U. S. Fish & Wildlife Service

Adaptive Harvest Management

1999 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 1999 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.

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Cover art: Jim Hautman's acrylic painting of greater scaup, which was selected for the 1999 federal "duck stamp."

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EXECUTIVE SUMMARY

In 1995, the U.S. Fish and Wildlife Service embraced 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. Moreover, adaptive harvest management (AHM) relies on an iterative cycle of monitoring, assessment, and decision making to clarify relationships among hunting regulations, harvests, and waterfowl abundance.

To date, AHM has been based on 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 ultimate goal is to develop Flyway-specific harvest strategies, which represent an average of optimal strategies for each mallard breeding population, weighted by the relative contribution of each population to the respective Flyways. Geographic boundaries used to define midcontinent and eastern mallards have been established, and mathematical models of population dynamics are available for predicting regulatory impacts. Investigations regarding the geographic bounds and population dynamics of western mallards are ongoing.

A critical need for successful implementation of AHM is a set of regulatory alternatives that remain fixed for an extended period. When AHM was first implemented in 1995, three regulatory alternatives characterized as liberal, moderate, and restrictive were defined based on recent regulatory experience. The 1995 regulatory alternatives also were considered for the 1996 hunting season. In 1997, the regulatory alternatives were modified in response to requests from the Flyway Councils. Changes included provisions for additional hunting opportunity under the moderate and liberal alternatives, as well as the addition of a very restrictive alternative. For the 1999 season, the USFWS is maintaining the same basic structure to the regulatory alternatives as that in 1997 and 1998.

Harvest strategies were derived for midcontinent and eastern mallards, but they do not yet allow for Flyway-specific regulatory choices. The strategy for midcontinent mallards was based on: (1) an objective to maximize long-term harvest and achieve a population goal of 8.7 million; (2) regulatory alternatives that are the same as in 1998; and (3) current understanding of regulatory impacts. Based on a breeding population size of 11.8 million mallards and 3.9 million ponds in Prairie Canada, the optimal regulatory choice for midcontinent mallards in 1999 is the liberal alternative. The strategy for eastern mallards was based on: (1) an objective to maximize long-term harvest; (2) regulatory alternatives that are the same as in 1998; and (3) a "working model" of population dynamics. Based on a breeding population size of 1.1 million mallards and spring precipitation of 8.3 inches, the optimal regulatory choice for eastern mallards in 1999 also is the liberal alternative.

Current AHM priorities include: (1) addressing communication needs related to institutional aspects of implementing AHM; (2) restoring our ability to reliably measure the harvest rates of midcontinent mallards; (3) improving the recruitment models for midcontinent mallards; (4) determining the appropriate number of duck stocks to include in AHM; (5) modifying the current AHM protocol to account for eastern mallards; and (6) exploring AHM mechanisms for northern pintails.

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 embraced 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, in terms of sustainable hunting opportunities, can be maximized only if regulatory effects can be predicted reliably. Thus, adaptive management relies on the iterative cycle of monitoring, assessment, and decision making described above 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) 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;

(4) 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.

Adaptive harvest management (AHM) was developed as a systematic process for dealing effectively 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 the environment 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

Since 1995, AHM strategies have been based on the status of midcontinent mallards, which are defined as those breeding in federal survey strata 1-18, 20-50, and 75-77, and in Minnesota, Wisconsin, and Michigan (Fig. 1). An optimal regulatory alternative for midcontinent mallards is 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 is applied in all four Flyways, although season lengths and bag limits are Flyway-specific.

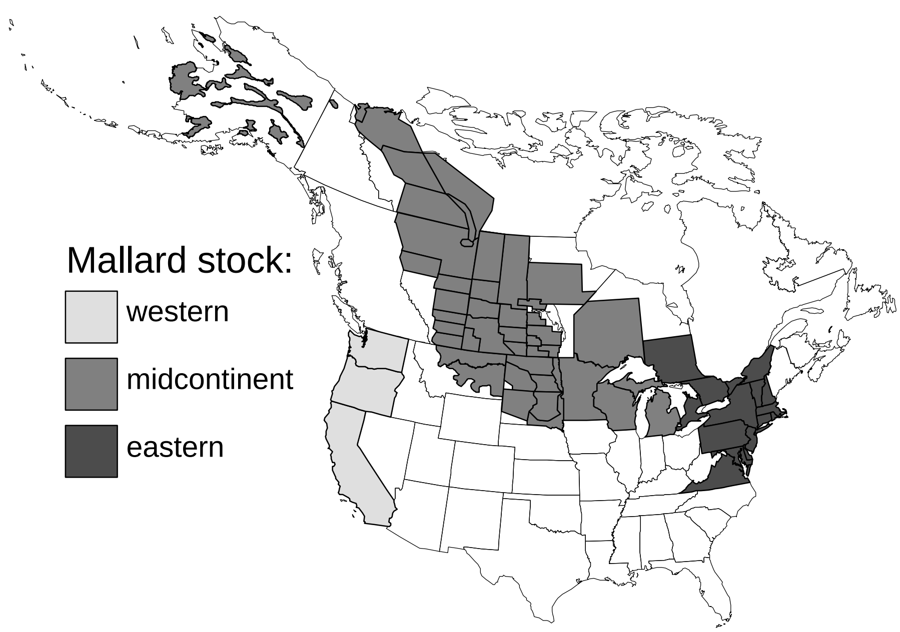

Fig. 1. Survey areas currently assigned to the western, midcontinent, and eastern stocks of mallards for the purpose of harvest management. Delineation of the western stock is preliminary pending additional information from British Columbia and other western areas with significant numbers of breeding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

