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# STRUCTURED DECISION MAKING

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## INTRODUCTION

Wildlife management is an exercise in decision making. While wildlife science is the pursuit of knowledge about wildlife and its environment (including wildlife ecology, physiology, behavior, evolution, demography, genetics, disease, habitat, and population dynamics), wildlife management is the application of that knowledge in a human social context, application that typically requires a choice of management options. Decisions require the integration of science with values, because in the end any decision is an attempt to achieve some future condition that is desirable to the decision maker (Keeney 1996*b*). Wildlife management, particularly under the North American Model of Wildlife Conservation (Chapter 2), is often practiced by federal, state, or private agencies on behalf of the public and thus integrates science, law, and public values (Chapter 4). For example, the development of hunting regulations for white-tailed deer (*Odocoileus virginianus*) in Pennsylvania is a complicated choice among many possible permutations of regulations, a choice designed to balance many desires: hunting opportunity, the long-term conservation of deer, a sense of fair pursuit, fair public access, population levels commensurate with habitat capacity and predator density, wildlife viewing, and state and local economic benefits from hunting and tourism. Certainly, there are decades of wildlife science about deer and social science about deer hunters to support this decision, but they alone cannot identify the best regulations. The decision (i.e., the choice of hunting regulations) needs to integrate science- and values-based components (Wagner 1989).

Decision analysis is to wildlife management as the scientific method is to wildlife science, a framework and a theory to guide practice. The field of decision science is broad, with roots in economics stretching back to the 1940s, if not earlier (von Neumann and Morgenstern 1944), and the cross-disciplinary nature of the field became evident in the 1960s, with contributions from cybernetics (computer science), business administration, and mathematics (Raiffa and Schlaifer 1961, Howard 1968). Modern decision science has added expertise in many areas, including psychology, operations research, sociology, risk analysis, and statistics. Decision analysis has been applied in many contexts, including nuclear warfare planning (Dalkey and Helmer 1963), energy planning (Diakoulaki et al. 2005), adoption of health-care technologies (Claxton et al. 2002), and top-level political decisions in the Finnish parliament (Hämäläinen and Leikola 1996), to name a few. Formal decision analysis techniques are increasingly used in environmental fields (Kiker et al. 2005), particularly fisheries (Bain 1987, Gregory and Long 2009, Runge et al. 2011*a*), but also in wildlife management (Ralls and Starfield 1995, Johnson et al. 1997, Regan et al. 2005, Lyons et al. 2008, Runge et al. 2009, McDonald-Madden et al. 2010, Moore et al. 2011, Runge et al. 2011*b*). But it is perhaps surprising that, although wildlife management focuses on integrating values and science to make decisions, formal decision analysis is not applied more often, nor is it a core element in graduate education (van Heezik and Seddon 2005).

Is wildlife management an art or a science? There are wildlife managers who will vigorously argue the former, that the decisions they make are the result of years of experience, a deep sense of intuition, and scientific training. This is perhaps a traditional view; the language can be traced to the very beginning of our field. Leopold (1933:3) wrote, "game management is the art of making land produce sustained annual crops of wild game for recreational use." More recently, Bailey (1982:366) similarly described wildlife management: "As an art wildlife management is the application of knowledge to achieve goals . . . In selecting goals, [wildlife managers] compare and judge values." But note that the art that Leopold (1933) and Bailey (1982) describe is the integration of wildlife science with values-based judgments. Leopold's (1933) example embeds three main goals: providing recreational use of wild game, having that use be sustainable, and having that use be consistent (i.e., annual). A deeper question is whether the integration of science and values in making wildlife management decisions can be more than the informal and loosely structured judgment of a decision maker. Are wildlife management decisions transparent and replicable? Does the public know what values were balanced in choosing the deci-

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sion, and what science was consulted? Would a different decision maker have weighed the evidence and the values in the same way, and would that person come to the same decision? Will the decision maker's successor be able to maintain continuity, or will knowledge be lost every time someone retires? Increasingly, the public is demanding more transparency of natural resource managers, and decision analysis provides the framework for this transparency. This is not to say that the intuitive decision making of experienced wildlife managers is without merit, only that modern demands of transparency, accountability, inclusiveness, and efficiency require structured approaches to wildlife management decisions.

## A FRAMEWORK FOR DECISION MAKING

Making decisions is a hallmark of human existence, something we do every day. Decisions are not always difficult to make, but some (e.g., public sector decisions) are sufficiently complex and challenging that the common tools and rules of thumb used by humans in daily decision making are inadequate for achieving good decisions reliably. Decision analysis, or structured decision making (SDM), is "a formalization of common sense for decision problems which are too complex for informal use of common sense" (Keeney 1982:806). This section describes the elements of decision analysis in the context of wildlife management.

What is a decision? A decision is an "irrevocable allocation of resources . . . not a mental commitment to follow a course of action but rather the actual pursuit of the course of action" (Howard 1966:55). In the United States, the annual federal waterfowl hunting framework and the corresponding state waterfowl hunting seasons are decisions: they irrevocably set in motion harvest of waterfowl. State wildlife action plans (Fontaine 2011) are not themselves decisions, but they give rise to decisions when staff and fiscal resources are dedicated to carrying out actions in the plans. Likewise, recovery plans under the U.S. Endangered Species Act (ESA) are not decisions, but the actions taken under their auspices are.

### The PrOACT Framework

There are two hallmarks of structured decision making: values-focused thinking and problem decomposition. Values-focused thinking emphasizes that all decisions are inherently statements about values, and so discussion of those values should precede other analysis (Keeney 1996*a*). Problem decomposition breaks a decision into its logical components, allowing identification of impediments to the decision, providing focus when and where needed, and creating an explicit, transparent, and replicable framework for decision making that improves performance and stands up to scrutiny. The logical components of decision analysis include defining the Problem, identifying Objectives, defining alternative Actions to be taken, evaluating Consequences of actions, and assessing Trade-offs among alternative actions (Fig. 5.1). These components constitute the PrOACT framework (Hammond et al. 1999). Problem framing is often an iterative process intended to facilitate insights about a decision throughout development of the analysis. Each step benefits from re-evaluation at the completion of subsequent steps (Fig. 5.1).

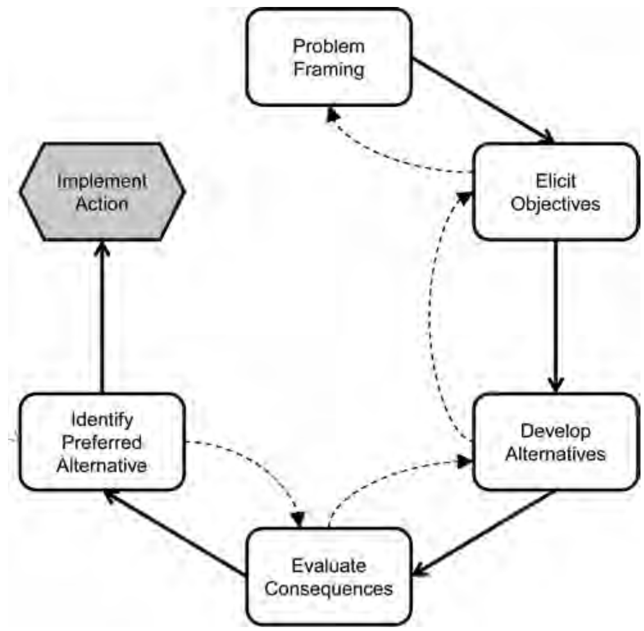


*Figure 5.1.* The steps of structured decision making: the PrOACT sequence.

