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Adaptive Regulation of Waterfowl Hunting in the U.S.

Fred A. Johnson
U.S. Fish and Wildlife Service, fred_a_johnson@fws.gov

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Introduction

The harvest of renewable natural resources is predicated on the theory of density-dependent population growth (Hilborn et al. 1995). This theory predicts a negative relationship between the intrinsic rate of population growth and population density (i.e., number of individuals per unit of limiting resource) due to intraspecific competition for resources. In a relatively stable environment, unharvested populations tend to settle around an equilibrium where births balance deaths. Populations respond to harvest losses by increasing reproductive output or through decreased natural mortality because more resources are available per individual. Population size eventually settles around a new equilibrium and the harvest, if not too heavy, can be sustained without destroying the breeding stock. Resource managers typically attempt to maximize the sustainable harvest by driving population density to a level that maximizes the intrinsic rate of population growth (Beddington and May 1977).

Although the theoretical basis for harvesting renewable resources is fairly straightforward, the practice of harvest management has had its share of difficulties. History is replete with cases where uncontrolled variation in harvests or the environment, naive assumptions about system response, and management policies with short time horizons have led to resource collapse (Ludwig et al. 1993). To be successful, sustainable harvesting depends on an ability to effectively regulate the size of the harvest, on a sound understanding of the biological system and its density-dependent responses, and on management objectives that are congruent with the renewal capacity of the resource. Even with a firm commitment to long-term resource conservation, harvest managers always will be burdened by complex, dynamic systems that are only partially observable, and by management controls that are indirect and limited. It is for these reasons that a coherent framework for managing ecological risk is necessary.

Harvest management decisions involve three fundamental components: (1) unambiguous objectives; (2) a set of alternative harvest actions, including any constraints on those actions; and (3) the predicted consequences of those actions in terms that are relevant to the stated management objectives. The consequences of harvest actions cannot be predicted with certainty, and the associated risk is what makes management decisions difficult. I define risk as the probability of a management outcome, where the probability can be assessed reliably from past experience with the resource or with a similar biological system. Thus, risk differs from true uncertainty, in which past experience provides no guide for the future (Costanza and Cornwell 1992). In keeping with the definitions in this book, ecological risk assessment involves associating empirical probabilities of possible system responses with alternative management actions. Ecological risk management then is the process of using management objectives

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to value those (probabilistic) responses so that a preferred management action can be identified.

My purpose here is to describe the process of risk assessment and management used to establish waterfowl hunting regulations in the United States. I begin by providing information about the regulations-setting process, and about the biological monitoring and assessment programs that provide the basis for decision making. Next, I provide a description of the conceptual framework and key features of waterfowl harvest management. Finally, I provide an example of this framework as it is applied to the management of mallard harvests.

Background

Federal regulations governing the sport hunting of waterfowl in the United States have significant biological and socioeconomic impacts. Each year, roughly 13 million waterfowl, principally mallards (*Anas platyrhynchos*), teal (*A. crecca*, *A. discors*), wood ducks (*Aix sponsa*), and Canada geese (*Branta canadensis*) are harvested by about 1.5 million sport hunters (U.S. Fish and Wildlife Service 1988). In some cases, sport harvests represent up to 25 percent of the post-breeding population size (Anderson 1975). The impact of hunting activity on the economy also is significant. Waterfowl hunters in the United States spend over $500 million in pursuit of their sport, and the total economic output is estimated at $1.6 billion annually (Teisl and Southwick 1995).

The U.S. government's authority for establishing waterfowl hunting regulations is derived from treaties for the protection of migratory birds signed with Great Britain (for Canada in 1916), Mexico (1936), Japan (1972), and the Soviet Union (1978) (U.S. Fish and Wildlife Service 1975). These treaties prohibit all take of migratory birds from March 10 to September 1 each year, and provide for hunting seasons not to exceed 3½ months. Each year, the U.S. Fish and Wildlife Service (USFWS) solicits proposals for hunting seasons from interested parties, and after extensive public deliberations, establishes guidelines within which States select their hunting seasons. States may be more restrictive, but not more liberal, than federal guidelines allow. Hunting regulations typically specify season dates, daily bag limits, shooting hours, and legal methods of take.

Waterfowl hunting regulations have worked reasonably well, as evidenced by levels of hunting opportunity and harvest that have been maintained for at least 30 years. This record of success is notable, given that natural resources often are over-exploited to the point of economic extinction (Ludwig et al. 1993). This is not to say, however, that the process of setting waterfowl hunting regulations has been without problems. The process often is plagued by controversy, contentiousness, and, on occasion, court challenges and Congressional intervention (Feierabend 1984, Babcock and Sparrowe 1989, Sparrowe and Babcock 1989). These difficulties stem from uncertainty (or disagreement) about the impacts of regulations on harvest and waterfowl abundance, and from harvest management objectives that often are vague, ambiguous, or incommensurate (Johnson et al. 1993). In the face of these ambiguities, the USFWS traditionally has taken a conservative approach to hunting regulations, thereby exacerbating the potential for conflict, particularly during periodic downturns in waterfowl abundance (Blohm 1989).

Beginning in the mid-1980s, the USFWS began searching for ways to improve the regulation of waterfowl harvests. An effort to stabilize regulations, and thus avoid much of the annual debate about appropriate regulatory responses to environmental variation, was eventually abandoned (U.S. Fish and Wildlife Service 1988). The search for an alternative approach intensified in the 1990s, when large changes in the abundance of ducks prompted renewed controversy about appropriate harvest levels. Eventually, improvements in the regulatory process were framed in terms of adaptive resource management, in which there is an explicit accounting for uncertainty as to management impacts, and for the influence of management actions on reducing that uncertainty (Williams and Johnson 1995). Since 1995, mallard hunting regulations in the United States have been prescribed by a formal process referred to as adaptive harvest management (Johnson et al. 1996). Efforts are now underway to extend the process to include other species of migratory game birds.