Efforts are underway 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). Extension of the current process to account for multiple mallard stocks and Flyway-specific regulatory choices involves:

(1) augmentation of the decision criteria to include population and environmental variables relevant to eastern and western mallards;

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

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

An optimal harvest strategy for each Flyway then can be derived, which in effect would represent an average of the optimal strategies for each breeding stock, weighted by the relative contribution of each stock to the respective Flyways.

For the purposes of this report, 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). Western mallards currently are defined as those breeding in Washington, Oregon, and California. This range may be extended if monitoring and assessment information becomes available for other important breeding areas of western mallards.

MALLARD POPULATION DYNAMICS

Midcontinent Mallards

Estimates of the entire midcontinent population (as defined above) are available only since 1992. Since then, the number of midcontinent mallards has grown by an average of 8.6 percent (SE = 1.0) per annum (Table 1).

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

[a] In thousands.

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.

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, access to hunting areas) 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 updating of model weights (Appendix C). These weights describe the relative ability of the alternative models to mimic 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 must account for sampling error (i.e., partial observability) in population size and pond counts, as well as for partial 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 about harvest and environmental impacts on mallard abundance. Model weights changed markedly in 1996, and have remained relatively stable since (Table 2). On the whole, comparisons of observed and predicted population sizes provide some evidence of strongly density-dependent reproduction, but little indication of a compensatory response to hunting mortality.

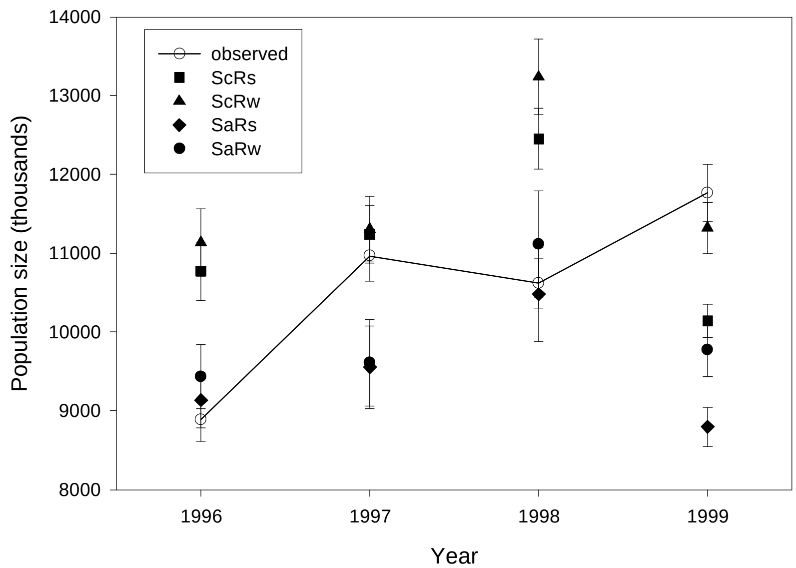

Fig. 2. Estimates of observed mallard population size (line with open circles) compared with predictions from four alternative models of population dynamics (ScRs = compensatory mortality and strongly density-dependent reproduction; ScRw = compensatory mortality and weakly density-dependent reproduction;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

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

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

Eastern Mallards

Midwinter counts and the Breeding Bird Survey provide evidence of exponential growth in the eastern mallard population since the mid-1970s. This pattern of growth also is apparent in the more recent fixed-wing (strata 51-54 and 56) and northeastern plot (New Hampshire south through Virginia) surveys (Table 3), although population growth seems to have slowed in more recent years.

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

[a] In thousands.

The population dynamics of eastern mallards were studied extensively by Sheaffer and Malecki (1996), but managers have not yet established a set of alternative models that characterize key uncertainties about the mortality and reproductive processes. In the interim, a "working model" has been developed to help managers understand the potential biological impacts of the current AHM process on eastern mallards.

The working model of eastern mallards incorporates natural mortality rates that are similar to those of midcontinent mallards and an assumption of completely additive hunting mortality. Reproductive rates are predicted based on the size of the population and regional precipitation during March-May of the current year. The reproductive process is characterized as strongly density dependent, predicting the highest reproductive rates during years in which population size is relatively low and spring precipitation is high. Mathematical details of the working model for eastern mallards are provided in Appendix B.