Defining the problem is the critical first step of SDM that guides the process toward appropriate tools and information, determines appropriate levels of investment, and ensures that the right problem is being solved. Its importance cannot be overstated; time taken to craft a concise yet comprehensive and accurate problem definition pays off (Hammond et al. 1999). A good problem statement comprises the actions that need to be taken; legal considerations; who the decision maker is; the scope, frequency, and timing of the decision; goals that need to be met; and the role of uncertainty.

Objectives make explicit what the decision maker cares most about, defining what will constitute successful outcomes in the decision-making process. Along with the problem statement, well-defined objectives are critical to all subsequent steps in structured decision making, allowing the creation and assessment of alternative actions, identification of pertinent information for making the decision, and explanation of the decision-making process to others.

Actions represent choices available to a decision maker, or alternative approaches to achieving at least a subset of objectives. Good alternative actions address the future (not the past), are unique, encompass a broad range of possible actions, and can be implemented by the decision maker (i.e., are financially, legally, and politically reasonable).

Once alternative actions have been defined, the consequences of taking each action need to be predicted with respect to the objectives. All decisions involve prediction, whether implicit or explicit. One of the strengths of wildlife science is the wealth of tools (e.g., sampling protocols, data

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analysis methods, and modeling approaches) designed to help managers make predictions.

The final step in the PrOACT sequence is an analysis of trade-offs among alternatives based on their expected performance relative to the objectives, an analysis designed to identify an alternative that best achieves the set of objectives. This analysis can be anywhere from narrative to mathematical, depending on the complexity of the problem. The key role of a decision maker is to integrate the values- and science-based elements of the decision. Done well, this analysis should be transparent, should be comprehensive with respect to all fundamental objectives, should be explicit, should make use of best available information, and should address uncertainty directly.

The PrOACT sequence is simple but surprisingly powerful. In many decision settings, simply framing the problem helps to remove impediments to the decision. But the PrOACT framework also provides direction toward more advanced tools that may be needed in some circumstances.

### When Is SDM Appropriate?

Structured decision making is a broad and flexible set of tools that can be applied in a variety of settings. The PrOACT model provides a useful framework for ordering and deploying these tools, but SDM is not appropriate in all settings. First, SDM assumes that there is a decision to be made, which is not always the case. Strategic planning processes, prioritization schemes, research design, species status assessment, and compiling of scientific findings are all activities in which a wildlife biologist might participate, and products a wildlife manager might want, but they are not always in service to a specific decision. In those cases, SDM might help guide thinking toward the decisions that might be downstream of those activities, but it might also be frustrating to apply. Second, SDM assumes either that there is a single decision maker, or a single decision-making body, or multiple decision makers who agree to a spirit of open-mindedness and discovery for the purposes of identifying a common path. In situations where multiple parties to a decision are in substantial conflict, the endeavor might be better served by other facilitation, mediation, joint fact finding, or conflict resolution techniques. In situations where there are multiple decision makers in competition with one another, who have no intention to openly reveal their objectives or search for common ground, another branch of the decision sciences—game theory—provides insights and methods for analysis.

There are a number of other processes meant to support decision making that wildlife managers will hear about, which have overlapping domains of application (Fig. 5.2). Structured decision making is useful when the objectives are known or can be developed, but conflict resolution methods are better when the objectives are deeply disputed. Structured decision making is broadly applicable whether the scientific aspects of the decision are well known or not; joint fact finding is sometimes used when the science is disputed, as a way to engage stakeholders and develop common ground (Karl et al. 2007). As discussed later in this chapter, adaptive management is a special case of structured decision making, valuable for recurrent decisions that are impeded by uncertainty.

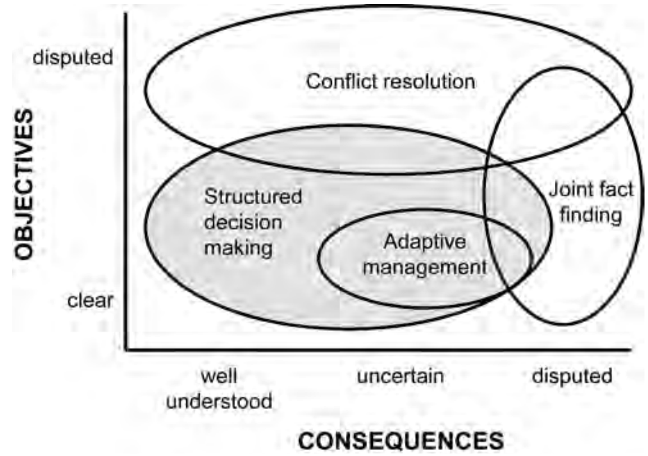


*Figure 5.2.* When is structured decision making appropriate?

### Classes of Decisions

One of the values of early attention to problem framing is the ability to recognize classes of decisions, which can in turn lead to identifying the best analytical tools to support the decision maker. Decisions can be classified on three axes: single- versus multiple-objective decisions; decisions in which uncertainty is, or is not, a major impediment; and stand-alone versus linked decisions (Table 5.1). The binary nature of these classes masks the complexity of true problems, so the reader should understand that there are some gray areas. Single-objective problems (or ones in which an objective carries significantly more weight than all others) that are not plagued by uncertainty (or for which the uncertainty in not consequential) are simple optimization problems for which a variety of tools (e.g., graphical, numerical, analytical) exist. Single-objective problems made in the face of uncertainty are the setting of classical decision analysis, and tools such as decision trees are valuable. Multiple-objective settings are supported by a broad array of multicriteria decision analysis (MCDA) techniques. Decisions that are linked to other decisions, either in a fixed sequence or in a recurrent pattern, require still more methods: dynamic optimization methods to address the linkages across time, and adaptive methods to account for resolution of uncertainty. Many of these methods are described in more detail later in this chapter, but it is helpful to have a context in which to place them.

## THE VALUES-BASED ASPECTS OF DECISIONS

In the absence of a structured framework for coherently integrating value judgments and scientific judgments, decision makers tend to confound personal preferences and technical predictions (Failing et al. 2007). One of the key benefits of the problem decomposition embodied in PrOACT is the ability to separate the values- and science-based aspects of the decision,

*Table 5.1.* Eight classes of decisions and the common decision analytic tools associated with them

| | Single objective | Multiple objective |
|---|---|---|
| **Single stand-alone decision** | | |
| Not impeded by uncertainty | Optimization tools | MCDA[a] |
| Impeded by uncertainty | Decision trees | MCDA with sensitivity analysis |
| **Linked decisions** | | |
| Not impeded by uncertainty | Dynamic optimization | Dynamic MCDA |
| Impeded by uncertainty | EVPI,[b] ARM[c] | Multiple-objective ARM |

[a]MCDA, multicriteria decision analysis.

[b]EVPI, expected value of perfect information.

[c]ARM, adaptive resource management.

which allows those pieces to be analyzed by the right people with the appropriate tools. In the spirit of value-focused thinking (Keeney 1996*a*), we first discuss the values-based aspects before turning attention to the science-based aspects.

## Defining the Problem

How a decision is framed affects how it should be analyzed, and this framing should reflect the values of the decision maker. Framing the decision can be surprisingly difficult and frustrating, but without a full definition of the problem and its context, considerable resources can be invested in solving the wrong problem. Further, a concise framing of the problem can aid clear communication with interested parties. For a simple, widely understood rubric to developing a problem statement, it is useful to refer to the five W's used in journalistic and technical writing. Many of the critical elements of the problem can be identified with explicit statements addressing the who, what, where, when, why, and how of a decision.

