303-236-8676
fax: 303-236-8680
e-mail: john_cornely@fws.gov

Gary Costanzo
Dept. of Game and Inland Fisheries
5806 Mooretown Road
Williamsburg, VA 23188
phone: 757-253-4180
fax: 757-253-4182
e-mail: gcostanzo@dgif.state.va.us

Jim Dubovsky
U.S. Fish & Wildlife Service
P.O. Box 25486 DFC
Denver, CO 80225-0486
phone: 301-497-5870
fax: 301-497-5706
e-mail: james_dubovsky@fws.gov

Ken Gamble
U.S. Fish and Wildlife Service
608 Cherry Street, Room 119
Columbia, MO 65201
phone: 573-876-1915
fax: 573-876-1917
e-mail: ken_gamble@fws.gov

Jim Gammonley
Division of Wildlife
317 West Prospect
Fort Collins, CO 80526
phone: 970-472-4379
fax: 970-472-4457
e-mail: jim.gammonley@state.co.us

George Haas
U.S. Fish and Wildlife Service
300 Westgate Center Drive
Hadley, MA 01035-9589
phone: 413-253-8576
fax: 413-253-8480
e-mail: george_haas@fws.gov

Jeff Haskins
U.S. Fish and Wildlife Service
P.O. Box 1306
Albuquerque, NM 87103
phone: 505-248-6827 ext 30
fax: 505-248-7885
e-mail: jeff_haskins@fws.gov

Dale Humburg
Dept. of Conservation
Fish & Wildlife Research Center
1110 South College Ave.
Columbia, MO 65201
phone: 573-882-9880 ext 3246
fax: 573-882-4517
e-mail: humbud@mail.conservation.state.mo.us

Fred Johnson
U.S. Fish & Wildlife Service
11510 American Holly Drive
Laurel, MD 20708-4017
phone: 301-497-5861
fax: 301-497-5706
e-mail: fred_a_johnson@fws.gov

Mike Johnson
Game and Fish Department
100 North Bismarck Expressway
Bismarck, ND 58501-5095
phone: 701-328-6319
fax: 701-328-6352
e-mail: mjohnson@state.nd.us

Jim Kelley
U.S. Fish and Wildlife Service
Division of Migratory Bird Management
BH Whipple Federal Building, 1 Federal Drive
Fort Snelling, MN 55111-4056
phone: 612-713-5409
fax: 612-713-5286
e-mail: james_r_kelley@fws.gov

Bill Kendall
U.S.G.S. Patuxent Wildlife Research Center
11510 American Holly Drive
Laurel, MD 20708-4017
phone: 301-497-5868
fax: 301-497-5666
e-mail: william_kendall@usgs.gov

Don Kraege
Dept. of Fish & Wildlife
600 Capital Way North
Olympia. WA 98501-1091
phone: 360-902-2509
fax: 360-902-2162
e-mail: kraegdkk@dfw.wa.gov

Bob Leedy
U.S. Fish and Wildlife Service
1011 East Tudor Road
Anchorage, AK 99503-6119
phone: 907-786-3446
fax: 907-786-3641
e-mail: robert_leedy@fws.gov

Mary Moore
U.S. Fish & Wildlife Service
206 Concord Drive
Watkinsville, GA 30677
phone: 706-769-2359
fax: 706-769-2359
e-mail: mary_moore@fws.gov

Jim Nichols
Patuxent Wildlife Research Center
11510 American Holly Drive
Laurel, MD 20708-4017
phone: 301-497-5660
fax: 301-497-5666
e-mail: jim_nichols@usgs.gov

Mark Otto
U.S. Fish & Wildlife Service
11500 American Holly Drive
Laurel, MD 20708-4016
phone: 301-497-5872
fax: 301-497-5871
e-mail: mark_otto@fws.gov

Paul Padding
U.S. Fish & Wildlife Service
10815 Loblolly Pine Drive
Laurel, MD 20708-4028
phone: 301-497-5980
fax: 301-497-5981
e-mail: paul_padding@fws.gov

Michael C. Runge
Field of Natural Resources
Cornell University
Ithaca, NY 14850
phone: 607-273-8127
e-mail: mcr5@cornell.edu

Jerry Serie
U.S. Fish & Wildlife Service
12100 Beech Forest Road
Laurel, MD 20708-4038
phone: 301-497-5851
fax: 301-497-5885
e-mail: jerry_serie@fws.gov

Dave Sharp
U.S. Fish and Wildlife Service
P.O. Box 25486, DFC
Denver, CO 80225-0486
phone: 303-275-2385
fax: 303-275-2384
e-mail: dave_sharp@fws.gov

Sue Sheaffer
Coop. Fish & Wildl. Research Unit
Fernow Hall, Cornell University
Ithaca, NY 14853
phone: 607-255-2837
fax: 607-255-1895
e-mail: ses11@cornell.edu

Graham Smith
U.S. Fish & Wildlife Service
11500 American Holly Drive
Laurel, MD 20708-4016
phone: 301-497-5860
fax: 301-497-5871
e-mail: graham_smith@fws.gov

Bryan Swift
Dept.of Environmental Conservation
108 Game Farm Road, Building 9
Delmar, NY 12054-9767
phone: 518-78-3022
fax: 518-478-3004
e-mail: bl.swift@gw.dec.state.ny.us

Bob Trost
U.S. Fish and Wildlife Service
911 NE 11th Ave.
Portland, OR 97232-4181
phone: 503-231-6162
fax: 503-231-6228
e-mail: robert_trost@fws.gov

Khristi Wilkins
U.S. Fish & Wildlife Service
11500 American Holly Drive
Laurel, MD 20708-4016
phone: 301-497-5557
fax: 301-497-5971
e-mail: khristi_a_wilkins@fws.gov