Western Mallards

The breeding range of western mallards includes the Pacific Flyway states (including Alaska), the Yukon Territories, and British Columbia. Although mallards breeding in southern Alberta are harvested primarily in the Pacific Flyway, estimated survival and reproductive rates for these birds are similar to those for birds breeding in southern Saskatchewan. As a result, mallards breeding in southern Alberta are modeled as part of the mid-continent population. Breeding pair surveys in the lower Pacific Flyway states were initiated in 1990 and have suggested a relatively stable or slightly increasing population size in this region during 1990-98. Highest numbers of breeding birds occur in California, Oregon, and Washington. Presently there are no breeding pair surveys and limited banding data for mallards breeding in Alaska or British Columbia. Managers will be unable to model the population dynamics of birds breeding in Alaska or British Columbia until operational surveys and banding programs are established in these regions. The initial working model for western mallards will focus on identifying key uncertainties affecting recruitment and survival of mallards breeding in the coastal states of California, Oregon, and Washington, where there is sufficient banding, harvest, and population survey data. Estimated natural mortality rates appear to be similar to those for mid-continent mallards. Annual reproductive rates have been estimated using female age ratios in the California harvest during October, when the harvest is comprised primarily of stocks from the lower Pacific Flyway states. Efforts are ongoing to identify environmental and demographic factors that affect reproductive success of western mallards. Preliminary analyses suggest that, in contrast to eastern and mid-continent mallards, annual reproductive success is not strongly density dependent. Environmental factors with the highest correlation to annual recruitment include spring precipitation and agriculture parameters in California.

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, managers avoid harvest 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). 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 losses in 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.

Eastern Mallards

For the purposes of this report, the 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.

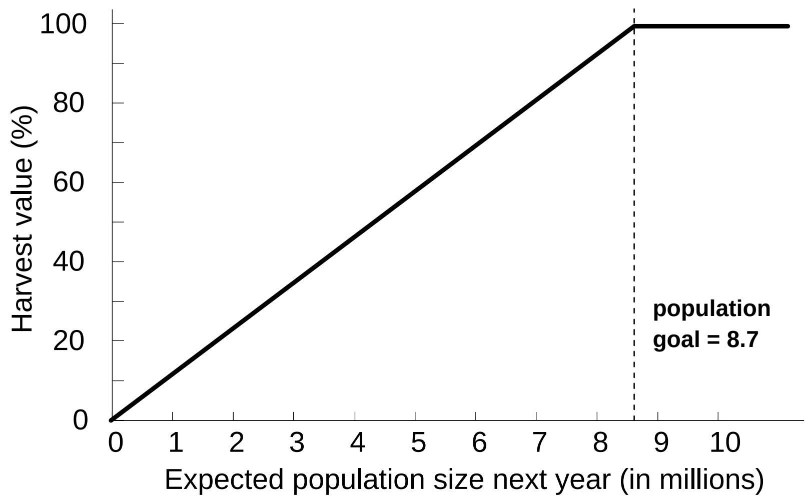

Fig. 3. The relative value of mallard harvest, expressed as a function of breeding-population size expected in the subsequent year.

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 been unchanged since 1997 (Table 4).

Predictions of Mallard Harvest Rates

Since 1995, harvest rates associated with the AHM regulatory alternatives have been predicted using empirical estimates from 1979-84, which have been adjusted to reflect differences in season length and bag limit, and for contemporary numbers of hunters (Table 5). These adjustments are not based on band-recovery data, but rather on estimates of hunting effort and success from hunter surveys (Appendix D). These predictions of harvest rates have large sampling variances, and their accuracy is uncertain. However, the estimated harvest rate during the 1998-99 season fell within the confidence limits of the prediction (Appendix E).

Harvest rates for each of the regulatory alternatives for 1999 were predicted assuming no change in the regulatory alternatives from 1997 and 1998. However, predicted harvest rates for 1997-99 differ from those published previously due to revised analytical procedures, which rely on mean numbers of hunters during 1981-95, rather than on short-term trends in annual hunter numbers. This change was made to prevent year-specificity in harvest rates predicted for a given alternative, and to better reflect uncertainty about hunter numbers in the future.

Adult female mallards tend to be less vulnerable to harvest than adult males, while young are more vulnerable (Table 6). 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 1999 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. Expected harvest rates (SE) of adult male midcontinent and eastern mallards under different regulatory alternatives, based on mean hunter numbers during 1981-95.

Mallard Population	Alternative	Regulatory alternatives for: 1995, 1996	1997, 1998, 1999
Midcontinent	Very restrictive	N/A	0.053 (0.011)
	Restrictive	0.067 (0.014)	0.067 (0.014)
	Moderate	0.089 (0.020)	0.111 (0.027)
	Liberal	0.118 (0.029)	0.131 (0.032)
Eastern	Very restrictive	N/A	0.121 (0.020)
	Restrictive	0.133 (0.021)	0.135 (0.022)
	Moderate	0.149 (0.023)	0.163 (0.025)
	Liberal	0.179 (0.028)	0.177 (0.028)

Table 6. Mean harvest vulnerability (SE) of 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

Midcontinent Mallards

The 1999 AHM strategy for midcontinent mallards was based on: (1) regulatory alternatives that are unchanged from 1997 and 1998; (2) model weights for 1999; and (3) the dual objectives to maximize long-term cumulative harvest and achieve a population goal of 8.7 million (Table 7). This strategy provides optimal regulatory choices for midcontinent mallards assuming that all four Flyways would use the prescribed regulation. Ultimately, regulatory choices will be Flyway-specific by accounting for the relative contribution of the three mallard breeding populations to each Flyway. The optimal harvest strategies for the 1995-98 seasons are provided in Appendix F (Tables F-2 to F-5) so that the reader can see how the strategy for midcontinent mallards has "evolved" over time. These strategies have been recalculated based on the most recent predictions of harvest rates and, thus, differ slightly from those published previously.