The Regulatory Process

The USFWS derives its responsibility for establishing sport-hunting regulations from the Migratory Bird Treat Act of 1918 (as amended), which implements provisions of the international treaties for migratory bird conservation. The Act directs the Secretary of Agriculture to periodically adopt hunting regulations for migratory birds, "having due regard to the zones of temperature and to the distribution, abundance, economic value, breeding habits, and times and lines of migratory flight of such birds" (U.S. Fish and Wildlife Service 1975). The responsibility for managing migratory bird harvests has since been passed to the Secretary of the Interior and the USFWS. Other legislative acts, such as the National Environmental Policy Act, the Endangered Species Act, the Administrative Procedure Act, the Freedom of Information Act, and the Regulatory Flexibility Act, provide additional responsibilities in the development of hunting regulations, and help define the nature of the regulatory process (Blohm 1989).

Goals of the regulatory process are:

(1) to provide an opportunity to harvest a portion of certain migratory game bird populations by establishing legal hunting seasons;
(2) to limit harvest of migratory game birds to levels compatible with their ability to maintain their populations;
(3) to avoid the taking of endangered or threatened species so that their continued existence is not jeopardized, and their conservation is enhanced;
(4) to limit taking of other protected species where there is a reasonable possibility that hunting is likely to adversely affect their populations;
(5) to provide equitable hunting opportunity in various parts of the country within limits imposed by abundance, migration, and distribution patterns of migratory birds; and
(6) to assist, at times and in specific locations, in preventing depredations on agricultural crops by migratory game birds (U.S. Fish and Wildlife Service 1988).

Most waterfowl hunting regulations are established annually, within a timetable that is constrained on one end by the timing of biological data collection, and on the other end by the need to give states and the public adequate opportunity for involvement before hunting seasons are established. Information on waterfowl population status, and on the outlook for annual production, is typically unavailable until early summer of each year. Some waterfowl hunting seasons open as early as mid-September, so that the time available for interpreting biological data, developing regulatory proposals, soliciting public comment, and for establishing and publishing hunting regulations, is extremely limited. Problems or delays in the process can result in closed hunting seasons because pro-active regulatory action is required to allow any harvest of migratory birds.

The annual regulatory process is documented in the *Federal Register*, which provides a detailed record of proposals, public comment, government responses, final regulatory guidelines, and hunting-season selections by individual states. The process includes two development schedules, dedicated to "early" and "late" hunting seasons. Early seasons generally are those opening prior to October 1, and include those for migratory birds other than waterfowl (*Gruidae, Rallidae, Phalaropodidae,* and *Columbidae*), and for all migratory birds in Alaska, Puerto Rico, and the Virgin Islands. Late-season regulations pertain to most duck and goose hunting seasons, which typically begin on or after October 1. The early-season and late-season processes occur concurrently, beginning in January and ending by late September of each year.

Early each year, the USFWS announces its intent to establish waterfowl hunting regulations and provides the schedule of public rule-making (Fig. 7.2.1). The director of the USFWS appoints a Migratory Bird Regulations Committee (SRC), which presides over the process and is responsible for regulatory recommendations. The SRC convenes two public meetings during summer to review biological information and to consider proposals from Regulations Consultants, who represent Flyway Councils (Fig. 7.2.2). Flyway Councils, and the state fish and wildlife agencies they represent, are essential partners in the management of migratory bird hunting. After deliberations by the SRC and Regulations Consultants, the USFWS presents hunting-season proposals at public hearings and in the *Federal Register* for comment.

Following public comment, the USFWS develops final regulatory guidelines and forwards them to the Secretary of the Interior for approval. These guidelines, referred to as framework regulations, are Flyway-specific and specify the earliest and latest dates for hunting seasons, the maximum number of days in the season, and daily bag and possession limits. States select hunting seasons within the bounds of these frameworks, usually following their own process for proposals and public comment. Final hunting regulations, including any state-imposed restrictions, are published in the *Federal Register*.

Biological Monitoring

A key component of the regulatory process consists of data collected each year on population status, habitat conditions, production, harvest levels, and other system attributes of management interest (Smith et al. 1989). This program of monitoring is essential for discerning resource status, and for modifying hunting regulations in response to changes in environmental conditions. The system of waterfowl monitoring in North America is unparalleled in both scope and intensity, and is made possible only by the cooperative efforts of the USFWS, the Canadian Wildlife Service, state and provincial wildlife agencies, and various research institutions. I here provide a brief description of these monitoring programs.

Surveys conducted from fixed-wing aircraft at low altitudes are a mainstay of waterfowl management. Among the most important of these surveys are those conducted in the principal breeding range of North American ducks (Smith 1995). Each spring, duck abundance and habitat conditions are monitored in over 5 million km^2 of breeding habitat, using 89 thousand km of aerial transects (Fig. 7.2.3). Ground surveys are conducted on a subset of the aerial transects to estimate the proportion of birds that are undetected from the air. The central portion of the breeding range is surveyed again in mid-summer to estimate the number of duck broods, and to assess the progress of the breeding season. These surveys have been operational since the 1950s and provide the most important criterion for setting annual duck-hunting regulations.

Waterfowl abundance also is determined during winter through a network of aerial surveys in the United States and Mexico (Smith et al. 1989). These surveys originated in the 1930s and were the basis for establishing duck-hunting regulations prior to the development of breeding-ground surveys. Winter surveys are intended to provide a census of major waterfowl concentration areas, but they lack the rigorous statistical design of breeding ground surveys. Therefore, estimates of winter waterfowl abundance lack measures of precision, and are subject to error resulting from variation in the distribution of birds relative to surveyed areas. Nonetheless, winter surveys provide useful information about large-scale waterfowl distribution and habitat conditions, and they remain the primary basis for setting most goose-hunting regulations.

Waterfowl are also monitored through a large-scale marking program, in which individually numbered leg bands are placed on over 350 thousand birds annually, usually just prior to the hunting season. The band inscription asks the hunter or finder of a dead bird to report the band number, date, and location to the USFWS. Banding is the principal tool used to understand migratory pathways, and was the basis for establishing the four administrative flyways (Lincoln 1935). The banding program also is essential for understanding temporal and spatial variation in rates of harvest and natural mortality (Brownie et al. 1985).