Dan Yparraguirre
Dept. of Fish & Game
1416 Ninth Street
Sacramento, CA 94244
phone: 916-653-8709
fax: 916-653-1019
e-mail: dyparrag@hq.dfg.ca.gov

APPENDIX B: Mallard Population Models

State and random variable definitions:

```
MBPOP        /* state variable index - midcontinent population */
PONDS        /* state variable index - Canadian ponds */
EBPOP        /* state variable index - eastern population */
RRES         /* random variable index - recruitment residuals for eastern population */
SSFVAR       /* random variable index - female summer survival - eastern population */
SSFRES       /* random variable index - residuals for female summer survival - eastern population */
PPT          /* random variable index - Canadian Prairie precipitation */
PROP         /* random variable index - proportion of midcontinent population in Lake States */
MRATE        /* random variable index - harvest rate - midcontinent adult males */
ERATE        /* random variable index - harvest rate - eastern adult males */
outcome[]    /* outcome of random variable */
cur_state[]  /* current value of state variable */
nxt_state[]  /* value of state variable in next time step */
```

Eastern mallard parameters:

```
wtr1b1s1     /* weight for model r1b1s1 - neg. exp. reproduction, log. BBS, constant survival */
wtr1b1s2     /* weight for model r1b1s2 - neg. exp. reprod., log. BBS, density-dependent survival */
wtr1b2s1     /* weight for model r1b2s1 - neg. exp. reprod., exp. BBS, constant survival */
wtr1b2s2     /* weight for model r1b2s2 - neg. exp. reprod., exp. BBS, density-dependent survival */
wtr2b1s1     /* weight for model r2b1s1 - logistic reprod., log. BBS, constant survival */
wtr2b1s2     /* weight for model r2b1s2 - logistic reprod., log. BBS, density-dependent survival */
wtr2b2s1     /* weight for model r2b2s1 - logistic reprod., exp. BBS, constant survival */
wtr2b2s2     /* weight for model r2b2s2 - logistic reprod., exp. BBS, density-dependent survival */
nxr1b1s1     /* model-specific prediction of population size in next time step */
nxr1b1s2     /* model-specific prediction of population size in next time step */
nxr1b2s1     /* model-specific prediction of population size in next time step */
nxr1b2s2     /* model-specific prediction of population size in next time step */
nxr2b1s1     /* model-specific prediction of population size in next time step */
nxr2b1s2     /* model-specific prediction of population size in next time step */
nxr2b2s1     /* model-specific prediction of population size in next time step */
nxr2b2s2     /* model-specific prediction of population size in next time step */
Ne           /* breeding population size */
bbsb1        /* BBS index - logarithmic model */
bbsb2        /* BBS index - exponential[max] model */
ar1b1        /* male age ratio - neg. exp. reproduction - log. BBS */
ar1b2        /* male age ratio - neg. exp. reproduction - exponential[max] BBS */
ar2b1        /* male age ratio - logistic reproduction - log. BBS */
ar2b2        /* male age ratio - logistic reproduction - exponential[max] BBS */
hafe         /* harvest rate - adult females */
hame         /* harvest rate - adult males */
hyfe         /* harvest rate - young females */
hyme         /* harvest rate - young males */
```

```
kafe            /* kill rate - adult females */
kame            /* kill rate - adult males */
kyfe            /* kill rate - young females */
kyme            /* kill rate - young males */
dafe=1.19       /* differential vulnerability - adult females */
dyme=1.47       /* differential vulnerability - young males */
dyfe=1.62       /* differential vulnerability - yong females */
ce=0.2          /* crippling loss rate */
swe=0.90        /* winter survival */
ssme=0.81       /* summer survival - males */
ssfvar          /* summer survival - females - random variation */
ssfmb1          /* summer survival - females - density dependent survival - log. BBS */
ssfmb2          /* summer survival - females - density dependent survival - exponential[max] BBS */
sexe=0.55       /* proportion males in May */
```