Table 7. Optimal regulatory choices[a] for midcontinent mallards during the 1999 hunting season. This strategy is based on regulatory alternatives unchanged from 1997 and 1998, current model weights (Table 2), 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

[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.

Blank cells in Table 7 (and in other 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.

We simulated the use of the harvest strategy in Table 7 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 1.3 (SE = 0.5) million and 8.3 (SE = 0.9) million, respectively.

Based on a breeding population size of 11.8 million mallards and 3.9 million ponds in Prairie Canada, the optimal regulatory choice for midcontinent mallards in 1999 is the liberal alternative.

Eastern Mallards

The 1999 AHM strategy for eastern mallards was based on: (1) regulatory alternatives unchanged from 1997 and 1998; (2) the working model of population dynamics; and (3) an objective to maximize long-term cumulative harvest (Table 8). The strategy is more liberal than that published last year, reflecting the most recent predicitions of harvest rates. Currently, this strategy only provides optimal regulations for eastern mallards under the condition that all Flyways would use the same regulation. Ultimately, regulatory choices will be Flyway-specific by accounting for the relative contribution of eastern and midcontinent mallards to each Flyway.

We simulated the use of this harvest strategy with the working model of population dynamics to determine expected performance characteristics. Assuming that harvest management adhered to this strategy, the annual harvest and breeding population size would average 327 (SE = 60) thousand and 1.06 (SE = 0.13) million, respectively.

Based on a breeding population size of 1.09 million mallards and spring precipitation of 8.34 inches, the optimal regulatory choice for eastern mallards in 1999 is the liberal alternative.

Table 8. Optimal regulatory choices[a] for eastern mallards during the 1999 hunting season. This strategy is based on regulatory alternatives unchanged from 1997 and 1998, the working model of population dynamics, and on an objective to maximize long-term cumulative harvest.

	Spring precipitation[b]									
Mallards[c]	6	7	8	9	10	11	12	13	14	15
500				VR	VR	VR	R	R	M	M
550		VR	VR	VR	R	M	M	L	L	L
600	VR	VR	R	M	M	L	L	L	L	L
650	R	M	M	L	L	L	L	L	L	L
700	M	L	L	L	L	L	L	L	L	L
750	L	L	L	L	L	L	L	L	L	L
800	L	L	L	L	L	L	L	L	L	L
850	L	L	L	L	L	L	L	L	L	L
>900	L	L	L	L	L	L	L	L	L	L

[a] VR = very restrictive, R = restrictive, M = moderate, and L = liberal.
[b] March to May precipitation in the northeastern U.S., in inches.
[c] Estimated number of eastern mallards in the combined fixed-wing and northeastern plot surveys, in thousands.

CURRENT AHM PRIORITIES

Communication Needs

Communication needs are becoming more complex, broader in scope, and more institutional in nature as implementation of AHM proceeds. Because of the explicit and formal nature of the AHM process, managers are being challenged to confront long-held beliefs about their ability to understand and influence the managed system, and about the potential of biological science to engender policy consensus. There seem to be three problem areas in particular:

(1) *Goal setting* - Effective management planning and evaluation depends on agreement among stakeholders about how to value harvest benefits, and how those benefits should be shared. These unresolved value judgements, and the lack of effective structures for organizing debate, present a serious threat to the viability of AHM. Moreover, the lack of information on the attitudes and preferences of the nation's waterfowl hunters is a continuing problem in the effort to determine appropriate harvest management objectives.

(2) *Limits to system control* - There are rather severe practical limits to our ability to predict, control, and measure harvests and, therefore, significant constraints on short-term harvest yields and the learning needed to increase long-term performance.

(3) *Management scale* - The history of waterfowl management has been characterized by persistent efforts to account for increasingly more spatial, temporal, and organizational variability in waterfowl biology. The cost-effectiveness of this approach is questionable; moreover, limited resources for monitoring and assessment rarely permit selection of the scale with the highest net benefit.

It may be these institutional issues, more than any of the most difficult technical problems, that pose the greatest challenge to the long-term success of AHM. Coping with these issues will require innovative mechanisms for producing effective dialogue, and for handling disputes within a process that all parties regard as workable. The Service, in cooperation with the AHM technical working group, is developing plans to address these communication issues.

Measuring Harvest Rates of Midcontinent Mallards

Since 1994 there has been a systematic effort to increase the rate at which hunters report band recoveries. This effort is expected to greatly increase the efficiency of banding programs, but has temporarily made it difficult to estimate the harvest rate of mallards. A study to evaluate recent changes in band-reporting rate is in the planning stage, with implementation to occur in 2000 or 2001.