The USFWS also conducts hunter surveys to determine hunting activity, harvest by species, date, and location, as well as age and sex composition of the harvest (Martin and Carney 1977). This monitoring program is conducted via a mail questionnaire, which is completed by a sample of 30-35 thousand waterfowl hunters across the United States. The sampling frame is derived from purchasers of federal Migratory Bird Hunting and Conservation ("duck") Stamps at randomly selected post offices or, more recently, directly from the sale of state hunting licenses. Questionnaire results provide the basis for estimating hunting effort and total waterfowl harvest. In addition to the questionnaire, about 8 thousand hunters send in wings or tails of harvested birds so that the species and demographic structure of the harvest can be determined reliably. A complete record of the waterfowl harvest in the United States extends back to 1962.

Predicting Regulatory Impacts

Long-term data from monitoring programs are used to estimate key population parameters such as survival and reproductive rates, and to associate levels of harvest with various regulatory scenarios

(Martin et al. 1979). These and other relevant data then are used to construct dynamic population models, which describe how waterfowl abundance varies in response to harvest and uncontrolled environmental factors (Williams and Nichols 1990). These models in turn are used to inform the regulations process, by assuming that population status is directly related to harvest, and that harvest can be predicted as a function of hunting regulations (Johnson et al. 1993). By building on accumulated monitoring data, these models constantly evolve to reflect a growing understanding of waterfowl population dynamics and the impacts of harvest.

Unfortunately, the modeling of waterfowl populations and their harvest continues to be characterized by great uncertainty. In many cases, the sheer number and complexity of historic hunting regulations, combined with inadequate replication and experimental controls, has precluded reliable inference about the relationship between regulations and harvests (Nichols and Johnson 1989). Managers know even less about the impact of harvest on subsequent waterfowl population size. Particularly problematic in this regard are questions about the nature of density-dependent population regulation, which provides the theoretical basis for sustainable exploitation (Hilborn et al. 1995). It is these uncertainties about the relationships among hunting regulations, harvest, and population size that are a principal source of controversy in the regulations-setting process.

Framework for Adaptive Harvest Management

Adaptive management can be defined as management in the face of uncertainty, with a focus on its reduction (Williams and Johnson 1995). In this approach, there is an explicit acknowledgment that uncertainty, and therefore risk, are inherent features of natural resource management. Unlike standard approaches to risk management, however, adaptive management involves the recognition that management itself can be a useful tool for reducing uncertainty, so that long-term management performance can be improved. Thus, adaptive management can be characterized as a problem of dual control, in which managers attempt to learn about system dynamics while simultaneously pursuing traditional management objectives (Walters 1986).

In adaptive harvest management, waterfowl managers seek to maximize long-term harvest yield against a background of various sources and degrees of uncertainty (Williams et al. 1996). These sources of uncertainty are identified using the terminology of operations research and decision theory, in part to emphasize that waterfowl harvest management falls within a broad class of problems in optimal stochastic control (Nichols et al. 1995). An easily recognized source of uncertainty is uncontrolled environmental variation, which produces random variation in resource status. Another source of uncertainty is partial controllability, which expresses a lack of concordance between intended and actual management controls, as a result of indirect actions (e.g., harvest regulations) that are imprecisely linked to specific control levels. A third source, referred to as partial observability, results from imprecision in the monitoring of harvest, population levels, and other system attributes. Finally, structural uncertainty refers to an incomplete understanding of biological processes and the impacts of hunting regulations. Although it is structural uncertainty that is the focus of adaptive harvest management, all sources of uncertainty influence both the ability to produce biologically acceptable harvests in the short term, and to learn about system dynamics so that harvest levels can be sustained over the long term.

To account for these sources of uncertainty, adaptive harvest management was framed in terms of sequential decision making under uncertainty, or more particularly in terms of a stochastic control process (Puterman 1994). In this conceptual model, the manager periodically observes the state of the resource system (e.g., population size and relevant environmental features) and takes some management action (e.g., hunting regulations) (Fig. 7.2.4). The manager receives an immediate return, expressed as a function of benefits and costs that are relevant to the stated objectives of management. Based on the management action, the resource system subsequently evolves to a new state, with the transition also being influenced by uncontrolled environmental factors. The manager then observes the new system state, and makes a new decision. The goal of the manager is to make a sequence of such decisions, each based on information about current system status, so as to maximize management returns over an extended time frame.

By taking advantage of the nature of decision making and system behaviors in waterfowl harvest management, it is possible to characterize the stochastic control problem as a Markov decision process. In this class of sequential decision process, management actions, returns, and system transitions are described only in terms of current system state and action, and not on states occupied or actions taken in the past. Given this simplifying constraint, computing algorithms and software are available for determining the optimal regulatory choice for the array of possible resource states (Puterman 1994, Lubow 1995, Williams 1996). An essential element of the optimization process is a set of state and action dependent probabilities, which are associated with possible management outcomes (i.e., returns and system transitions). It is these probabilities that reflect key stochastic effects and uncertainties in system dynamics.

A major advantage of adaptive harvest management over traditional approaches is in the explicit acknowledgment of alternative hypotheses describing the effects of regulations and other environmental factors on population dynamics. These hypotheses are codified in a set of system models, which is associated with a set of model-specific probabilities. These probabilities reflect the relative ability of the alternative models to describe system dynamics. Over time, some models are expected to perform better than others, and this performance is assessed by comparing the model-specific prediction of changes in population size with the actual change observed from the monitoring program. By iteratively updating model probabilities and optimizing regulatory choices, the process eventually should identify which model is most appropriate to describe the dynamics of the managed population.

Thus, the adaptive approach is a four-step process:

(1) each year, an optimal regulatory decision is identified based on resource status and current model probabilities;
(2) once the decision is made, model-specific predictions for subsequent breeding-population size are determined;
(3) when monitoring data become available, model probabilities are increased to the extent that observations and predictions agree, and decreased to the extent that they don't agree; and

(4) the new set of model probabilities then are used to start another iteration of the process.

The optimization algorithm and process for updating model probabilities are described in more detail in the Appendix to this chapter.

The key operational elements of the process include:

(1) a set of alternative models, describing population responses to harvest and uncontrolled environmental factors;
(2) a set of model-specific probabilities, which change through time based on comparisons of predicted and observed population sizes;
(3) a set of alternative choices for harvest regulations; and
(4) an objective function, by which harvest strategies can be evaluated.

These components are used to derive an optimal harvest policy, which specifies the appropriate regulatory choice for various resource states and probabilities associated with the alternative models of population dynamics (Johnson et al. 1997).