Eastern mallard dynamics:

```
hame  =  outcome[ERATE];
hafe  =  min(1.0, hame*dafe);
hyme  =  min(1.0, hame*dyme);
hyfe  =  min(1.0, hame*dyfe);
kafe  =  min(1.0, hafe/(1-ce) );
kame  =  min(1.0, hame/(1-ce) );
kyfe  =  min(1.0, hyfe/(1-ce) );
kyme  =  min(1.0, hyme/(1-ce) );
bbsb1 = 0.6185*exp(1.3534*cur_state[EBPOP]/1000000);
bbsb2 = 11292.7921*(1-exp(-0.0002*cur_state[EBPOP]/1000000));
ar1b1 = max(0.0, (1.7330*exp(-0.2036*bbsb1))+outcome[RRES]);
ar1b2 = max(0.0, (1.7330*exp(-0.2036*bbsb2))+outcome[RRES]);
ar2b1 = max(0.0, (1.5027/(1+exp(-(bbsb1-2.8608)/-0.6490)))+outcome[RRES]);
ar2b2 = max(0.0, (1.5027/(1+exp(-(bbsb2-2.8608)/-0.6490)))+outcome[RRES]);
ssfvar = outcome[SSFVAR];
ssfmb1 =
 exp(1.6746-0.5422*bbsb1+outcome[SSFRES])/(1+exp(1.6746-0.5422*bbsb1+outcome[SSFRES]));
ssfmb2 =
 exp(1.6746-0.5422*bbsb2+outcome[SSFRES])/(1+exp(1.6746-0.5422*bbsb2+outcome[SSFRES]));
Ne = cur_state[EBPOP];
nxr1b1s1=max(0.0, Ne*((1-sexe)*ssfvar*(1-kafe)*swe + sexe*ssme*(1-kame)*swe +
        (sexe)*ssme*ar1b1*(1-kyfe)*swe + (sexe)*ssme*ar1b1*(1-kyme)*swe));
nxr1b1s2=max(0.0, Ne*((1-sexe)*ssfmb1*(1-kafe)*swe + sexe*ssme*(1-kame)*swe +
        (sexe)*ssme*ar1b1*(1-kyfe)*swe + (sexe)*ssme*ar1b1*(1-kyme)*swe));
nxr1b2s1=max(0.0, Ne*((1-sexe)*ssfvar*(1-kafe)*swe + sexe*ssme*(1-kame)*swe +
        (sexe)*ssme*ar1b2*(1-kyfe)*swe + (sexe)*ssme*ar1b2*(1-kyme)*swe));
nxr1b2s2=max(0.0, Ne*((1-sexe)*ssfmb2*(1-kafe)*swe + sexe*ssme*(1-kame)*swe +
        (sexe)*ssme*ar1b2*(1-kyfe)*swe + (sexe)*ssme*ar1b2*(1-kyme)*swe));
nxr2b1s1=max(0.0, Ne*((1-sexe)*ssfvar*(1-kafe)*swe + sexe*ssme*(1-kame)*swe +
        (sexe)*ssme*ar2b1*(1-kyfe)*swe + (sexe)*ssme*ar2b1*(1-kyme)*swe));
nxr2b1s2=max(0.0, Ne*((1-sexe)*ssfmb1*(1-kafe)*swe + sexe*ssme*(1-kame)*swe +
```

```
        (sexe)*ssme*ar2b1*(1-kyfe)*swe + (sexe)*ssme*ar2b1*(1-kyme)*swe));
nxr2b2s1=max(0.0, Ne*((1-sexe)*ssfvar*(1-kafe)*swe + sexe*ssme*(1-kame)*swe +
        (sexe)*ssme*ar2b2*(1-kyfe)*swe + (sexe)*ssme*ar2b2*(1-kyme)*swe));
nxr2b2s2=max(0.0, Ne*((1-sexe)*ssfmb2*(1-kafe)*swe + sexe*ssme*(1-kame)*swe +
        (sexe)*ssme*ar2b2*(1-kyfe)*swe + (sexe)*ssme*ar2b2*(1-kyme)*swe));
nxt_state[EBPOP] =
 max(0.0, nxr1b1s1*wtr1b1s1+nxr1b1s2*wtr1b1s2+nxr1b2s1*wtr1b2s1+nxr1b2s2*wtr1b2s2+
        nxr2b1s1*wtr2b1s1+nxr2b1s2*wtr2b1s2+nxr2b2s1*wtr2b2s1+nxr2b2s2*wtr2b2s2);
```

Midcontinent mallard parameters:

```
 wt1           /* model 1 weight - compensatory mortality, strong density-dependent reproduction
               (ScRs) */
 wt2           /* model 2 weight - compensatory mortality, weak density-dependent reprod. (ScRw) */
 wt3           /* model 3 weight - additive mortality, strong density-dependent reprod. (SaRs) */
 wt4           /* model 4 weight - additive mortality - weak density-dependent reprod. (SaRw) */
nxt1           /* model-specific prediction of population size in next time step */
nxt2           /* model-specific prediction of population size in next time step */
nxt3           /* model-specific prediction of population size in next time step */
nxt4           /* model-specific prediction of population size in next time step */
Nm             /* breeding population size */
P              /* May ponds in Prairie Canada */
Ai             /* fall age ratio - females - weakly density-dependent reproduction */
Ad             /* fall age ratio - females - strongly density-dependent reproduction */
Hafm           /* harvest rate - adult females */
Hamm           /* harvest rate - adult males */
Hyfm           /* harvest rate - young females */
Hymm           /* harvest rate - young males */
Kafm           /* kill rate - adult females */
Kamm           /* kill rate - adult males */
Kyfm           /* kill rate - young females */
Kymm           /* kill rate - young males */
shafim         /* hunt season survival - adult females - additive mortality */
shafdm         /* hunt season survival - adult females - compensatory mortality */
shamim         /* hunt season survival - adult males - additive mortality */
shamdm         /* hunt season survival - adult males - compensatory mortality */
shyfim         /* hunt season survival - young females - additive mortality */
shyfdm         /* hunt season survival - young females - compensatory mortality */
shymim         /* hunt season survival - young males - additive mortality */
shymdm         /* hunt season survival - young males - compensatory mortality */
dafm=0.748     /* differential vulnerability - adult females */
dymm=1.361     /* differential vulnerability - young males */
dyfm=1.188     /* differential vulnerability - young females */
cm=0.2         /* crippling loss rate */
s0m=0.81       /* survival in absence of hunting - male */
s0f=0.64       /* survival in absence of hunting - female */
swm=0.90       /* winter survival */
ssmm=0.90      /* summer survival - males */
```

```
ssfm=0.71     /* summer survival - females */
ctf=0.36      /* compensatory threshold - females */
ctm=0.19      /* compensatory threshold - males */
sexm=0.55     /* proportion of males in May */
```