One way to begin is to ask, who needs to make a decision? Sometimes the decision maker is obvious (e.g., where mandated by law or regulations), but other times, identifying the decision maker can be challenging. First, it is useful to distinguish decision makers from those that implement a decision. The decision maker is the authority upon whom responsibility for the decision rests. Second, there may not be a single decision maker. In some collaborative settings, decision making is the joint responsibility of representatives from multiple agencies or interests; if that is the case, it is important for the decision analyst to understand the governance structure that supports that group. Third, in many public agency settings, the authority for the decision may be delegated. For example, in the United States, the secretary of interior has statutory responsibility under the ESA, but typically that authority is delegated to the director of the U.S. Fish and Wildlife Service (USFWS), who in turn may further delegate portions of that authority. This can create a challenge, because while the field office supervisor might be the decision maker with the motivation to analyze the decision, it is not clear at the outset how much consultation will be required up the delegated chain.

The question of who can be broadened considerably by asking, who is interested in the decision? Stakeholders include anyone with an interest in the outcome of the decision. These include individuals who could be directly or indirectly affected by the actions under consideration. In the case of the private landowner, it may be relatively simple to identify the stakeholders on the basis of familial and business relationships. However, many natural resource problems faced by public agencies affect a diverse group of stakeholders, including such consumers as hunters, anglers, hikers, and bird watchers, and groups that are seemingly detached from the natural resources in question but that are intensely interested in their status. For example, few individuals will ever visit the Alaskan arctic, but interest in the effects of such stressors as mineral extraction and climate change on arctic wildlife has evoked reactions from countless individuals across North America. The field of human dimensions offers methods to identify, understand, and involve stakeholders in decisions (Chapter 4).

The central question that a problem statement needs to address is, what is the decision to be made? To put it differently, what choice does the decision maker face? In wildlife management, decisions can be simple or exceedingly complex. For example, a wildlife manager might be faced with the relatively simple decision of whether to plant wildlife openings with native legumes or to allow old-field succession to take its course. The same manager may be tasked with developing a management plan that involves making decisions about dozens or hundreds of sites that will play out over many years.

Knowing explicitly where the affected resources are helps define the geographic and taxonomic scale of the problem. By asking when a decision is needed, we define two important aspects of the problem: timing and frequency. The first concerns the urgency for a decision; a short time scale may limit the complexity of the decision analysis. The second concerns whether the decision is made one time or recurrently. In many cases, the decision occurs once, such as the placement of infrastructure—roads, buildings, or dams. In other cases, decisions are recurrent, as in setting annual harvest regulations. In still others, a series of sequential decisions that hinge on the success of previous actions are considered.

The problem statement should address why the decision is important. To do so, the consequences of failing to make a decision can be examined. Will it result in strongly negative consequences, such as extinction, loss of hunting opportunities, loss of revenue, or litigation? In some cases, there may be a legal mandate related to agency mission, as in setting harvest regulations, listing species that are candidates for protection as threatened or endangered, or reviewing management alternatives (e.g., an Environmental Impact Statement under the National Environmental Policy Act, or NEPA). In other cases, decisions can be related to meeting an agency strategic objective such as providing public hunting or other recreational opportunities. In still other cases, a decision might relate to meeting tactical objectives of an agency, such as minimizing

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risk to natural resources, maximizing effectiveness of management, or meeting an agreed upon population objective.

The problem statement should also describe how to solve the problem. This description should be broad and conceptual; an explicit statement of alternatives and their relative value to solving the problem comes later in the process. A good way to think about this portion of the problem statement is a description of the natural resource management tools that could be implemented in reaching a solution. For example, manipulating harvest regulations at continental scales can maximize harvest of waterfowl. Meeting population objectives for nongame species can be achieved by enhancing habitat quality. These statements may put bounds on the alternatives that will be considered in the analysis, but they might also stimulate discussion and require revision during the development of the decision analysis.

Many insights about the nature of the decision arise out of the analysis, however, so problem definition often evolves. A well-constructed decision process allows the decision maker to revisit the elements of the decision framework repeatedly as the analysis proceeds.

## Articulating the Objectives

In wildlife management the development of unambiguous, meaningful objectives of the decision makers and the stakeholders is a critical step in the decision-making process. Ambiguous, poorly formed, and hidden objectives often lead to poor decision making, as does the exclusion of objectives that are important to large or important segments of the community of stakeholders. Clear, concise objectives with measureable attributes are the key to making informed, smart decisions because they define the decision's purpose (Keeney 1996*a*). However, when forced to make decisions in natural resources management, few individuals actually take the time to fully describe the purpose of the actions under consideration. We find it useful to distinguish four steps in the development of objectives: eliciting objectives, classifying objectives, structuring objectives, and developing measurable attributes.

### Eliciting Objectives

In developing objectives, it is often useful to start by eliciting the concerns of the decision makers and other stakeholders. Elicitation takes many forms, including workshops, public meetings, and one-on-one interviews. The important concept here is to be inclusive, empowering stakeholders and their representatives to articulate objectives that are important to making an informed decision. A variety of objectives is typical in wildlife management. Traditional concerns relate to the abundance and distribution of wildlife species, the health and quality of individual animals, the resources on which they depend, and their availability for consumptive or nonconsumptive uses. During the last several decades, new concerns related to maintaining or increasing biodiversity have made their way into wildlife conservation and management. And, increasingly, we recognize that wildlife management takes place in a sociopolitical context, and so a broader set of objectives is important, including economic, cultural, aesthetic, and spiritual concerns.

Objectives related to wildlife population abundance usually stem from worries about their viability (e.g., rare species), long-term persistence (e.g., many migratory songbirds), or harvestable surplus (e.g., most game species). Stakeholders often express these types of concerns in terms of declining populations or harvest levels. However, concerns over wildlife populations may also stem from overabundance, especially where there are large economic impacts—for example, cormorants (*Phalacrocorax* spp.), white-tailed deer, nutria (*Myocaster coypus*), muskrat (*Ondatra zibethicus*), and raccoons (*Procyon lotor*)—or environmental impacts—for example, western Canada geese (*Branta canadensis*) and lesser snow goose (*Chen caerulescens*).

Wildlife managers are often concerned about objectives above and beyond wildlife abundance, including distribution and quality of wildlife populations. For example, recovery criteria for listed species usually include a description of the number and distribution of distinct populations—like the red-cockaded woodpecker (RCW, *Picoides borealis*; USFWS 2003)—as an indication of viability and as a fundamental desire to see the species restored to its former range. The quality of the individuals in a population is also often a concern, both as an indication of the health of the population and also as a fundamental objective. For example, management of wildlife populations for trophy harvest will focus on elements such as age structure, size, and other indicators of individual health.

Concerns over biodiversity have increased as the field of wildlife management has been broadened beyond traditional game management. Large-scale programs such as gap analysis (Scott 1993) have increased awareness about the impacts of cumulative habitat loss by focusing on land management practices and areas of high biotic diversity. Federal aid programs like state wildlife grants have enabled many state agencies to identify concerns and to develop objectives related to the conservation of biodiversity and populations of concern.