The framework of adaptive harvest management has improved the regulatory process by providing a formal and coherent structure to the decision-making problem and, thus, by informing debate about appropriate levels of harvest. Unlike the traditional theory of maximum sustained yield (Beddington and May 1977), the adaptive framework accounts explicitly for the dynamic nature of ecological systems and of our *understanding* of those systems. The framework does have its shortcomings, however. Adaptive harvest management cannot resolve conflict over management objectives, nor can it be effective without a long-term commitment to the resource and to the pursuit of useful information about population dynamics. The adaptive harvest management process also cannot determine which management actions to consider nor prescribe specific biological hypotheses. These issues demand effective institutional structures for determining how harvests should be valued by society, and for ensuring productive partnerships between resource management and research.

An example: Mallard Harvest Management

Four alternative population models capture key uncertainties (or risks) regarding the effects of harvest and environmental conditions on mallard abundance. The four models result from combinations of two discrete mortality and two discrete reproductive hypotheses (Fig. 7.2.5). The mortality hypotheses express different views about the effects of harvest on annual survivorship. Under the additive mortality hypothesis, survival rate declines as a linear function of harvest rate. Under the compensatory mortality hypothesis, increases in harvest rate below some threshold do not result in corresponding decreases in survivorship. The theoretical underpinning of the compensatory hypothesis is density-dependent mortality, in which mortality due to hunting is offset by declines in natural mortality. The reproductive hypotheses represent alternative views regarding the degree to which per-capita reproductive rate declines with increases in mallard abundance and, thus, are also expressions of density-dependent population regulation.

In addition to structural uncertainty, there is an explicit accounting for uncontrolled environmental variation and for partial controllability of harvest rates. Stochasticity in environmental conditions is characterized by a set of probabilities assigned to various amounts of annual precipitation in southern Canada (Fig. 7.2.6). Precipitation influences the number of available ponds, which are an important determinant of mallard reproductive success. To account for partial controllability, regulations-specific probabilities are assigned to possible rates of harvest (Fig. 7.2.7).

Conditioned on the specification of structural uncertainty, environmental variation, and partial controllability, an optimal regulatory policy is one that is expected to maximize long-term cumulative harvest utility. Harvest utility may be defined simply as harvest yield, or as a function of harvest and other performance metrics such as waterfowl population size. For mallards, managers seek to maximize long-term cumulative harvest, but proportionally devalue harvests whenever population size is expected to fall below the goal of the North American Waterfowl Management Plan (Johnson et al. 1996). Defining harvest utility in this way decreases the likelihood of regulatory decisions that are expected to produce population sizes below goal. Of course, harvest utility also should account for costs, but this has not been necessary in mallard harvest management because the cost of promulgating hunting regulations does not depend on the nature of the regulatory decision.

Optimal harvest regulations for mallards are highly dependent both on the status of the resource and on the probabilities associated with the alternative models of system dynamics (Fig. 7.2.8). Regardless of model probabilities, hunting regulations become more liberal with increasing mallard and pond numbers. For a given number of mallards and ponds, optimal regulatory choices become more liberal as the probability of compensatory hunting mortality and strongly density-dependent reproduction increases.

When the AHM process was initiated in 1995, the four alternative models of population dynamics were considered equally likely, reflecting a high degree of disagreement about harvest and environmental impacts on mallard abundance. Model probabilities changed markedly in 1996, and have remained relatively stable since (Table 1). On the whole, comparisons of observed and predicted population sizes provide strong evidence of additive hunting mortality and moderate evidence of strongly density-dependent reproduction. However, the set of model probabilities simply reflect the relative performance of alternative models, and conclusions regarding biological mechanisms are equivocal due to the lack of a rigorous experimental design.

Relationship to the ERM Framework

The AHM process was conceived and implemented independently of the ERM framework described in this book. Nonetheless, the general (i.e., ERM) and specific (i.e., AHM) approaches to ecological risk management are in conceptual agreement. Both AHM and ERM begin with a clear articulation of the management issue, including a bounding of the problem in ecological, social, and political dimensions. Both approaches acknowledge that management goals and objectives are value based, but nonetheless must be unambiguous and quantified if they are to be useful in selecting a preferred management policy or strategy. Both approaches require an *a priori* specification of management options or alternatives, recognizing that the set of acceptable alternatives must be limited to facilitate their assessment. Finally, both ERM and AHM depend on empirical data and its assessment to predict (probabilistically!) the ecological and social consequences of alternative management actions.

The principal difference between the ERM and AHM approaches involves the higher degree of formalism and analytical rigor in the latter. AHM relies heavily on the application of decision theory (Puterman 1994, Clemen 1996), in which an analytical structure provides a more systematic and objective approach to decision making. This structure is especially useful in harvest management, involving as it does sequential or dynamic decision making. Ecological management rarely involves situations in which decisions are made only once. There are many more examples where the same decision-making problem presents itself at either regular or irregular intervals (e.g., harvesting or stocking of animals, vegetation management, water releases at a dam). The characteristic feature of a sequential decision-making process is the need to account for both current and future consequences associated with decisions made in the present. Recognizing that consequences cannot be predicted with certainty, a key difficulty in analyzing dynamic problems involves understanding how various sources of uncertainty (i.e., uncontrolled environmental variation, partial system controllability, structural uncertainty, and partial system observability) propagate over time. Fortunately, there have been recent advances in computing algorithms and software for stochastic, sequential decision-making problems, and optimal solutions for small-dimension problems now can be derived on modest desk-top computers (Lubow 1995). Perhaps the most notable feature of AHM, however, is the explicit recognition that our *understanding* of ecological systems is also dynamic, and controlled (to some extent) by the choice of management actions. An *a priori* consideration of the impacts of management choices on future levels of uncertainty distinguishes adaptive management (Walters 1986) from the more traditional tracking-and-evaluation approaches envisioned in ERM.