Midcontinent mallard dynamics:

```
Nm = cur_state[MBPOP];
P = cur_state[PONDS];
Hamm = outcome[MRATE];
Hafm  =  min(1.0, Hamm*dafm);
Hymm  =  min(1.0, Hamm*dymm);
Hyfm  =  min(1.0, Hamm*dyfm);
Kafm  =  min(1.0, Hafm/(1-cm) );
Kamm  =  min(1.0, Hamm/(1-cm) );
Kyfm  =  min(1.0, Hyfm/(1-cm) );
Kymm  =  min(1.0, Hymm/(1-cm) );
Ai = max(0.0, 0.8249-(0.0547*((1-outcome[PROP])*Nm/1000000.0))+(0.1130*(P/1000000.0)));
Ad = max(0.0, 1.1081-(0.1128*((1-outcome[PROP])*Nm/1000000.0))+(0.1460*(P/1000000.0)));
shafim=(1-Kafm); shamim=(1-Kamm); shyfim=(1-Kyfm); shymim=(1-Kymm);
if (Kafm>ctf) shafdm=(1-Kafm)/s0f; else shafdm=1.0;
if (Kamm>ctm) shamdm=(1-Kamm)/s0m; else shamdm=1.0;
if (Kyfm>ctf) shyfdm=(1-Kyfm)/s0f; else shyfdm=1.0;
if (Kymm>ctm) shymdm=(1-Kymm)/s0m; else shymdm=1.0;
nxt_state[PONDS] = max(1.0, -3835087.53+0.45*P+13695.47*outcome[PPT]) ;
nxt1=Nm*((1.-sexm)*ssfm*(shafdm+Ad*(shyfdm+shymdm)) + sexm*ssmm*shamdm)*swm;
nxt2=Nm*((1.-sexm)*ssfm*(shafdm+Ai*(shyfdm+shymdm)) + sexm*ssmm*shamdm)*swm;
nxt3=Nm*((1.-sexm)*ssfm*(shafim+Ad*(shyfim+shymim)) + sexm*ssmm*shamim)*swm;
nxt4=Nm*((1.-sexm)*ssfm*(shafim+Ai*(shyfim+shymim)) + sexm*ssmm*shamim)*swm;
nxt_state[MBPOP] = max(0.0, wt1*nxt1+wt2*nxt2+wt3*nxt3+wt4*nxt4);
```

APPENDIX C: Updating of Model Weights

Adaptive harvest management prescribes regulations for midcontinent mallards based on passive adaptive optimization using weighted models of population and harvest dynamics (Johnson et al. 1997). We update model weights (or probabilities) based on how predictions from each of the four population models compare to the observed breeding population in year *t*+1. This posterior updating of model probabilities is based on a version of Bayes Theorem:

$$p_{t+1}\ (model\ i \mid data) = \frac{p_t\ (model i)\ p_{t+1}\ (data \mid model\ i)}{\sum_j p_t\ (model\ j)\ p_{t+1}\ (data \mid model\ j)} \qquad (1)$$

where $p_t(model\ i)$ is the probability that *model i* is correct. We assume that some element of our model set is the "correct" model for the system, and remains the correct model throughout. Equation (1), then, tracks the probability that each of the candidate models is the correct one through time. The state of the system in year *t*+1 consists of breeding population size (N_{t+1}) and number of ponds (P_{t+1}). Under our current approach, information on ponds in year *t*+1 is not informative with respect to updating model probabilities in year *t*, because all four candidate models predict the same number of ponds every year. We can rewrite the likelihood above as:

$$p_{t+1}(data \mid model\ i) = f\ (N_{t+1}^{data} \mid \hat{N}_{t+1}^{(i)}) \quad , \qquad (2)$$

where N_{t+1}^{data} comes from the Breeding Waterfowl and Habitat Survey (May Survey), and $\hat{N}_{t+1}^{(i)}$ is the predicted size of the population based on *model i.*

A formal approach involves modeling the conditional likelihood in (2) as a normal distribution:

$$f\ (N_{t+1}^{data} \mid \hat{N}_{t+1}^{(i)}) \sim normal[E(N_{t+1}^{data} | \hat{N}_{t+1}^{(i)}),\ Var(N_{t+1}^{data} \mid \hat{N}_{t+1}^{(i)})]. \qquad (3)$$

This form is intuitively appealing, because the value of the likelihood for the observed population size will depend on:

$$\frac{N_{t+1}^{data} - E(N_{t+1}^{data} | \hat{N}_{t+1}^{(i)})}{\sqrt{var(N_{t+1}^{data} | \hat{N}_{t+1}^{(i)})}},$$

which includes the difference between the observed population size and that predicted by *model i,* and the variance in the observed state of the system one would expect under *model I.*

Next, we must address the estimation of the mean and variance of $f(N_{t+1}^{data} | \hat{N}_{t+1}^{(i)})$. First,

$$\hat{N}_{t+1}^{(i)} = g^{(i)}\ (N_t^{data},\ P_t^{data},\ \{h_{as}\}_t) \quad , \qquad (4)$$

where $g^{(i)}$ is a model-specific description of population dynamics and $\{h_{as}\}_t$ is the set of age- and sex-specific harvest rates in year *t*. All of the models we are considering are stochastic, allowing for partial controllability of the system (i.e., h_{ast} is a random variable whose distribution is based on the regulatory package that is chosen in year *t*). In addition, N_t^{data} and P_t^{data} are subject to error, due to partial observability of the system (i.e., sampling variation in the May Survey), but we assume they are unbiased estimators. Therefore $\hat{N}_{t+1}^{(i)}$ is subject to error in predicting the actual population size, N_{t+1}, under *model i*. Based on this we derive the mean and variance of interest using conditional arguments:

$$E[N_{t+1}^{data} | \hat{N}_{t+1}^{(i)}] = E_{N_{t+1}}[E(N_{t+1}^{data} | N_{t+1}, \hat{N}_{t+1}^{(i)})] = E(N_{t+1} | \hat{N}_{t+1}^{(i)}) = \hat{N}_{t+1}^{(i)} , \tag{5}$$

$$\begin{aligned} Var[N_{t+1}^{data} | \hat{N}_{t+1}^{(i)}] = \; & E_{N_{t+1}}[Var(N_{t+1}^{data} | N_{t+1}, \hat{N}_{t+1}^{(i)})] \\ & + Var_{N_{t+1}}[E(N_{t+1}^{data} | N_{t+1}, \hat{N}_{t+1}^{(i)})] \; . \end{aligned} \tag{6}$$