The objectives related to wildlife management, however, transcend concerns about wildlife. Economic concerns, too, are deeply important to stakeholders. The development of the Northwest Forest Plan needed to consider old-growth habitat for spotted owls (*Strix occidentalis*), the viability of the forest products industry, and the livelihood of its employees (Thomas et al. 2006). Reintroduction of wolves (*Canis lupus*) into the northern Rocky Mountains needed to consider the viability of the wolves and the impact on hunting opportunity for big game, but also the economic concerns of cattle and sheep ranchers (Fritts et al. 1997). Social concerns related to the impacts of wildlife management go beyond economic considerations and include spiritual, aesthetic, cultural, and recreational objectives (Bengston 2000; Chapter 4). Wildlife and fish management in Grand Canyon needs to take into consideration the spiritual and cultural objectives of native tribes, the opportunity for wilderness recreation, and the provision of energy and water to the arid Southwest in addition to economic and strictly wildlife-related objectives (Runge et al. 2011*a*).

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## Classifying Objectives

Objectives can be classified into four broad categories: strategic, fundamental, means, and process objectives (Keeney 2007). Strategic objectives are the highest-level objectives and are often associated with the mission of the agency or individual. For example, the legal mandates of a state agency associated with the maintenance of imperiled species and productivity of game species would be considered strategic objectives. These objectives are frequently beyond the scope of the management decisions faced by wildlife managers, and as such they often do not help discern among management alternatives. But they do define the context of the fundamental objectives, which are perhaps the most important category. Fundamental objectives are the "ends" of the wildlife management problem and the highest-level objectives incorporated in a decision analysis. Means objectives are the methods by which we achieve the fundamental objectives, but they may not be necessary if there are multiple pathways to achieve the fundamental objectives. Finally, process objectives govern how the decision is made but do not affect discrimination among the alternatives. For example, a decision maker—for legal, strategic, or ethical reasons—may desire that public meetings and outreach are included in the decision-making process.

Fundamental objectives are the focus of decision analysis; they alone are used to distinguish among the alternatives. Good fundamental objectives have several key characteristics. First, they are measurable. Attributes can be developed for them that can be measured on an unambiguous scale. Second, good fundamental objectives are controllable; that is, they can be influenced by the management actions under consideration. Third, fundamental objectives are those the decision maker deems essential—there is no acceptable substitute.

It often requires careful thought to distinguish fundamental from means objectives. A useful way to make such distinctions is to ask why each objective is important, which frequently leads to the discovery of new, higher-level objectives that describe the most important, desired outcomes. For example, managers interested in wildlife populations in longleaf pine (*Pinus palustris*) habitats often identify concerns related to the absence or infrequent use of fire in those systems. A concise initial objective might be to increase the use of prescribed fire in longleaf pine. When asked why, managers often respond that it improves habitat quality; the restated objective may be to increase foraging habitat for RCW and northern bobwhite (NOBO; *Colinus virginianus*). Asking why again can reveal that there is concern over the productivity or abundance of those populations, suggesting an objective to increase populations of both species. Asking the question yet again may elicit concerns over the viability of the RCW population and the size of the harvest of NOBO. Asking why once more may reveal that the agency has a mandate to maintain populations of endangered species (e.g., RCW) and to increase harvestable populations of game species (e.g., NOBO). So, classifying objectives identifies two fundamental goals (i.e., to maintain a viable population of RCW and to maximize harvest potential of NOBO) from a nested set of means objectives.

## Structuring Objectives

A fundamental objectives hierarchy illustrates the relationships among the most important objectives in a decision problem. A generic fundamental objectives hierarchy can be used to stimulate discussion and to identify problem-specific objectives. In many natural resource–related problems, useful generic fundamental objectives include: improving or maintaining wildlife populations, minimizing cost, and providing utilitarian and nonutilitarian benefits to stakeholders. A generic fundamental objectives hierarchy (Fig. 5.3) can be modified to develop specific objectives related to a specific problem. Depending on the problem at hand, objectives surrounding the status of wildlife populations may be more specifically defined as one or more of the following: abundance, distribution, health, genetic diversity, and species diversity. Cost is nearly always a consideration and, given a choice between two equally effective and likely solutions, the less expensive option is almost always more desirable. In other situations, where a budget is fixed or cost is viewed as a constraint, the solution that results in the best population status and stakeholder satisfaction for the same cost is the logical choice. A broader set of stakeholder concerns is often a crucial consideration for wildlife populations held in public trust. Notice that the elements of this fundamental objectives hierarchy do not overlap; they

1. Maximize ecological benefits
   a. Maximize persistence of native species (or communities)
      i. Maximize population size
      ii. Maximize distribution
      iii. Maximize individual quality
      iv. Maintain genetic and species diversity
   b. Minimize nonnative and invasive species (or communities)
   c. Maintain ecosystem function
2. Minimize costs
   a. Minimize capital (fixed) costs
   b. Minimize ongoing (variable) costs
3. Maximize public and private benefits (utilitarian benefits)
   a. Maximize consumptive recreational benefit
   b. Maximize nonconsumptive recreational benefit
   c. Maximize public services (e.g., energy generation, water delivery)
   d. Maximize public health and safety
   e. Maximize private economic opportunity
   f. Provide sustainable subsistence use, where appropriate
4. Facilitate cultural values and traditions (nonutilitarian benefits)
   a. Maximize aesthetic and spiritual values
   b. Minimize taking of life
   c. Treat animals in a humane manner

*Figure 5.3.* Hierarchy of generic fundamental objectives for wildlife management.

express independent elements of concern in the decision problem, so there is no double counting. A fundamental objectives hierarchy must be complete, including all of the concerns that bear on the decision.

### Measurable Attributes

Attributes are the measurement scales for fundamental objectives. Identifying attributes not only allows measurement of achievement, it forces clarity in the definition of each objective. The purpose of decision analysis is to provide a transparent comparison of the alternatives, and the attributes provide the quantitative measure of the consequences of each alternative for each objective. The capacity to make informed trade-offs is severely compromised if attributes are not clearly described (Keeney 2002). Because fundamental objectives are the focus of decision analysis, measurable attributes should be developed for fundamental objectives. Attributes that might be used by a manager interested in wildlife populations in longleaf pine habitats vary (Table 5.2).

There are three types of measurable attributes: natural attributes, proxy attributes, and constructed attributes. Each of the examples (Table 5.2) is a natural attribute—the scales directly capture the objective of interest, they are easily interpreted by anyone familiar with wildlife management, and there are widely accepted techniques or guidelines for their empirical measurement or estimation. However, for many objectives, appropriate natural attributes do not exist or are impractical for assessing consequences (e.g., data may not be available). In some cases an attribute can be constructed based on a relative scale. For example, absent measurement of fitness of individuals in a habitat, no universal scale exists for measuring the degree to which an area provides habitat for a species, because habitat requirements vary among species, and for most species we can only measure what we perceive to be the important requisites for habitat. An attribute for measuring habitat quality must be constructed and scored on an ordinal scale. By their very nature, constructed scales are subjective; therefore clear definitions of the levels are required for repeatable, transparent scoring (Table 5.3). By contrast, proxy attributes are usually natural attributes for quantities (sometimes associated with means objectives) that provide an indirect measure of the objective of interest. For example, if our true objective was to increase hunting opportunities on public lands, the number of hectares open to public hunting might be a useful proxy attribute. Although many other factors—weather, access, and habitat condition—influence hunting opportunity, we assume that the area available for public hunting is highly correlated with hunting opportunities on public lands. In general, natural attributes are preferable to proxies or constructed scales. But often this preference has to be relaxed to achieve a complete description of the decision problem (Keeney 2007).