Summary

The Migratory Bird Treaty Act (as amended) authorizes the federal government to establish annual regulations governing the sport hunting of waterfowl within the United States. Because of the need to collect and analyze biological data each year, the time available for developing regulatory proposals, soliciting public comment, and setting hunting seasons is extremely limited. Although the regulatory process has worked reasonably well from a biological perspective, it tends to be controversial because of uncertainties and disagreements about the impacts of regulations on harvest and waterfowl abundance. The USFWS recently developed an approach referred to as adaptive harvest management, in which managers seek to maximize long-term harvest yield against a background of various sources and degrees of uncertainty. The key feature of this approach is an explicit accounting for uncontrolled environmental variation, incomplete control over harvest levels, and key uncertainties regarding waterfowl population dynamics. Using stochastic control methodology, regulatory policies are designed to produce both short-term harvest yield, as well as the biological learning need to improve long-term management performance. This adaptive process, which has been used to regulate mallard harvests since 1995, has proved to be an effective tool for considering the relative risks of alternative management outcomes, and for reducing uncertainty about regulatory impacts.

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Appendix

Regulatory policies governing waterfowl harvests are identified using a recursive algorithm, in which the expected utility (or value) of harvest $V(\underline{R}_t|\underline{X}_t)$ over the time frame $\tau = t, t+1, ..., T$ is conditioned on system state $\underline{X}_t$ at time t, with $\underline{R}_t$ being a policy of time-specific and state-specific regulatory decisions:

$$V(\underline{R}_t|\underline{X}_t) = \sum_i p_{i,t}\left[E\left[\sum_{\tau=t}^{T} u_{i,\tau}|\underline{X}_t\right]\right]$$

$$= \sum_i p_{i,t}\left[E\left[u_{i,t}|\underline{X}_t + \sum_{\tau=t+1}^{T} u_{i,\tau}|\underline{X}_t\right]\right]$$

where $u_{i,t}$ is a model-specific harvest utility and and $p_{i,t}$ represents the probability that model i is the most appropriate model of system dynamics (Johnson et al. 1997). The expectation (E) is taken with respect to environmental variation and partial controllability using discrete, empirical probability distributions. An optimal regulatory policy is one that maximizes the expected cumulative harvest utility, $V(\underline{R}_t|\underline{X}_t)$.

System models that are relatively good predictors of population size gain probability mass according to

Bayes Theorem:

$$p_{i,\,t+1} = \frac{p_{i,t}\; l_i(X1_t,\; X1_{t+1})}{\sum_i p_{i,t}\; l_i(X1_t,\; X1_{t+1})}$$

where l_i $(X1_t, X1_{t+1})$ is the probability of observed changes in population size from t to $t+1$, conditioned on model i (Hilborn and Walters 1992:503-504). This probability is calculated by assuming that observed population sizes will be distributed normally around the prediction (Hilborn and Walters 1992:504, Williams et al. 1996), and by deriving a simulated probability density function of predicted population size (W. Kendall, Patuxent Wildlife Research Center, personal communication). These density functions are generated from the structure of model i, and from assumed distributions for sampling variation in $\underline{X}_t$ (i.e., partial observability) and variation in harvest rates under a given regulatory decision (i.e., partial controllability).

Table 7.2.1. Year-specific probabilities associated with alternative hypotheses of mallard population dynamics. The additive mortality hypothesis predicts a linear decrease in annual survivorship with increases in harvest mortality. The compensatory hypothesis predicts that, below some threshold, annual survivorship will remain unchanged for increases in harvest mortality. The strong density-dependent reproductive hypotheses predicts a greater decrease in reproductive output with increases in population size than the hypothesis of weak density dependence.

		Model probabilities			
Mortality hypothesis	Reproductive hypothesis	1995	1996	1997	1998
Additive	Strong density dependence	0.2500	0.6417	0.5668	0.6462
Additive	Weak density dependence	0.2500	0.3576	0.4235	0.3537
Compensatory	Strong density dependence	0.2500	0.0005	0.0082	0.0001
Compensatory	Weak density dependence	0.2500	0.0002	0.0015	0.0000

Fig. 7.2.1. Approximate timetable used by the U.S. Fish and Wildlife Service for setting annual hunting regulations for migratory birds.