We estimate the first term in equation (6) with the sampling variance from the May Survey in year *t*+1. The second term can be simplified to:

$$Var_{N_{t+1}}[E(N_{t+1}^{data} \mid N_{t+1}, \hat{N}_{t+1}^{(i)})] = Var \; [N_{t+1} \mid \hat{N}_{t+1}^{(i)}], \tag{7}$$

Therefore (6) can be reexpressed as:

$$\hat{Var}[N_{t+1}^{data} \mid \hat{N}_{t+1}^{(i)}] = sampling \; variance + \hat{Var} \; [N_{t+1} \mid \hat{N}_{t+1}^{(i)}] \; , \tag{8}$$

The variance in the second term of (8) is derived from the sources of uncertainty inherent in the function in (4): partial observability of the state of the system, and partial controllability of harvest, in year *t*.

We use parametric bootstrapping for approximating the likelihood in (2) without assuming a distributional form. It also precludes the need to derive an explicit estimate of the variance in (8). Instead we assume distributional forms for more basic quantities.

We simulate the transition from the state of the system in year *t*, to the state of the system in year *t*+1, under each model, described by *g* in (4). We acknowledge uncertainty about the values of N_t, P_t, and $\{h_{as}\}_t$, and to incorporate this uncertainty we use random values from the following assumed distributions in their place:

$$\begin{aligned} f(N_t^{boot}) &\sim normal[N_t^{data}, \; Var(N_t^{data} | N_t)], \\ f(P_t^{boot}) &\sim normal[P_t^{data}, \; Var(P_t^{data} | N_t)], \\ f(h_{ast}^{boot}) &\sim normal[\hat{h}_{ast}, \; Var(\hat{h}_t | h_{ast})]. \end{aligned} \tag{9}$$

Because we anticipate a sampling covariance between N_t^{data} and P_t^{data}, and do not currently have an estimate of its value, we make the conservative (i.e., largest $Var[N_{t+1}^{data} | \hat{N}_{t+1}^{(i)}]$ possible) assumption that the two are perfectly correlated. Practically speaking, this implies that the simulation of these two random variables will be based on the same draw from a standard normal distribution.

Because we update the model probabilities after direct recovery rates are available from the hunting season in year *t*, we use estimates and sampling variances of realized harvest rates (recovery rates, adjusted for reporting rate) in the updating process whenever possible. Because there is no sampling covariance between estimates of harvest rate for the four age-sex classes, we generate an independent normal random variate for each.

For each model, in each repetition of the simulation, the generated value of N_t is projected to the actual value of N_{t+1} ($N_{t+1}^{(i)boot}$). Finally, to represent partial observability in year *t*+1, we generate another random number from the following distribution:

$$N_{t+1}^{data} | N_{t+1}^{(i)boot} \sim normal[N_{t+1}^{(i)boot}, (c.v.(N_{t+1}^{data}) \cdot N_{t+1}^{(i)boot})^2]. \quad (10)$$

We base the variance of the model-dependent distribution in (10) on the estimated coefficient of variation from the May Survey, instead of its variance, because experience has shown that the standard error is proportional to population size. This process produces an observed population size in year *t*+1 for each repetition of the simulation. By repeating the process a large number of times we produce an empirical distribution to compare against the realized N_{t+1}^{data} from the May Survey. We use 10,000 iterations and then use smoothing techniques to estimate a likelihood function. Finally, we determine the likelihood value for *model i* based on N_{t+1}^{data}, and incorporate it into equations (2) and (1).

APPENDIX D: Predicting Harvest Rates

This procedure involves: (1) linear models that predict total seasonal mallard harvest for varying regulations (daily bag limit and season length), while accounting for trends in numbers of successful duck hunters; and (2) use of these models to adjust historical estimates of mallard harvest rates to reflect differences in bag limit, season length and trends in hunter numbers. Using historical data from both the U.S. Waterfowl Mail Questionnaire and Parts Collection Surveys, and with the use of several key assumptions, the resulting models allowed us to predict total seasonal mallard harvest and associated predicted harvest rates for varying combinations of season length and daily bag limits.

Total seasonal mallard harvest is predicted using two separate models: the "harvest" model which predicts average daily mallard harvest per successful duck hunter for each day of the hunting season (Table D-1), and the "hunter" model which predicts the number of successful duck hunters (Table D-2). The "harvest" model uses as the dependent variable the square root of the average daily mallard harvest (per successful duck hunter). The independent variables include the consecutive day of the hunting season (splits were ignored), daily mallard bag limit, season length, and the interaction of bag limit and season length. Also included is an effect representing the opening day (of the first split), an effect representing a week (7 day) effect, and several other interaction terms. Seasonal mallard harvest per successful duck hunter is obtained by back-transforming the predicted values that resulted from the model, and summing the average daily harvest over the season length. The "hunter" model uses information on the numbers of successful duck hunters (based on duck stamp sales information) from 1981-95. Using daily bag limit and season length as independent variables, the number of successful duck hunters is predicted for each state.

Both the "harvest" and "hunter" models were developed for each of seven management areas: the Atlantic Flyway portion with compensatory days; the Atlantic Flyway portion without compensatory days; the Mississippi Flyway; the low plains portion of Central Flyway; the High Plains Mallard Management Unit in the Central Flyway; the Columbia Basin Mallard Management Unit in the Pacific Flyway; and the remainder of the Pacific Flyway excluding Alaska. The numbers of successful hunters predicted at the state level are summed to obtain a total number (H) for each management area. Likewise, the "harvest" model results in a seasonal mallard harvest per successful duck hunter (A) for each management area. Total seasonal mallard harvest (T) is formed by the product of H and A.