As part of the planning effort, a pilot study was conducted in southern Saskatchewan in 1998 to obtain a preliminary estimate of band-reporting rates for adult mallards. A total of 1,675 reward bands ($100.00 each) were placed on adult mallards in three separate sites in southern Saskatchewan (Kindersley, Wynyard, Last Mt. Lake). The recovery rate for standard bands was 0.075 (S.E. 0.005), and the recovery rate for reward bands was 0.093 (S.E. 0.007). Based on these data, the estimate of the band-reporting rate is 0.805 (S.E. 0.082), or about twice that from the late 1980's. Plans are being made to expand the area where reward bands are used in 1999 to include the Great Lakes and other important breeding areas. This effort should permit reasonable estimates of harvest rates for midcontinent mallards until the full band-reporting rate study is completed.

Modeling Reproduction of Midcontinent Mallards

We continue to explore predictive models that describe how the reproductive success of midcontinent mallards varies in response to environmental conditions across the core breeding area. Recent efforts involved investigating the relationship between the fall age ratio of female mallards and: (1) size of the mallard population; (2) number of ponds in survey strata 26-49; (3) average latitude of ponds; (4) average longitude of ponds; (5) slope of the regression between strata-specific crop acreage and pond abundance, and (6) selected interactions of these independent variables. The "best" model ($R^2 = 0.81$, $P < 0.01$) included negative associations with (1) and (3), and a positive relationship with (2), consistent with *a priori* hypotheses. The "best" six models, as indicated by Akaike's Information Criterion, all included a spatial component (i.e., either latitude, longitude, or their interaction); only one included the slope variable. These results confirm that landscape attributes other than pond numbers might be useful for predicting fall age ratios, although the appropriate environmental features, and the mechanism(s) by which those features influence the age ratio, have not been identified. Future work will focus on methods to reliably measure recruitment at smaller spatial scales, and on remote-sensing techniques to monitor wetland and upland habitat conditions across the Prairie Pothole Region.

AHM Protocol for Multiple Duck Stocks

All ecological systems exhibit variability on a broad range of temporal, spatial, and organizational (or taxonomic) scales as a function of how individuals respond to their environment. The scale at which individuals are aggregated for harvest-management purposes is an arbitrary decision, but one that can strongly influence both the benefits and costs of management. Harvest management systems defined at scales that account for large amounts of biological variation will produce relatively high benefits, but also are characterized by high monitoring and assessment costs. Determining the optimal scale for harvest management depends on the availability of explicit performance criteria (i.e., management goals, objectives, and constraints, including how harvest should be allocated among users), and on descriptions of how biological attributes vary among different scales.

We have begun to explore various temporal, spatial, and organizational scales for regulating duck harvests. We are focusing on the appropriate number of breeding duck stocks (i.e., species and/or populations), and the spatial configuration of regulatory decisions. Preliminary investigations of management scale suggest that harvest utility often is insensitive to the level of aggregation, even when duck stocks are characterized by relatively large demographic differences. This lack of sensitivity is even more pronounced in the face of poor control over stock-specific harvests. Therefore, managers potentially face a tradeoff between relatively small gains in harvest opportunity, and the increased assessment costs and regulatory complexity associated with fine-scale management.

AHM for Eastern and Western Mallards

Modifying the AHM protocol to account for both eastern and western mallards is perhaps the most challenging technical issue facing duck harvest managers. Never before have we tried to consider the status of multiple mallard stocks in such a formal way, nor have we attempted to give all Flyways the ability to choose regulations that are tied to their particular derivation of mallards. Although progress has been significant, there are three issues in this effort that require further attention: (1) development of population models; (2) agreement on harvest management objectives; and (3) modification of decision rules to allow Flyway-specific regulatory choices. Population models for eastern and western mallards are still in the developmental stage, and major sources of uncertainty have yet to be articulated or their management implications explored. Another difficulty involves agreeing on population-specific harvest management objectives, and then combining them into one objective function so that multiple-stock harvest strategies can be derived. Finally, we must modify the decision rules to allow for Flyway-specific regulatory choices, but this greatly complicates the optimization process. Instead of five regulatory alternatives, we must evaluate $5^4 = 625$ possible decisions for each combination of population level and environmental variable for all three mallard stocks. The USFWS and AHM working group have assigned a high priority to addressing these technical issues, and hope to fully integrate eastern mallards and western mallards into the AHM process in 2000 and 2001, respectively.

AHM for Northern Pintails

The first step in developing an AHM process for pintails has been to develop a set of alternative models that represent the dynamics of the continental population. Efforts to model annual recruitment for pintails have focused on four areas of uncertainty thought to affect reproductive success: population density, population distribution, habitat conditions on the breeding range, and habitat conditions in wintering areas. Annual productivity is indexed using age-ratios in the U.S. harvest. The initial recruitment model for pintails predicts annual reproductive success based on the average latitude of the breeding population, the size of the breeding population, and mean monthly precipitation (January-March) for the Prairie Pothole Region. These three variables explain 57% of the historical variation in the index to recruitment. The average latitude of the breeding population is a better predictor of recruitment than the May ponds index, perhaps because it is a more direct measurement of the behavioral response of the birds to environmental conditions. Attempts to include a predictor related to wintering ground conditions have not been successful; further work is needed to identify appropriate predictors.