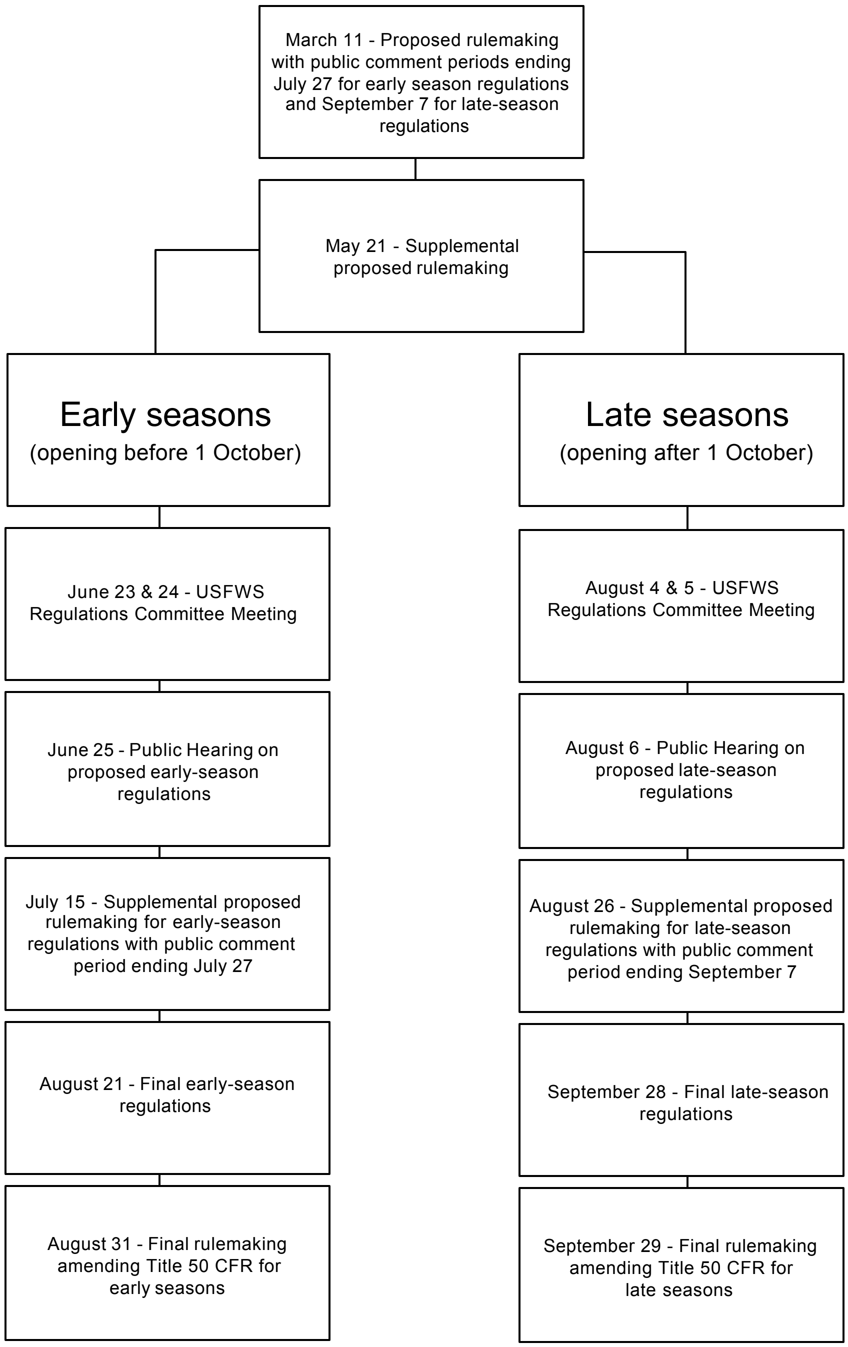

Fig 7.2.2. Waterfowl flyways used for administering sport-hunting regulations.

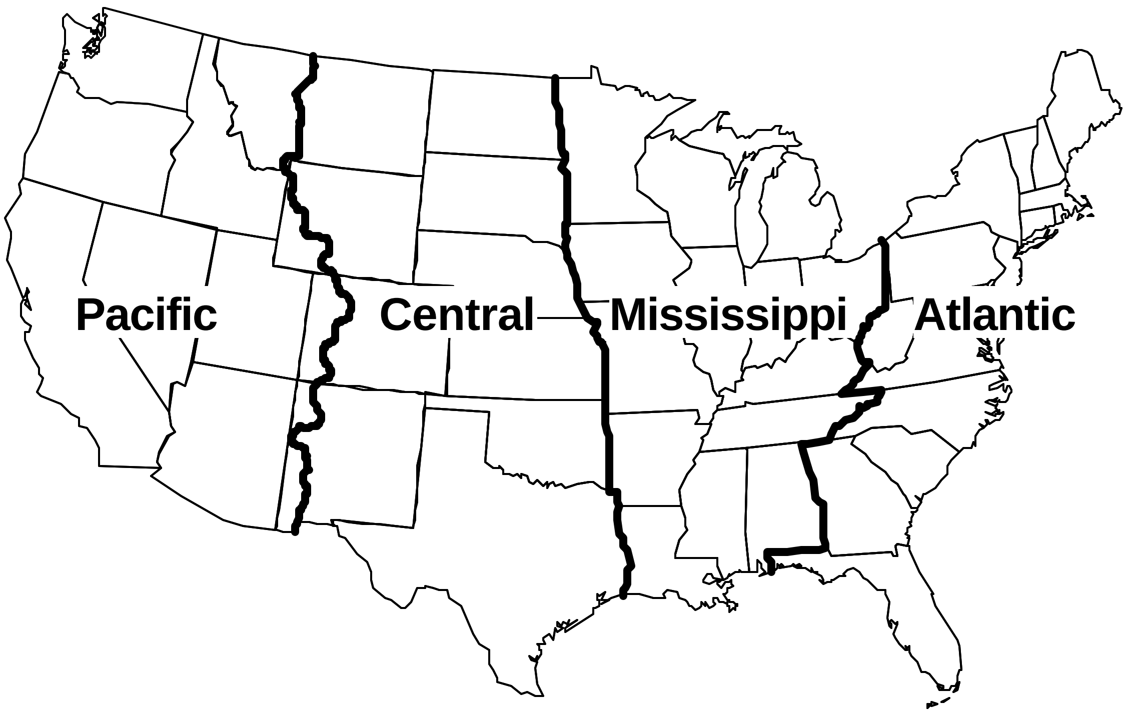

Fig. 7.2.3. Strata and transects of the Waterfowl Breeding Population and Habitat Survey, which is conducted annually by the U.S. Fish and Wildlife Service, the Canadian Wildlife Service, and state and provincial partners.

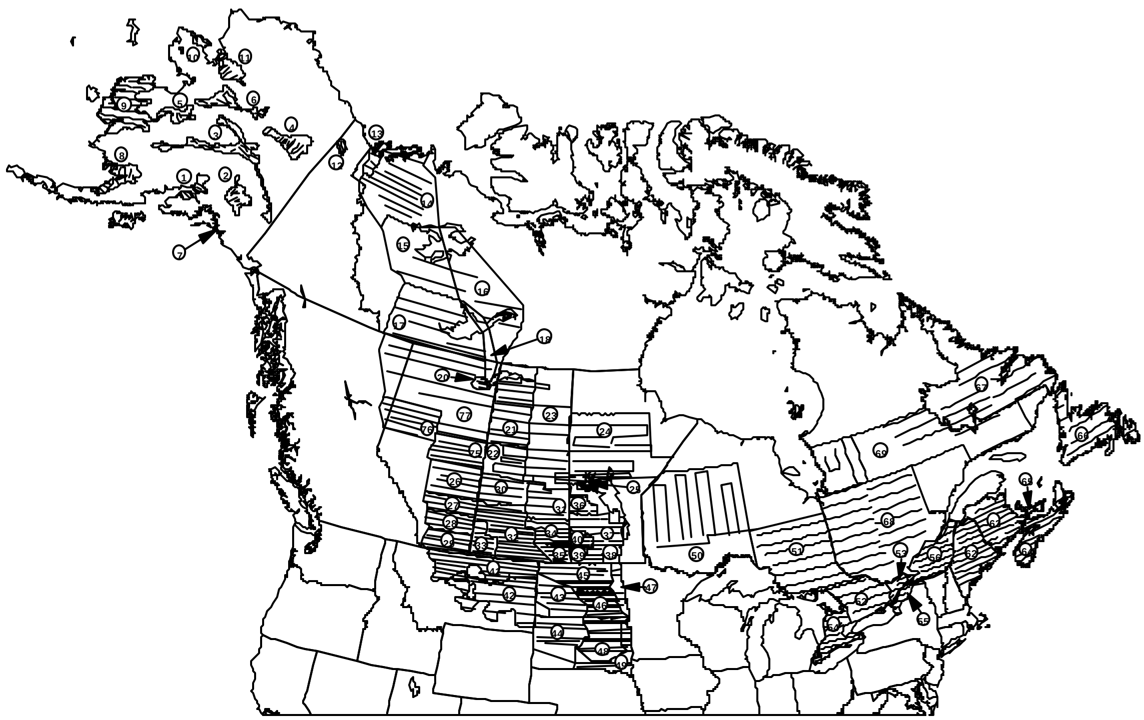

Fig. 7.2.4. A sequential decision-making process, in which management decisions made over time (t) elicit an immediate return (benefits-costs) and then, along with uncontrolled environmental factors, drive the resource system to a new state.