*Table 5.2.* Natural attributes for objectives in the longleaf pine example

| Objective | Attribute |
|---|---|
| Increase use of prescribed fire (means) | Return interval or frequency of fires |
| Increase foraging habitat (means) | Ha of pine burned in the last four years |
| Increase NOBO[a] harvest (fundamental) | Number of birds shot by hunters annually |
| Increase viability of RCW[b] (fundamental) | Probability of persistence over 100 years |

Measurable attributes are normally developed only for fundamental objectives, but the attributes for some means objectives are shown, too, for illustrative purposes.

[a]NOBO, northern bobwhite.

[b]RCW, red-cockaded woodpecker.

## Generating Alternative Actions

Generating alternatives is a values-based exercise and a scientific exercise. The values-based element recognizes that alternatives are the admissible ways of achieving the objectives. Alternative actions can vary from simple to complex. In some cases, the alternative actions are a small set of discrete options, such as whether to use prescribed fire, mowing, or herbicide to set back succession in a grassland. In other cases, the alternative actions come from a continuous set, such as possible sustained harvest rates for a waterfowl population, which could take any value between zero and the logistic growth rate for the population. But often in wildlife management, the alternatives have quite complex structures. Portfolios are alternative actions that are composed of permutations of like elements. For example, a management agency allocating resources to invasive species control could consider a large number of potential portfolios of invasive species, each portfolio a list of invasive species targeted by management control. The number of potential portfolios in this case would include all permutations of the set of invasive species in that ecosystem. Strategies (or strategy tables) are alternative actions composed of permutations of unlike elements. For example, the options considered in an analysis of potential responses to the emergence of white-nose syndrome in bats were strategies composed of such elements as the methods of addressing the fungal agent, methods of captive propagation, cave access restrictions, and management of disease spread (Szymanski et al. 2009).

Frequently, the need for structured decision making arises from the desire to compare alternatives that are developed

*Table 5.3.* Example of a constructed scale for habitat quality

| Attribute level | Description of level |
|---|---|
| 3 | Very good: >80% canopy closure, >75% of canopy trees mast-producing oak, hickory, or beech |
| 2 | Good: 60–80% canopy closure, 26–75% of canopy trees mast-producing oak, hickory, or beech |
| 1 | Poor: <60% canopy closure, ≤25% of canopy trees mast-producing oak, hickory, or beech |
| 0 | No value: no mast-producing trees in forest canopy |

before the problem is well defined, but a thorough analysis of any problem will attempt to consider a wide variety of alternatives. There are a number of pitfalls that limit our ability to develop creative, potentially valuable alternatives. One of the most common pitfalls is "anchoring." Anchoring is the tendency to conduct business as usual, choosing solutions to recently addressed problems, or grasping at the first suggested alternative (Keeney 1996*a*). Choices made by anchoring constrain creativity and thoughtful development of alternatives. There are many techniques that can be applied to avoid anchoring and to encourage development of good alternatives (Keeney 1996*a*). One method offers constructive insight: developing creative alternatives may result from broadening the decision context. This usually occurs when the decision maker or analyst determines that additional fundamental objectives exist. For instance, a game manager facing dissatisfied stakeholders (e.g., hunters) may assume that their objective is to harvest trophy animals and may perceive the trigger to be low harvest of trophy animals, which could result in a set of alternatives related to increasing the frequency of trophy characteristics in populations. But if the actual trigger is that hunters are seeing fewer deer, then broadening opportunities to view deer could lead to alternatives that do not result in increased harvest.

In summary, the intent is not to develop an exhaustive set of potential actions, but to develop a set of alternatives for impartial evaluation that represents the spectrum of potential solutions to the problem at hand. The set of alternatives must influence all of the fundamental objectives via means objectives, but it is not necessary to limit alternatives to just those that affect every fundamental objective. It is also possible to find that some important objectives are not controllable within the set of feasible alternatives and may require either consideration as sources of uncontrollable uncertainty, broadening the context of the problem, or elimination of those objectives from the analysis.

### Evaluating the Trade-offs

The crux of any decision is the set of values placed on the objectives. In a single-objective problem, once the measurable attribute for the objective is established and the values-based aspects of the decision are expressed, the solution is the alternative that best achieves that objective. But a common wildlife management framework that might be cast as a single-objective problem—harvest management—reveals the complexity inherent in objectives. The solution of a maximum sustained yield problem is really a balance between two objectives: maximizing the short-term harvest and sustaining the population in perpetuity. The optimal harvest rate balances these two objectives to produce a maximum annual harvest that can be sustained indefinitely (Runge et al. 2009). But it is possible to ask whether these objectives might be balanced in some other way, or perhaps in deference to even more objectives; such has been the dialogue in the North American waterfowl management community in the 21st century (Runge et al. 2006).

Most wildlife management decisions involve trade-offs among multiple objectives, and meaningful evaluation of those trade-offs is grounded in values preferences among fundamental objectives. It is rare for all of the objectives to be achieved under a single alternative; typically the objectives compete, and the challenge for the decision maker is how to choose an alternative that best balances those objectives. The balancing of objectives is a values judgment that should reflect the preferences of the decision maker, preferences that often reflect societal priorities embodied in the organization the decision maker represents.

There are several tools from the field of decision analysis that are designed to elicit these value judgments from decision makers. A commonly used method is swing weighting (von Winterfeldt and Edwards 1986), which has the desirable property of encouraging decision makers to think about the range of consequences associated with alternatives together with their importance (Keeney 2002). In this method, the decision maker is asked to consider a series of hypothetical orthogonal scenarios in which the objectives are swung from their worst consequence to their best consequence one at a time; the decision maker ranks these scenarios and then assigns a score that represents how much any scenario is preferred over another. From these scores, weights are derived for each objective, and these weights are used in a multicriteria decision analysis (MCDA; see below). These weights on the individual objectives explicitly state how much one objective is valued over another, and can be used to balance the trade-offs in the analysis.

Another way to examine and value trade-offs is to look at the "efficiency frontier." The efficiency frontier, also called the Pareto frontier, is the set of possible actions for which no gain in one objective can be achieved without a loss in some other objective. For two-objective problems, the Pareto frontier is often depicted as a graph of performance on one objective against performance on the other objective. Such a graph makes the trade-off visually evident and can be used to engender discussion about which solution best balances the two objectives.

One important point to emphasize is that the judgment about how to balance competing objectives cannot be answered by science. At its heart, wildlife management is an expression of a rich array of societal objectives that speak to a complex set of economic, recreational, aesthetic, and spiritual values. How these values are expressed in decision analysis is one of the most important things a decision maker needs to be able to judge and communicate.

## THE SCIENCE-BASED ASPECTS OF DECISIONS

Wildlife management is, of course, founded in wildlife science; our decisions about how to manage wildlife are, and should be, influenced by our understanding of how natural systems respond to management. The science-based aspects of decisions include three sets of activities: generating alternative actions, predicting the consequences of those actions, and coherently integrating value judgments and technical judgments through reasoned use of decision analysis tools.

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### Predicting the Consequences

One of the critical roles of science in a decision analysis is the evaluation of the alternatives against the objectives. Often, this involves predicting how the alternative actions will affect the resources in question, and how those effects will influence achievement of the fundamental objectives. These predictions are often made using empirical data, inferring future responses based on past observations, but increasingly we recognize the importance of expert elicitation for predicting consequences. In a full decision analysis, the consequences need to be predicted for all the fundamental objectives; while predictions about natural resources themselves are the mainstay of traditional wildlife management, predictions about the human responses to wildlife management are also critical.