Efforts to model annual survival for pintails have focused on the uncertainty about whether the harvest is an additive or compensatory form of mortality. Analyses to estimate relationships between annual survival and factors such as population density, reproductive success, and habitat conditions have been unsuccessful. This is primarily due to the imprecision of annual survival rate estimates. A simple model of annual survival as a function of the kill rate, which closely follows the model for midcontinent mallards, was developed. Additive and compensatory models were parameterized by finding a value for survival in the absence of harvest that provided equally good fits to the historical data for both the additive and compensatory models. At the low level of harvest typical in recent years, these two models do not differ greatly in their predictions; however, the practical implications of the two models have not yet been determined. Finally, there is some suggestion in the immature male survival data that some other important dynamic might be at work, but this has yet to be fully explored.

The next step in the development of an AHM process for pintails involves an exploration of the implications of these recruitment and survival models for harvest management. If optimal harvest strategies for pintails are significantly different than those for midcontinent mallards, managers will need to agree on acceptable mechanisms for regulating the harvests of pintails independently of mallards.

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APPENDIX B: Mallard Population Models

Variable definitions:

MALM	/* index to midcontinent mallard state variable */
PONDM	/* index to midcontinent pond state variable */
MALE	/* index to eastern mallard state variable */
PPTE	/* index to eastern precipitation state variable */
RAINM	/* random variable index to midcontinent precipitation */
RAINE	/* random variable index to eastern precipitation */
PROP	/* random variable index to proportion of midcontinent population in WI, MN, MI */
HRATEM	/* index to stochastic midcontinent harvest-rate */
HRATEE	/* index to stochastic eastern harvest-rate */
outcome[]	/* outcome of random or stochastic variable */
cur_state[]	/* current value of state variable */
nxt_state[]	/* value of a state variable in the next time step */
wt1m	/* model 1 weight (compensatory survival, strong density-dependent recruitment) for midcontinent mallards */
wt2m	/* model 2 weight (compensatory survival, weak density-dependent recruitment) for midcontinent mallards */
wt3m	/* model 3 weight (additive mortality, strong density-dependent recruitment) for midcontinent mallards */
wt4m	/* model 4 weight (additive mortality, weak density-dependent recruitment) for midcontinent mallards */
nxt1m	/* model 1 prediction for next state - midcontinent mallards */
nxt2m	/* model 2 prediction for next state - midcontinent mallards */
nxt3m	/* model 3 prediction for next state - midcontinent mallards */
nxt4m	/* model 4 prediction for next state - midcontinent mallards */
Awm	/* weak density-dependent fall age ratio - midcontinent mallards */
Asm	/* strong density-dependent fall age ratio - midcontinent mallards */
Hafm	/* harvest rate - adult females - midcontinent mallards */
Hamm	/* harvest rate - adult males - midcontinent mallards */
Hyfm	/* harvest rate - young females - midcontinent mallards */
Hymm	/* harvest rate - young males - midcontinent mallards */
Kafm	/* kill rate - adult females - midcontinent mallards */
Kamm	/* kill rate - adult males - midcontinent mallards */
Kyfm	/* kill rate - young females midcontinent mallards */
Kymm	/* kill rate - young males - midcontinent mallards */
shafam	/* hunt-season survival - adult females -additive mortality - midcontinent mallards */
shafcm	/* hunt-season survival - adult females - compensatory survival - midcontinent mallards*/
shamam	/* hunt-season survival - adult males - additive mortality - midcontinent mallards */
shamcm	/* hunt-season survival - adult males - compensatory survival - midcontinent mallards */
shyfam	/* hunt-season survival - young females - additive mortality - midcontinent mallards */
shyfcm	/* hunt-season survival - young females - compensatory surv. - midcontinent mallards */
shymam	/* hunt-season survival - young males - additive mortality - midcontinent mallards */
shymcm	/* hunt-season survival - young males - compensatory survival - midcontinent mallards*/
dafm=0.748	/* differential harvest vulnerability - adult females - midcontinent mallards */
dymm=1.361	/* differential harvest vulnerability - young males - midcontinent mallards */
dyfm=1.188	/* differential harvest vulnerability - young females - midcontinent mallards */