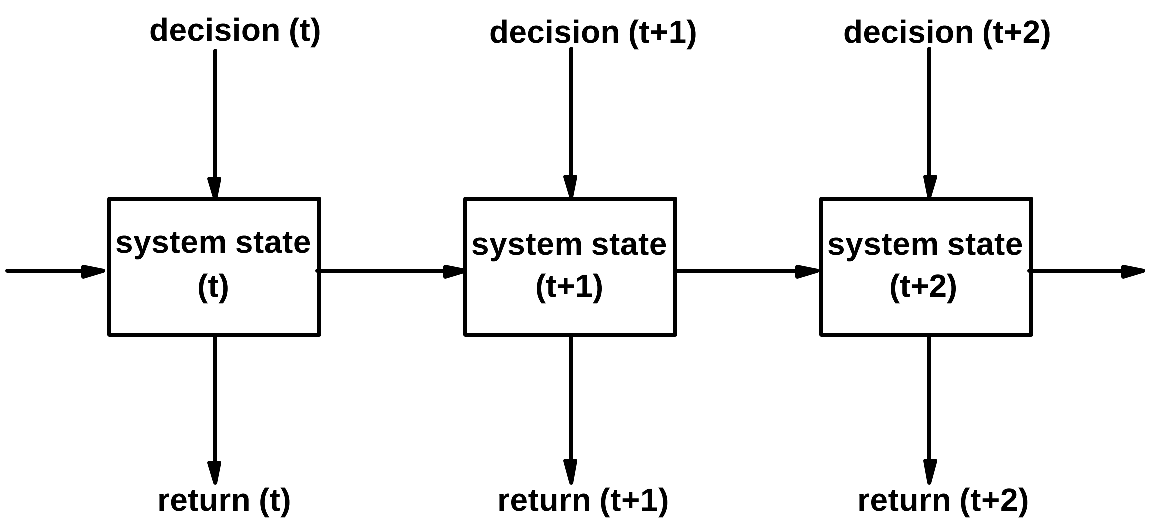

Fig. 7.2.5. Examples of structural uncertainty: (a) hypotheses of additive and compensatory hunting mortality; and (b) hypotheses of weakly and strongly density-dependent reproductive rates.

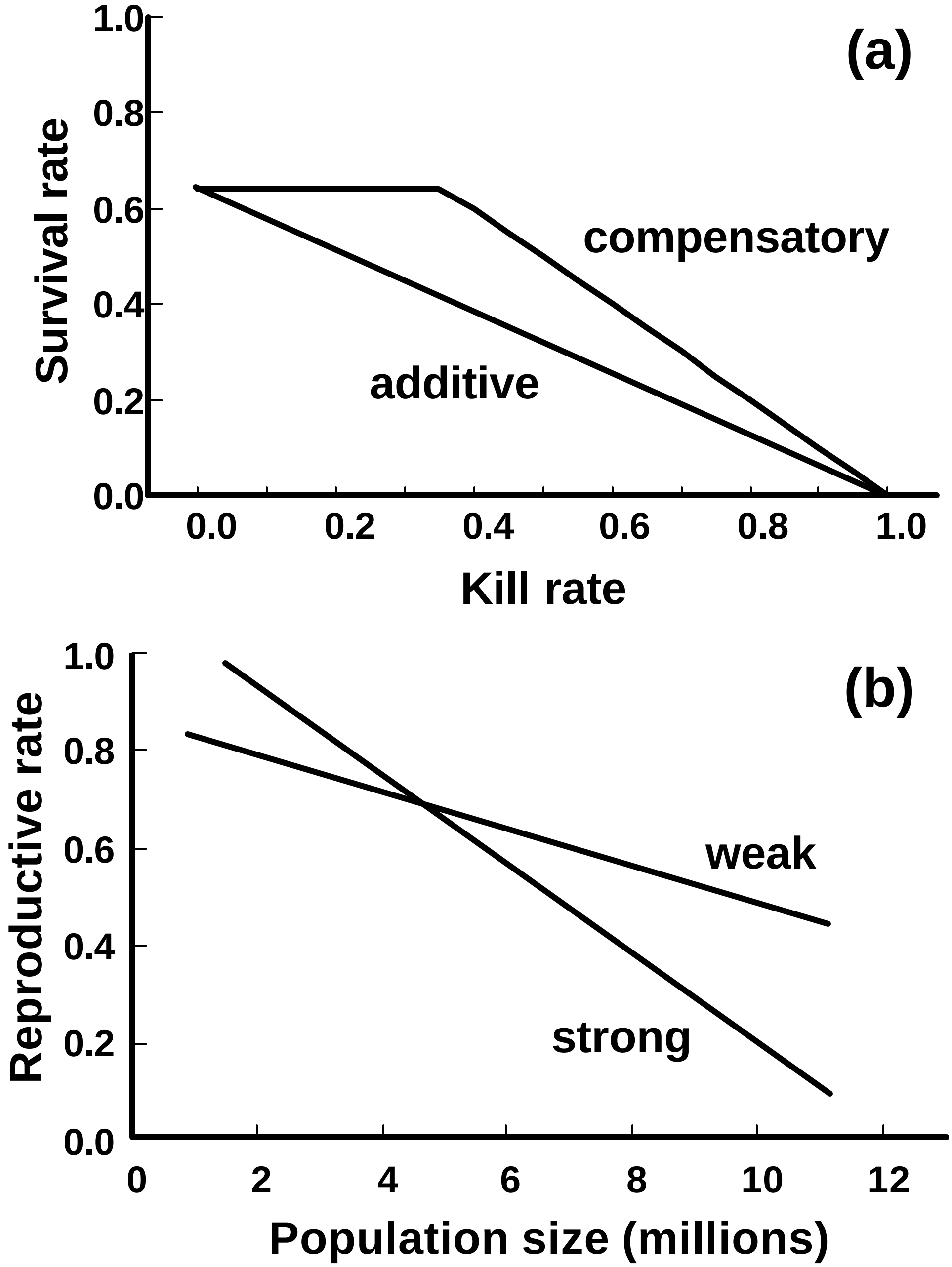

Fig. 7.2.6. An example of environmental uncertainty: frequencies of total annual precipitation in south-central Canada over the last 50 years.