A central theme in wildlife science is prediction of how individual animals, wildlife populations, and the ecosystems in which they reside respond to management actions (Chapters 7 and 19). The wildlife literature is rich with examples of predictive models based on empirical data, including age-structured population models (Caswell 2001), harvest and take models (Runge et al. 2009), population viability analyses (Beissinger and McCullough 2002), wildlife-habitat models (Morrison et al. 2006), resource selection functions (Boyce and McDonald 1999), and, increasingly, coupled climate-wildlife models (Hunter et al. 2010). There are two steps in the development of these predictive models: development of the model structure and estimation of the parameters. In an applied setting, the model structure is in part determined by the decision context; the alternative actions serve as the inputs to the model, and the measurable attributes of the fundamental objectives are the outputs. The innards of the model structure are an expression of the current understanding of the causal linkages between the actions and the outcomes. Methods for empirical estimation of parameters flourished in wildlife science since the 1990s (Williams et al. 2002) and require little comment here.

In a decision-making context, there are often other fundamental objectives besides wildlife resource objectives, and the consequences of the alternatives for these objectives need to be predicted, too. These objectives include economic, recreational, and spiritual objectives, and appropriate methods of prediction need to be found for each. Economic models related to wildlife management are being used more and more (Pickton and Sikorowski 2004). The nature of human satisfaction with recreational opportunities can be complex, but empirical models are increasingly available (Chapter 4). Models for predicting spiritual and aesthetic outcomes are not common, although some initial attempts have been made (Failing et al. 2007). One of the challenges the human dimensions field faces in incorporating its work into decision-making contexts is moving from descriptive to predictive models. Many of the current models describe patterns in economic, recreation, and aesthetic outcomes, but they are not yet able to predict those outcomes under alternative management actions.

For all types of outcomes that are important in wildlife management, there are often occasions when there is not enough empirical information to build predictive models, and not enough time to collect new data. In these settings, there is increasing use of methods of expert elicitation (Kuhnert et al. 2010). These methods typically rely on the accrued knowledge of a group of experts, rather than on empirical data, to structure a predictive model and to provide parameter estimates. There is a considerable literature on the reliability and fallibility of experts, and from this literature emerges some best practices in expert elicitation (Burgman 2005). Briefly, these methods seek to tap into the privileged knowledge of experts while avoiding common cognitive biases to which humans are prone. In the modified Delphi method (MacMillan and Marshall 2006), a group of experts makes individual judgments about a parameter, fact, or relationship; they share their initial responses (often anonymously) with the group; discussion ensues; and then the experts are asked to make a final, private judgment. The feedback step promotes clarity, eliminates linguistic uncertainty, and allows sharing of insights, and the private judgments allow individual insights to be retained, capture uncertainty as expressed by the range of experts, and avoid the effects of damaging group dynamics. Some other recent methods of elicitation guard against the overconfidence of experts by asking them to be explicit about their degree of uncertainty (Speirs-Bridge et al. 2010).

In most cases, there is uncertainty about the predictions from any model, whether empirically or expert based, and this uncertainty can affect the identification of a preferred alternative. Several taxonomies of uncertainty have been advanced (Morgan and Henrion 1990, Nichols et al. 1995, Regan et al. 2002); a combination of them is useful here. Broadly, uncertainty can be aleatory or epistemic. Aleatory uncertainty arises from stochastic processes that are outside of the manager's control. For example, environmental stochasticity (e.g., weather patterns), demographic stochasticity (i.e., the chance events that determine which animals survive), and partial controllability (i.e., our inability to completely control the implementation of our actions) give rise to aleatory uncertainty. Epistemic uncertainty arises from our lack of knowledge about the managed system. Structural uncertainty (i.e., uncertainty about how the system works), parametric uncertainty (i.e., imprecision in the model parameters), and partial observability (i.e., the inability to know exactly the condition of the resource) are examples of epistemic uncertainty. The distinction between aleatory and epistemic uncertainty is often important to a decision maker, because research or monitoring can theoretically reduce epistemic uncertainty. Incorporation and expression of uncertainty in the consequences are important aspects of prediction; they allow the decision maker to understand—and therefore manage—risk.

### Generating Alternative Actions

In the section on values-based decisions, we discussed the generation of alternative actions, but there is also a technical side to this step of decision analysis. In some cases, one of the primary impediments to a decision is that none of the available actions can satisfactorily solve the problem, and the

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decision maker looks to scientists or engineers to craft a novel approach. For example, when white-nose syndrome emerged in cave-dwelling bats in eastern North America, no known method existed for controlling the fungus that causes the disease; one avenue of research was to identify a fungicide that might eradicate it (Chaturvedi et al. 2011).

The generation of novel alternatives through scientific investigation actually switches the order of analysis implied in PrOACT by putting the consequence analysis before the generation of alternatives. An engineering approach to decision analysis begins with the objectives, works backward through an understanding of how the system works, and then identifies an action that will achieve the objectives. A means-ends network is a useful graphical tool for this approach. The objectives (the ends) are identified, and then means to achieve those ends are drawn based on a current understanding of how the system works. Proceeding backward in this way to more proximate influences leads to actions that might be investigated as potential solutions.

## Decision Analysis Tools

In addition to the array of tools it provides to help structure a problem, decision science also provides a diverse set of tools for analysis. These analytical tools offer insight into the nature of decisions and frequently motivate even deeper reflection by decision makers. The complete set of analytical tools is too large to be fully discussed here; what follows is a sampling of some of the most commonly applied techniques. Skilled decision analysts diagnose a decision problem and identify the most appropriate analytical tools to apply.

### Multicriteria Decision Analysis

As the field of human dimensions has made evident, wildlife management decisions involve many objectives on the part of many stakeholders. Understanding these objectives, being able to measure these objectives, and predicting the consequences of alternative actions with regard to these objectives are critical steps in evaluation of a multiple-objective problem. Multicriteria decision analysis is a set of techniques to analyze and balance the trade-offs inherent in multiple objectives (Herath and Prato 2006). A consequence table, one that shows the consequences of each alternative action in units of the measurable attribute for each objective, embodies the central expression of the decision problem in MCDA. The analytical question is how to identify the single alternative that best achieves the array of objectives, recognizing that there are trade-offs.

The first step in MCDA is to simplify the problem by examining the structure of the consequence table. A dominated alternative is one that can be improved without sacrifice—one for which there is another alternative that is at least as good on all objectives. Given that there should be no reason to choose a dominated alternative, it can be removed from further consideration. An irrelevant objective is one that does not help distinguish the alternatives because they have similar scores on the corresponding measurable attribute. Irrelevant objectives may be important in the absolute sense (the decision maker may care very much about the performance of an action on an irrelevant objective), but they are not important in the relative sense (because they do not help the decision maker choose among the alternatives under consideration); thus they can also be dropped from further analysis. Often, an objective that is initially relevant may become irrelevant as dominated alternatives are identified and removed. When a consequence table no longer has any dominated alternative or irrelevant objectives, the remaining alternatives are said to be "pareto optimal"; for any alternative, no improvement can be made on one objective without sacrificing another.

To proceed further with analysis requires grappling with how to trade one objective with another. Some analysts will stop here, and simply ask the decision makers to make an intuitive judgment about the trade-offs and choose a preferred alternative. Quantitative analysis of the trade-offs requires expressing the objectives on a common scale. There are numerous ways to do this—including even swapping, pricing out, the analytical hierarchy process and outranking—but perhaps the most common is the weighted additive model embodied in the Simple Multi-attribute Rating Technique (SMART; Goodwin and Wright 2004). The consequences are first converted to a common scale by normalizing the scores on each objective to a range of zero (i.e., the worst-performing alternative) to one (i.e., the best-performing alternative). Second, the decision maker provides weights, which reflect value judgments about the relative importance of the different objectives, through a process such as swing weighting (von Winterfeldt and Edwards 1986). Third, the weighted sum of the normalized consequences is taken across objectives, using the swing weights, and used to rank the alternatives. Sensitivity analysis can be performed to evaluate the robustness of the preferred alternative to uncertainty in the weights or uncertainty in the consequence values.