To compare total seasonal mallard harvest under different regulatory alternatives, ratios of T are formed for each management area and then combined into a weighted mean. *Under the key assumption that the ratio of harvest rates realized under two different regulatory alternatives is equal to the expected ratio of total harvest obtained under the same two alternatives*, the harvest rate experienced under the historic "liberal" package (1979-84) was adjusted by T to produce predicted harvest rates for the current regulatory alternatives.

The models developed here were not designed, nor are able, to predict mallard harvest rates directly. The procedure relies heavily on statistical and conceptual models that must meet certain assumptions. We have no way to verify these assumptions, nor can we gauge their effects should they not be met. The use of this procedure for predicting mallard harvest rates for regulations alternatives for which we have little or no experience warrants considerable caution.

Table D-1. Parameter estimates by management area for models of seasonal harvest per successful hunter.

Model effect[a]	AF- COMP.	AF-NOCOMP	MF	CF-lp	CF-HP	PF-CB	PF
INTERCEPT	0.378359	0.555790	0.485971	0.554667	0.593799	0.736258	0.543791
(SE)	(0.061477)	(0.134516)	(0.037175)	(0.041430)	(0.059649)	(0.154315)	(0.054712)
OPEN	0.194945	0.263793	0.175012	0.092507	0.113074	0.361696	0.322255
(SE)	(0.010586)	(0.018365)	(0.011258)	(0.015623)	(0.018530)	(0.040605)	(0.012730)
WEEK	0.024232	0.040392	-0.016479	-0.108472	-0.074895	-0.063422	-0.060477
(SE)	(0.006561)	(0.011436)	(0.006965)	(0.008860)	(0.009437)	(0.018220)	(0.006118)
WEEK2	-0.003586	-0.006823	0.000422	0.010472	0.006782	0.003573	0.004893
(SE)	(0.000796)	(0.001392)	(0.000847)	(0.001075)	(0.001150)	(0.002266)	(0.000746)
WK*SDAY	-0.001245	-0.001395	-0.000073	0.002578	0.001222	-0.000102	0.000116
(SE)	(0.000231)	(0.000407)	(0.000248)	(0.000260)	(0.000215)	(0.000289)	(0.000120)
WK2*SDAY	0.000163	0.000219	0.000052	-0.000271	-0.000109	0.000045	0.000007
(SE)	(0.000028)	(0.000050)	(0.000030)	(0.000032)	(0.000026)	(0.000037)	(0.000015)
SEASDAY	0.000419	-0.001034	-0.002559	-0.006322	-0.003174	-0.000615	-0.000909
(SE)	(0.000407)	(0.000712)	(0.000434)	(0.000464)	(0.000382)	(0.000476)	(0.000209)
MALBAG	-0.025557	-0.062755	0.026729	0.016049	-0.029753	-0.049532	-0.021774
(SE)	(0.019282)	(0.043020)	(0.015007)	(0.010766)	(0.013918)	(0.047903)	(0.017457)
SEASLEN	-0.004852	-0.008836	-0.004869	-0.001250	-0.003089	0.001562	-0.001931
(SE)	(0.001260)	(0.002750)	(0.000768)	(0.000833)	(0.000995)	(0.001682)	(0.000591)
BAG*SEAS	0.000926	0.002018	0.000332	-0.000033	0.000732	0.000024	0.000328
(SE)	(0.000393)	(0.000877)	(0.000310)	(0.000202)	(0.000216)	(0.000464)	(0.000184)

[a]Model Effect	Description
INTERCEPT	Intercept
OPEN	Opening Day of First Split (Y,N)
WEEK	Day of Week (1,2,3,4,5,6,7)
WEEK2	Week * Week (Quadratic Effect)
WK*SDAY	Week * Day of Season Interaction
WK2*SDAY	Week * Week * Day of Season Interaction
SEASDAY	Day of Season (Consecutive)
MALBAG	Daily Mallard Bag Limit
SEASLEN	Season Length
BAG*SEAS	Daily Mallard Bag Limit * Season Length Interaction

Table D-2. Parameter estimates by management area for models to predict hunter numbers.

Mgmt Area	Effect	State/Zone	Estimate	SE
AF-Comp.	Malbag		-229.854	320.613
	Seaslen		119.595	28.473
	Intercepts:	CT	925.275	823.888
		DE	376.732	829.784
		ME	3,581.062	825.956
		MD	10,712.000	809.333
		NJ	5,940.028	813.652
		NC	12,798.000	836.186
		PA	17,683.000	822.566
		VA	7,276.371	809.333
		WV	-2,884.782	818.825
		MA_3	1,679.885	818.507
		MA_R	-336.288	843.081
AF-No comp.	Malbag		71.885	188.301
	Seaslen		62.574	18.776
	Intercepts:	FL	9,709.872	530.458
		GA	7,058.253	541.184
		RI	-1,515.873	543.352
		SC	10,004.000	541.184
		VT	679.453	541.184
		NH_1	-1,536.280	541.184
		NH_2	201.430	536.395
		NY_1	336.305	537.703
		NY_2	-2,122.214	541.184
		NY_5	7,070.786	541.184
		NY_R	8,650.966	538.322
		OH_1	-2,426.542	535.906
CF - lp	Malbag		577.848	715.617
	Seaslen		317.973	100.931
	Intercepts:	KS	-6,006.131	3,108.375
		NE	-4,997.796	3,114.451
		ND	-3,930.604	3,021.002
		OK	-8,010.002	3,208.936
		SD	-4,053.537	3,021.002
		TX	33,480.000	3,021.002
CF - HP	Malbag		734.041	181.624
	Seaslen		-1.332	16.318
	Intercepts:	CO	12,354.000	687.696
		KS	-973.654	688.526
		MT	482.197	699.176
		NE	3,222.880	688.526
		NM	447.280	688.526
		ND	4,559.079	541.659
		OK	-2,299.609	687.696
		SD	748.221	695.658
		TX	2,817.864	695.658
		WY	1,639.613	688.526
PF - CB	Malbag		505.129	411.451
	Seaslen		31.446	48.602
	Intercepts:	OR	-3,910.659	2,311.323
		WA	5,433.261	2,334.479