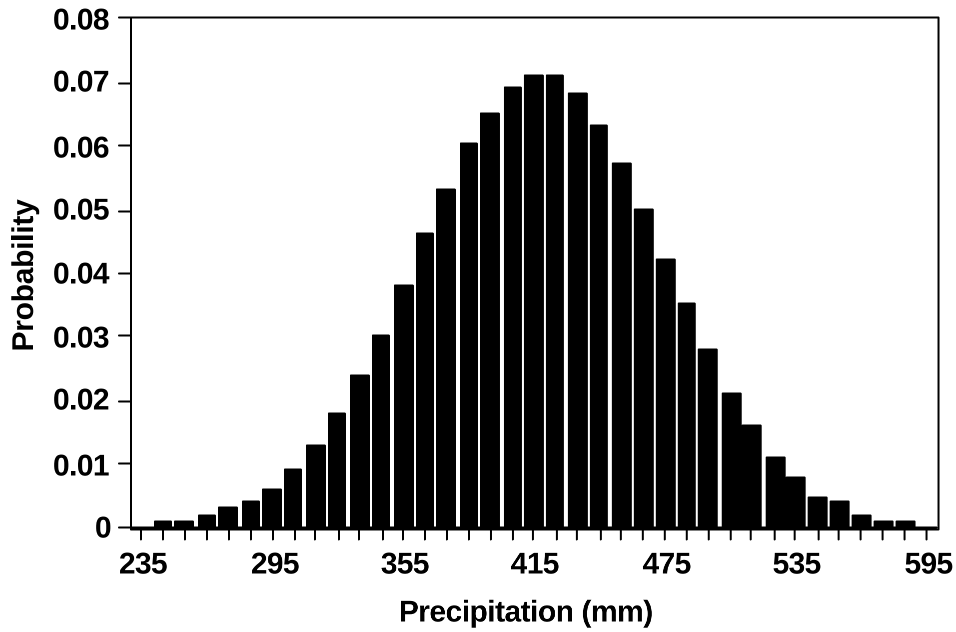

Fig. 7.2.7. An example of partial controllability: frequency distributions for the harvest rates of adult male mallards resulting from four different sets of hunting regulations as based on past experience.

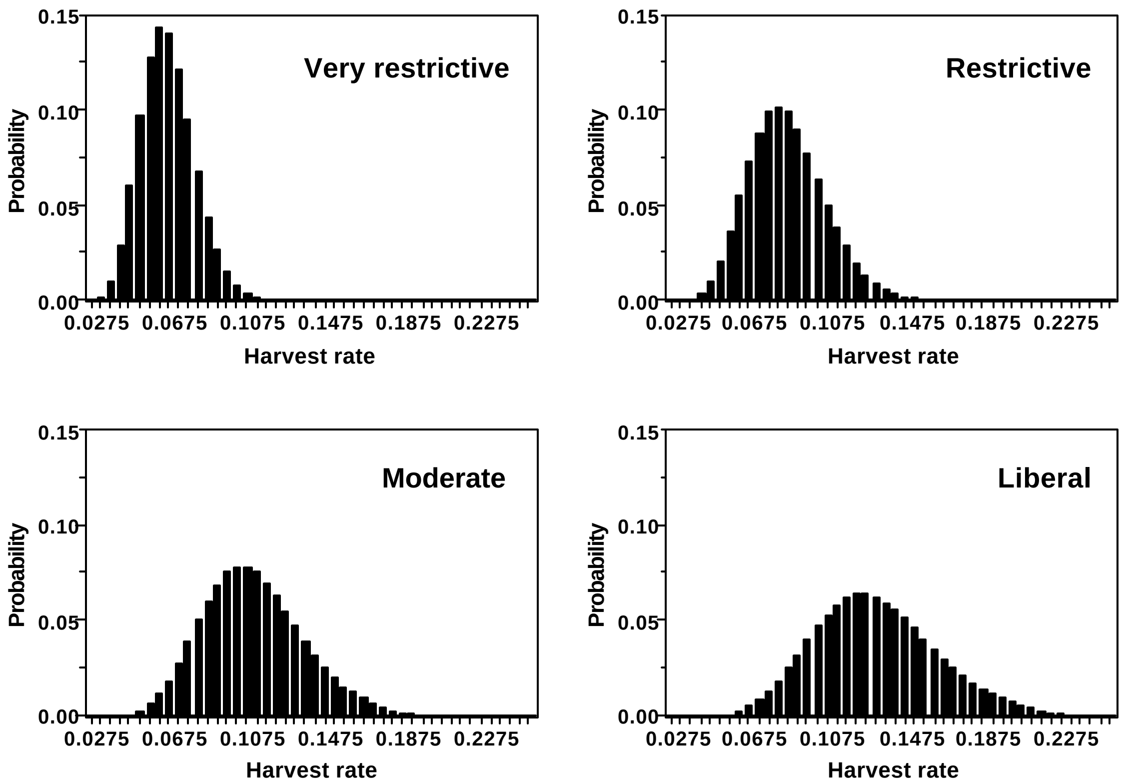

Fig. 7.2.8. Optimal regulatory choices for mallard hunting regulations, conditioned on mallard population size (in millions), pond numbers (in millions) on the breeding grounds, and the probabilities of additive hunting mortality and strongly density-dependent reproduction (C=closed season, VR=very restrictive, R=restrictive, M=moderate, and L=liberal).