Multicriteria decision analysis has been applied extensively in natural resource management (Kiker et al. 2005, Herath and Prato 2006). Specific applications in wildlife management are increasing (Redpath et al. 2004, Szymanski et al. 2009). Case study two (wolf hunting management in Montana) uses an MCDA approach.

### Decision Trees

Some decisions have to be made in the face of uncertainty, without recourse to resolving the uncertainty first. This may be because the uncertainty is aleatory, or because the uncertainty is epistemic, but the decision has to be made before the uncertainty can be reduced. In either case, the decision maker must accept the possibility of regret associated with an undesired outcome. Decision trees make clear the risks (and regrets) associated with alternatives, effectively insulating against poor decisions. This setting was the genesis of decision theory in economics, but it is just as applicable in wildlife management. For example, imagine a manager of a 400-km$^2$ tract of arid land whose primary objective is to provide habitat for pronghorn (*Antilocapra americana*). Without prescribed fire, grasses increase and native forbs, which pronghorns thrive

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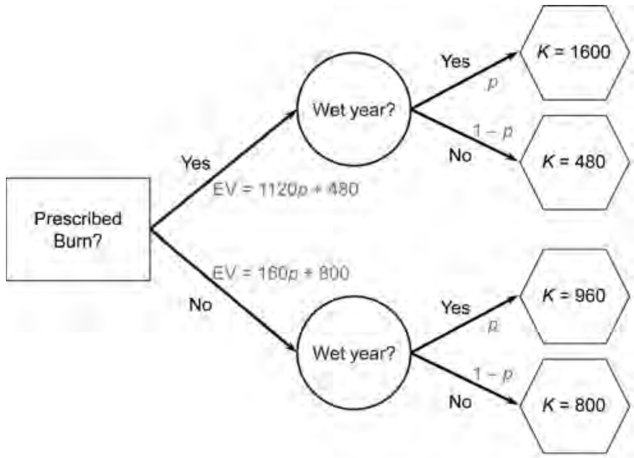


*Figure 5.4.* Decision tree for pronghorn habitat management. The outcomes are the expected carrying capacities of the refuge as a function of whether a prescribed fire was instituted and whether the year was wet. The expected value (EV) of the outcome depends on the probability of a wet year ($p$) and can be used to identify a preferred action. With the values shown here, if $p > 33\%$, the expected capacity is higher with a prescribed burn than without.

on, decline. Prescribed fire returns nutrients to the soil and encourages growth of forbs, especially in a wet year, but in a dry year, prescribed fire can remove moisture from the system and substantially reduce the total biomass available for forage. The manager has a predictive model for the carrying capacity of the refuge, but whether a particular year will be wet is an uncontrollable uncertainty (Fig. 5.4). The manager can use the decision tree shown in Figure 5.4 to calculate the expected carrying capacity under either decision by taking a weighted average of the carrying capacities in each branch, where the weights describe the likelihood of a wet year. In this particular case, if the probability of a wet year is greater than 33%, the manager should institute the prescribed burn.

There are a number of more advanced methods to make a simple decision tree (Fig. 5.4) more realistic. The tree might have additional branches to represent the likelihood of wildfire occurring and restoring some habitat condition. The manager might assign nonlinear values to the outcomes, to reflect a nonneutral attitude toward risk. The tree could be extended to acknowledge that this decision can be made annually, and the manager might care more about the cumulative responses over many years. The value in all these methods is in helping the manager think about how to make decisions in the face of uncontrollable uncertainty.

### Expected Value of Information

There may be recourse to resolve uncertainty before having to commit to a decision. As wildlife scientists, we are always interesting in reducing uncertainty, but a wildlife manager has a different perspective. The decision maker needs to ask whether the benefits that accrue from acquiring new information are worth the costs of obtaining that information. Decision analysis offers a formal method for answering this question. The expected value of information is the amount by which the outcome can be improved by reducing uncertainty before making the decision (Runge et al. 2011*b*). A powerful and underutilized method in natural resource management, calculating the value of information can help decide what research is valuable, what monitoring should be instituted, and whether adaptive management is warranted.

## ADAPTIVE MANAGEMENT

Although use of a broad set of formal decision analysis techniques in wildlife management is only beginning, for decades there has been a very widespread call for and use of a special class of decision analysis, namely adaptive management. Developed in the context of fisheries management in the 1970s (Holling 1978, Walters 1986), adaptive management is now a central tenet of all natural resource management, including wildlife management (Lancia et al. 1996, Callicott et al. 1999, Allen et al. 2011).

### A Special Class of Decision

Adaptive management is a special case of structured decision making for recurrent decisions made under uncertainty (Fig. 5.2). Many wildlife management decisions have two key features: they are recurrent (a similar decision is made on a regular basis), and they are impeded by uncertainty (the consequences of the alternatives are not fully understood). To address the first feature, a wildlife manager needs to understand and anticipate the dynamics of the system—namely, the immediate costs or rewards from taking an action—and also the future opportunities, costs, and potential rewards attending subsequent actions that might be taken. System modeling and dynamic optimization are tools that can support recurrent decisions. To address the second feature, the wildlife manager needs to know how to make decisions in the face of uncertainty, by evaluating and balancing risks. Decision analytical techniques exist for making decisions in the face of uncertainty; in fact, they are the basis for the entire discipline. When these two key features occur together, when recurrent decisions need to be made in the face of uncertainty, there is an opportunity to learn from actions taken early on to reduce uncertainty so better decisions can be made in the future. The ability to adapt future decisions to information that arises during the course of management is the purpose and foundation of adaptive management.

The PrOACT sequence is central to adaptive management: objectives need to be expressed; alternative actions need to be developed; consequences need to be predicted; and a solution, through optimization or balancing trade-offs, needs to be found. To this sequence, adaptive management adds several details: developing dynamic predictive models, articulating and evaluating uncertainty, implementing monitoring to provide feedback, updating the predictive models based on new information, and adapting future decisions based on the updated understanding of how the resource responds to management.

***CARL J. WALTERS (b. 1944)***

Carl J. Walters is a fisheries biologist who pioneered the concept of adaptive management. He received his doctorate from Colorado State University in 1969, and has been a professor of zoology and fisheries at the University of British Columbia ever since. His 1986 book *Adaptive Management of Renewable Resources* offered a full decision-analytical treatment of natural resource management, and formally considered how to make optimal recurrent decisions in the face of epistemic uncertainty. His interest in adaptive environmental assessment led to the 2004 publication, with Steven Martell, of *Fisheries Ecology and Management*, a graduate-level textbook on the use of quantitative models in fisheries management. The influence of his work on the practice of wildlife and fisheries management cannot be overstated. Among other honors, Walters received The Wildlife Society's best paper award in 1976, the American Fisheries Society Award of Excellence in 2006, and the Volvo Environment Prize in 2006. He is a fellow of the Royal Society of Canada.

Photo courtesy of Sandra Buckingham

First, the predictive models that are constructed need to be dynamic; that is, they need to predict current rewards and future conditions of the system that could affect subsequent decision making. Predictive models need to incorporate the temporal linkage among decisions. Predictive models of habitat and population dynamics for wildlife have included such dynamics, even outside of formal decision analysis.