Mgmt Area	Effect	State/Zone	Estimate	SE	Mgmt Area	Effect	State/Zone	Estimate	SE
MF	Malbag		-4,523.798	1,231.622	PF	Malbag		790.844	284.473
	Seaslen		897.413	120.583		Seaslen		59.303	31.696
	Intercepts:	AL	-15,044.000	2,361.763		Intercepts:	AZ	-3,958.814	1,402.487
		AR	5,599.384	2,361.763			CO	-4,832.461	1,400.722
		IL	7,438.650	2,361.763			ID	6,285.454	1,384.878
		IN	-13,932.000	2,361.763			MT	-887.114	1,458.939
		IA	-1,346.879	2,337.443			NV	-2,483.897	1,369.116
		KY	-15,477.000	2,394.393			NM	-7,588.133	1,395.432
		LA	41,690.000	2,543.303			OR	11,687.000	1,397.194
		MI	10,232.000	2,361.763			UT	6,803.640	1,415.495
		MN	61,174.000	2,635.798			WY	9,398.653	1,402.487
		MS	-9,207.288	2,285.436			CA_1	-3,696.948	1,385.102
		MO	-2,225.616	2,361.763			CA_2	-5,421.502	1,427.980
		TN	-6,958.016	2,361.763			CA_3	3,580.319	1,385.102
		WI	27,254.000	2,361.763			CA_4	-6,475.400	1,378.069
		OH_R	-9,163.989	2,635.798			CA_5	29,744.000	1,385.102

APPENDIX E: Estimating the Mallard Harvest Rate for the 1999-00 Season

We estimated the overall harvest rate of adult male mallards in the midcontinent region using harvest-rate estimates for reference areas 2, 4 and 5 (Anderson and Henny1972) that were derived from reward banding. Harvest rates in the unsampled banding reference areas (1, 3, 6-7 and 12-14) was treated as missing, and conventional *data augmentation* (or *multiple imputation*) techniques were employed (Schafer, J. L. 1997. Analysis of incomplete multivariate data. Chapman and Hall, London. 430pp.).

The model under which estimates were produced assumes that the vector of harvest rates for the 10 reference areas is a multivariate normal random variable with some unknown mean vector and variance-covariance matrix. The variance-covariance matrix describes the correlations between harvest rate among the reference areas. Nominally, the harvest rate for a given reference area is correlated with the harvest rate in the other reference areas, and it is this aspect which facilitates estimation of “unobserved” harvest rates from those which are estimated from data.   The mean vector and variance-covariance matrix in the model were estimated from 36 years of historic data.

Estimates and their variances were computed for each of the seven unsampled reference areas. These predictions were then weighted by the proportion of the midcontinent mallard population in each area during spring 1999 to construct an estimate of the overall harvest rate. The estimated harvest rate of adult male mallards in the midcontinent region during the 1999-00 hunting season was 0.098 (SE = 0.0097), which is consistent with the liberal regulatory alternative.

Appendix F: Past Regulations and Harvest Strategies

Table F-1. Regulatory alternatives considered for the 1995 and 1996 duck-hunting seasons.

	Flyway			
Regulation	Atlantic	Mississippi	Central[a]	Pacific[b]
Shooting hours	one-half hour before sunrise to sunset for all Flyways			
Framework dates	Oct 1 - Jan 20	Saturday closest to October 1 and Sunday closest to January 20		
Season length (days)				
Restrictive	30	30	39	59
Moderate	40	40	51	79
Liberal	50	50	60	93
Bag limit (total / mallard / female mallard)				
Restrictive	3 / 3 / 1	3 / 2 / 1	3 / 3 / 1	4 / 3 / 1
Moderate	4 / 4 / 1	4 / 3 / 1	4 / 4 / 1	5 / 4 / 1
Liberal	5 / 5 / 1	5 / 4 / 1	5 / 5 / 1	6-7[c] / 6-7[c] / 1

[a] The High Plains Mallard Management Unit was allowed 12, 16, and 23 extra days under the restrictive, moderate, and liberal alternatives, respectively.

[b] The Columbia Basin Mallard Management Unit was allowed seven extra days under all three alternatives.

[c] The limits were 6 in 1995 and 7 in 1996.

Table F-2. Optimal regulatory choices[a] for midcontinent mallards during the 1995 hunting season. This strategy is based on the regulatory alternatives for 1995, equal weights for four alternative models of population dynamics, and the dual objectives of maximizing long-term cumulative harvest and achieving a population goal of 8.7 million.