c=0.2	/* crippling loss rate */
s0mm=0.81	/* survival in absence of hunting - male - midcontinent mallards */
s0fm=0.64	/* survival in absence of hunting - female - midcontinent mallards */
swm=0.90	/* winter survival - midcontinent mallards */
ssmm=0.90	/* summer survival - males - midcontinent mallards */
ssfm=0.71	/* summer survival - females - midcontinent mallards */
cfm=0.36	/* compensatory threshold - females - midcontinent mallards */
cmm=0.19	/* compensatory threshold - males - midcontinent mallards */
sexm=0.55	/* proportion of males in population - midcontinent mallards */
nxt1e	/* model 1 prediction for next state - eastern mallards */
nxt2e	/* model 2 prediction for next state - eastern mallards */
nxt3e	/* model 3 prediction for next state - eastern mallards */
nxt4e	/* model 4 prediction for next state - eastern mallards */
wt1e=0.00	/* model 1 weight (compensatory survival, strong density-dependent recruitment) for eastern mallards */
wt2e=0.00	/* model 2 weight (compensatory survival, weak density-dependent recruitment) for eastern mallards */
wt3e=0.00	/* model 3 weight (additive mortality, strong density-dependent recruitment) for eastern mallards */
wt4e=1.00	/* model 4 weight (additive mortality, weak density-dependent recruitment) for eastern mallards */
BBSr	/* BBS index - eastern mallards */
logits	/* logit of age ratio for strong density-dependent recruitment model - eastern mallards */
Ase	/* strong density-dependent age ratio - eastern mallards */
logitw	/* logit of age ratio for weak density-dependent recruitment model - eastern mallards */
Awe	/* weak density-dependent age ratio - eastern mallards */
Hafe	/* harvest rate - adult females - eastern mallards */
Hame	/* harvest rate - adult males - eastern mallards */
Hyfe	/* harvest rate - young females - eastern mallards */
Hyme	/* harvest rate - young males - eastern mallards */
Kafe	/* kill rate - adult females - eastern mallards */
Kame	/* kill rate - adult males - eastern mallards */
Kyfe	/* kill rate - young females - eastern mallards */
Kyme	/* kill rate - young males - eastern mallards */
shafae	/* hunt-season survival - adult females - additive mortality - eastern mallards */
shafce	/* hunt-season survival - adult females - compensatory survival - eastern mallards */
shamae	/* hunt-season survival - adult males - additive mortality - eastern mallards */
shamce	/* hunt-season survival - adult males - copmpensatory survival - eastern mallards */
shyfae	/* hunt-season survival - young females - additive mortality - eastern mallards */
shyfce	/* hunt-season survival - young females- compensatory survival - eastern mallards */
shymae	/* hunt-season survival - young males -additive mortality - eastern mallards */
shymce	/* hunt-season survival - young males - compensatory survival - eastern mallards */
dafe=0.98	/* differential vulnerability - adult females - eastern mallards */
dyme=1.45	/* differential vulnerability - young males - eastern mallards */
dyfe=1.32	/* differential vulnerability - young females - eastern mallards */
s0me=0.81	/* survival in absence of hunting - male - eastern mallards */
s0fe=0.64	/* survival in absence of hunting - female - eastern mallards */
swe=0.90	/* winter survival - eastern mallards */
ssme=0.90	/* summer survival - males - eastern mallards */
ssfe = 0.71	/* summer survival - females - eastern mallards */
cfe=0.36	/* compensatory threshold - females - eastern mallards */

```
cme=0.19                /* compensatory threshold - males - eastern mallards */
sexe=0.55               /* proportion males in May - eastern mallards */
```

Hunting mortality rates:

```
Hamm=outcome[HRATEM];
Hafm=min(1, Hamm*dafm);
Hymm=min(1, Hamm*dymm);
Hyfm=min(1, Hamm*dyfm);
Kafm=min(1, Hafm/(1-c));
Kamm=min(1, Hamm/(1-c));
Kyfm=min(1, Hyfm/(1-c));
Kymm=min(1, Hymm/(1-c));
Hame=outcome[HRATEE];
Hafe=min(1, Hame*dafe);
Hyme=min(1, Hame*dyme);
Hyfe=min(1, Hame*dyfe);
Kafe=min(1, Hafe/(1-c));
Kame=min(1, Hame/(1-c));
Kyfe=min(1, Hyfe/(1-c));
Kyme=min(1, Hyme/(1-c));
```

Recruitment rates:

```
Awm=max(0, 0.8249-(0.0547*((1-outcome[PROP])*cur_state[MALM]/1000000.0))+
        (0.1130*(cur_state[PONDM]/1000000.0)));
Asm=max(0, 0.1081-(0.1128*((1-outcome[PROP])*cur_state[MALM]/1000000.0))+
        (0.1460*(cur_state[PONDM]/1000000.0)));
BBSr=-2.315455 + 0.000007081*cur_state[MALE];
logits=-0.483415-0.284774*BBSr+0.121664*cur_state[PPTE];
Ase=3.0*exp(logits)/(1+exp(logits));
logitw=-0.573898-0.170945*BBSr+0.109462*cur_state[PPTE];
Awe=3.0*exp(logitw)/(1+exp(logitw));
```