	Ponds[b]									
Mallards[c]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
4.5	M	M	M	L	L	L	L	L	L	L
5.0	L	L	L	L	L	L	L	L	L	L
5.5	L	L	L	L	L	L	L	L	L	L
6.0	L	L	L	L	L	L	L	L	L	L
6.5	L	L	L	L	L	L	L	L	L	L
7.0	L	L	L	L	L	L	L	L	L	L
7.5	L	L	L	L	L	L	L	L	L	L
8.0	L	L	L	L	L	L	L	L	L	L
8.5	L	L	L	L	L	L	L	L	L	L
9.0	L	L	L	L	L	L	L	L	L	L
9.5	L	L	L	L	L	L	L	L	L	L
10.0	L	L	L	L	L	L	L	L	L	L
10.5	L	L	L	L	L	L	L	L	L	L
11.0	L	L	L	L	L	L	L	L	L	L

[a] R = restrictive, M = moderate, and L = liberal.
[b] Estimated number of ponds in Prairie Canada in May, in millions.
[c] Estimated number of midcontinent mallards during May, in millions.

Table F-3. Optimal regulatory choices[a] for midcontinent mallards during the 1996 hunting season. This strategy is based on the regulatory alternatives and model weights for 1996, and the dual objectives of maximizing long-term cumulative harvest and achieving a population goal of 8.7 million.

	Ponds[b]									
Mallards[c]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
4.5										
5.0								R	R	R
5.5					R	R	R	R	M	M
6.0	R	R	R	R	R	R	M	M	L	L
6.5	R	R	R	M	M	M	L	L	L	L
7.0	M	M	M	L	L	L	L	L	L	L
7.5	M	L	L	L	L	L	L	L	L	L
8.0	L	L	L	L	L	L	L	L	L	L
8.5	L	L	L	L	L	L	L	L	L	L
9.0	L	L	L	L	L	L	L	L	L	L
9.5	L	L	L	L	L	L	L	L	L	L
10.0	L	L	L	L	L	L	L	L	L	L
10.5	L	L	L	L	L	L	L	L	L	L
11.0	L	L	L	L	L	L	L	L	L	L

[a] R = restrictive, M = moderate, and L = liberal.
[b] Estimated number of ponds in Prairie Canada in May, in millions.
[c] Estimated number of midcontinent mallards during May, in millions.

Table F-4. Optimal regulatory choices[a] for midcontinent mallards during the 1997 hunting season. This strategy is based on regulatory alternatives and model weights for 1997, and on the dual objectives of maximizing long-term cumulative harvest and achieving a population goal of 8.7 million.

	Ponds[b]									
Mallards[c]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
4.5										
5.0										
5.5								VR	VR	VR
6.0			VR	VR	VR	VR	VR	R	R	R
6.5	VR	VR	VR	VR	R	R	R	M	M	M
7.0	R	R	R	R	R	M	M	M	L	L
7.5	R	R	M	M	M	M	L	L	L	L
8.0	M	M	M	M	L	L	L	L	L	L
8.5	M	M	L	L	L	L	L	L	L	L
9.0	L	L	L	L	L	L	L	L	L	L
9.5	L	L	L	L	L	L	L	L	L	L
10.0	L	L	L	L	L	L	L	L	L	L
10.5	L	L	L	L	L	L	L	L	L	L
11.0	L	L	L	L	L	L	L	L	L	L

[a] VR = very restrictive, R = restrictive, M = moderate, and L = liberal.
[b] Estimated number of ponds in Prairie Canada in May, in millions.
[c] Estimated number of mid-continent mallards during May, in millions.

Table F-5. Optimal regulatory choices[a] for midcontinent mallards during the 1998 hunting season. This strategy is based on regulatory alternatives and model weights for 1998, and on the dual objectives of maximizing long-term cumulative harvest and achieving a population goal of 8.7 million.

	Ponds[b]									
Mallards[c]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
4.5										
5.0										VR
5.5							VR	VR	VR	R
6.0		VR	VR	VR	VR	VR	R	R	R	M
6.5	VR	VR	VR	R	R	R	M	M	M	L
7.0	R	R	R	R	M	M	M	L	L	L
7.5	R	M	M	M	M	L	L	L	L	L
8.0	M	M	M	L	L	L	L	L	L	L
8.5	M	L	L	L	L	L	L	L	L	L
9.0	L	L	L	L	L	L	L	L	L	L
9.5	L	L	L	L	L	L	L	L	L	L
10.0	L	L	L	L	L	L	L	L	L	L
10.5	L	L	L	L	L	L	L	L	L	L
11.0	L	L	L	L	L	L	L	L	L	L

[a] VR = very restrictive, R = restrictive, M = moderate, and L = liberal.
[b] Estimated number of ponds in Prairie Canada in May, in millions.
[c] Estimated number of mid-continent mallards during May, in millions.

Table F-6. Optimal regulatory choices[a] for midcontinent mallards during the 1999 hunting season. This strategy is based on regulatory alternatives and model weights for 1999, and on the dual objectives of maximizing long-term cumulative harvest and achieving a population goal of 8.7 million.

	Ponds[b]									
Mallards[c]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
<5.0										
5.0										VR
5.5							VR	VR	VR	R
6.0		VR	VR	VR	VR	VR	R	R	R	M
6.5	VR	VR	VR	R	R	R	M	M	M	L
7.0	R	R	R	R	M	M	M	L	L	L
7.5	R	M	M	M	M	L	L	L	L	L
8.0	M	M	M	L	L	L	L	L	L	L
8.5	M	L	L	L	L	L	L	L	L	L
9.0	L	L	L	L	L	L	L	L	L	L
9.5	L	L	L	L	L	L	L	L	L	L
10.0	L	L	L	L	L	L	L	L	L	L
10.5	L	L	L	L	L	L	L	L	L	L
11.0	L	L	L	L	L	L	L	L	L	L

[a] VR = very restrictive, R = restrictive, M = moderate, and L = liberal.
[b] Estimated number of ponds in Prairie Canada in May, in millions.
[c] Estimated number of midcontinent mallards during May, in millions.

U.S.
FISH & WILDLIFE
SERVICE

DEPARTMENT OF THE INTERIOR