Hunting-season survival rates:

```
shafam=(1-Kafm); shamam=(1-Kamm); shyfam=(1-Kyfm); shymam=(1-Kymm);
if (Kafm>cfm) shafcm=(1-Kafm)/s0fm; else shafcm=1.0;
if (Kamm>cmm) shamcm=(1-Kamm)/s0mm; else shamcm=1.0;
if (Kyfm>cfm) shyfcm=(1-Kyfm)/s0fm; else shyfcm=1.0;
if (Kymm>cmm) shymcm=(1-Kymm)/s0mm; else shymcm=1.0;
shafae=(1-Kafe); shamae=(1-Kame); shyfae=(1-Kyfe); shymae=(1-Kyme);
if (Kafe>cfe) shafce=(1-Kafe)/s0fe; else shafce=1.0;
if (Kame>cme) shamce=(1-Kame)/s0me; else shamce=1.0;
if (Kyfe>cfe) shyfce=(1-Kyfe)/s0fe; else shyfce=1.0;
if (Kyme>cme) shymce=(1-Kyme)/s0me; else shymce=1.0;
```

Next states:

```
nxt_state[PONDM=max(1, -3835087.53+0.45*cur_state[PONDM]+13695.47*outcome[RAINM]) ;
nxt1m=cur_state[MALM]*((1.-sexm)*ssfm*(shafcm+Asm*(shyfcm+shymcm)) + sexm*ssmm*shamcm)*swm;
```

```
nxt2m=cur_state[MALM]*((1.-sexm)*ssfm*(shafcm+Awm*(shyfcm+shymcm)) + sexm*ssmm*shamcm)*swm;
nxt3m=cur_state[MALM]*((1.-sexm)*ssfm*(shafam+Asm*(shyfam+shymam)) + sexm*ssmm*shamam)*swm;
nxt4m=cur_state[MALM]*((1.-sexm)*ssfm*(shafam+Awm*(shyfam+shymam)) + sexm*ssmm*shamam)*swm;
nxt_state[MALM]=max(0, wt1m*nxt1m+wt2m*nxt2m+wt3m*nxt3m+wt4m*nxt4m);
nxt_state[PPTE]=outcome[RAINE];
nxt1e=cur_state[MALE]*((1.-sexe)*ssfe*(shafce+Ase*(shyfce+shymce)) + sexe*ssme*shamce)*swe;
nxt2e=cur_state[MALE]*((1.-sexe)*ssfe*(shafce+Awe*(shyfce+shymce)) + sexe*ssme*shamce)*swe;
nxt3e=cur_state[MALE]*((1.-sexe)*ssfe*(shafae+Ase*(shyfae+shymae)) + sexe*ssme*shamae)*swe;
nxt4e=cur_state[MALE]*((1.-sexe)*ssfe*(shafae+Awe*(shyfae+shymae)) + sexe*ssme*shamae)*swe;
nxt_state[MALE]=max(0, wt1e*nxt1e+wt2e*nxt2e+wt3e*nxt3e+wt4e*nxt4e);
```

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:

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

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:

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

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:

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

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,

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

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:

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

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

Mgmt Area	Effect	State/Zone	Estimate	SE
CF - Ip	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 1998-99 Season

Harvest rate estimates were obtained for banding reference areas 1-3, 5-7 and 12-14 using a single estimate from reference area 4 (Anderson and Henny 1972), based on estimated correlations between harvest rates among reference areas. The harvest rate estimate for reference area 4 was based on reward banding (see Current AHM Priorities). The assumed model for the harvest rate in area j during year t was $h_t(j) = \mu_j + \eta_{jt}$, where μ_j is the area-specific mean and η_{jt} is correlated noise with variance δ^2 and correlations $Corr(\eta_{jt},\eta_{kt}) = \rho_{jk}$, where ρ_{jk} is the correlation between the harvest rates in reference areas j and k. These were estimated from the 36 years of available data. The strength of the correlation with area 4 harvest rates varied substantially with a maximum value of 0.783 occurring between areas 10 and 4 and a minimum value of -0.11 (essentially 0) occurring between areas 1 and 4. We wish to predict the value of $h_t(j)$ for any value of j from the observed value $h_t(4)$. In general, the best linear unbiased predictor (i.e., the "BLUP") of any random variable, say Z, given another random variable, say Y, is equivalent to the conditional expectation of Z given Y; i.e., $E[Z|Y]$. It can be shown that $E[Z|Y] = E[Z] + Cov(Z,Y)Var(Y)^{-1}(Y - E[Y])$.

In our case, this expression takes on the very simple form (not so, in general) $E[h_t(j)] = \mu_j + \rho_{j4}(h_t(4) - \mu_4)$, and it can be shown that this is equivalent to the prediction obtained by regression of $h_t(j)$ onto $h_t(4)$. The estimate is obtained by substituting parameter estimates into this expression (e.g., $\hat{\mu}_j$ for μ_j). The variance of this prediction is obtained as: $Var(\hat{h}_t(j)) = \delta^2(1 - \rho^2_{j4} + 1/n)$. Thus, we see that as the correlation with reference area 4 approaches 1, the prediction variance approaches δ^2/n, which is the variance of the mean. The prediction and associated prediction variance were computed for each of the nine reference areas. These predictions were then weighted by the proportion of the midcontinent mallard population in each area during spring 1998 to construct an estimate of the overall harvest rate.

The estimated harvest rate of adult male mallards in the midcontinent region during the 1998-99 hunting season was 0.10845 (SE = 0.013).

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.

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