Second, uncertainty needs to be articulated and evaluated. What aspects of the predictions are not well known and might impede the decision? Nichols et al. (1995) describe four sources of uncertainty relevant to wildlife management: environmental variation, structural uncertainty, partial observability, and partial controllability. Two of these (i.e., environmental variation and partial controllability) are types of aleatory uncertainty (Helton and Burmaster 1996), uncertainty that cannot be reduced. The other two (i.e., structural uncertainty and partial observability) are types of epistemic uncertainty—uncertainty due to our lack of knowledge, which (at least theoretically) can be reduced through investment in monitoring. Formal approaches to decision analysis attempt to express these uncertainties quantitatively, so that the uncertainty in the predictions can be stated clearly. To evaluate the uncertainties, the decision maker wants to know whether reduction of any uncertainty would improve the expected outcome of the decision. In the context of management, relevant uncertainty is uncertainty that affects the *decision*, not simply the *predictions*. The expected value of information measures how much a decision could improve if uncertainty could be reduced, and it is important for identifying the critical uncertainty to address in an adaptive program (Runge et al. 2011*b*). Key uncertainty is often expressed as a set of plausible models, each of which makes a different prediction about the effects of management actions on the outcomes that are relevant to the decision maker.

Third, an appropriate monitoring program that provides the necessary feedback to resolve critical uncertainty is central to meeting the promise of adaptive management. The needs of this monitoring program stem from the decision context and serve three fundamental purposes: evaluation of performance against the objectives, tracking of key variables that are tied to decision thresholds, and reduction of key uncertainty (Nichols and Williams 2006). This "targeted" monitoring is important to make efficient use of scarce resources, allocating funds and staff time only to monitoring that is expected to improve management outcomes in the long term. Lyons et al. (2008) provide examples of monitoring design for management on national wildlife refuges that reflect these principles.

Fourth, monitoring data are valuable only if they are analyzed. In an adaptive management setting, analysis consists of confronting the predictive models with the observed data (Hilborn and Mangel 1997). Each of the alternative models makes a prediction about the outcome associated with the action that was last implemented, and the monitoring system provides information about the actual outcome. The comparison of the observed response to the expected responses allows the predictive models to be updated, often through an application of Bayes' theorem. The degree of belief increases for those models whose predictions most closely matched the observed response, and decreases for models that performed poorly (Johnson et al. 2002).

Fifth, what makes adaptive management adaptive is the application of learning to subsequent decisions. This adaptation can be anticipated; that is, the decision maker can articulate in advance how future decisions will change as a result of monitoring outcomes. In "active adaptive management," this anticipation goes one step farther: in making a decision, the decision maker may choose an action that will accelerate learning, if the long-term gains from that learning are anticipated to offset the short-term costs (Walters and Hilborn 1978).

## Single-, Double-, and Triple-loop Learning

One of the real challenges of decision analysis is correctly framing the decision. For recurrent decisions, each iteration provides the opportunity to learn and reflect about the framing of the decision, in addition to the predictions of the system models. There is another layer of learning, and hence another layer of adaptive management. This "double-loop" learning (Argyris and Shon 1978) focuses on emerging understanding

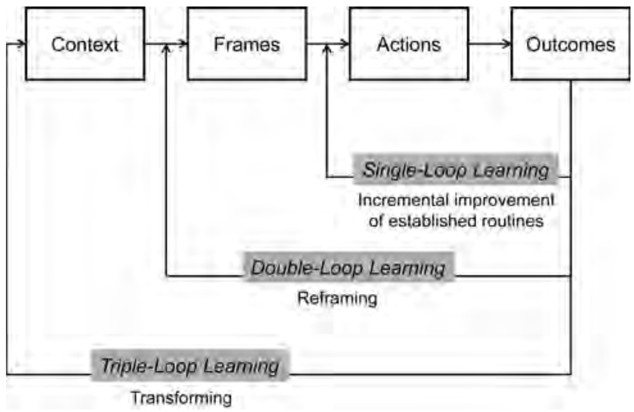


*Figure 5.5.* Adaptive learning cycles. From Pahl-Wostl (2009)

of the framing of the decision; in particular, the objectives, the set of potential actions, and the relevant uncertainties (Fig. 5.5). In the most challenging natural resource management problems, where the ecological and institutional dynamics are very complex, experience managing the system may give rise to insights about the context in which management is occurring. "Triple-loop" learning (Fig. 5.5; Pahl-Wostl 2009) can result in transformative adaptation (e.g., through changes to the institutional relationships, governance structures, regulatory frameworks, or even the social and organizational values that are associated with the managed resources).

### Schools of Adaptive Management

Adaptive management has seized the imagination of natural resource managers since the phrase was coined, but in recent years a number of writers have decried its failure to live up to its promise, documenting the challenges and alleged failures of implementation (McLain and Lee 1996, Gregory et al. 2006, Allen and Gunderson 2011). One of the challenges is that there is not a single definition of adaptive management. There are many layers on which learning and adaptive management can occur (Fig. 5.5). So perhaps it is not surprising that there are very different schools of thought regarding adaptive management, each focused on a different layer of adaptation. McFadden et al. (2011) provide the beginnings of a long-needed taxonomy of adaptive management, identifying two primary schools of thought: the resilience-experimentalist school, exemplified by Gunderson et al. (1995), and the decision-theoretic school, exemplified by Williams et al. (2007).

#### The Resilience-experimentalist School

The resilience-experimentalist (RE) school has arisen from the management challenges in large-scale, complex socioecological systems, where framing the decisions and constructing effective institutional arrangements for collaborative management pose enormous challenges. The ecological dynamics are so complex that the notion of being able to articulate critical uncertainty seems ambitious. So the focus is on double- and triple-loop learning, with an emphasis on collaboration and adaptive governance, with reduction of uncertainty occurring through experimental manipulation. The most-noted examples include management of the Columbia River (Lee and Lawrence 1985), the Everglades (Gunderson and Light 2006), and Grand Canyon (Hughes et al. 2007). All of these examples reveal the ecosystem focus of the RE school; this broader scope encompasses wildlife management.

#### The Decision-theoretic School

The decision-theoretic (DT) school is grounded in the seminal writings of Holling (1978) and Walters (1986), but it was perhaps most profoundly influenced by the adaptive harvest management of waterfowl in North America (Johnson et al. 1997, Nichols et al. 2007). The emphasis is on management of dynamic systems in the face of uncertainty, through explicit use of a decision-theoretic framing of the problem, with reduction of uncertainty not occurring through experimentation but through ongoing monitoring and management. The approach taken by the DT school emphasizes single-loop learning but has the flexibility to accommodate learning and adaptation at all three levels. The DT school is as useful for local decisions with a single decision maker as it is for broad-scale decisions with multiple management partners.

## CASE STUDIES

Consider three case studies of the application of structured decision ranging in scale from local (Skyline Wildlife Management Area) to state (wolf harvest management in Montana) to continental (adaptive harvest management of waterfowl in North America). Each of the case studies exemplifies particular elements of the SDM process, but they share the underlying PrOACT structure.

### Case Study One: Skyline Wildlife Management Area

The Alabama Department of Conservation and Natural Resources (ADCNR), like many state agencies, is obligated to implement management to improve the status of the species of greatest conservation need identified in the state wildlife action plan. This project sought to balance game and nongame wildlife population objectives for the J. D. Martin Skyline Wildlife Management Area (SWMA) as a test case for other state-owned lands. The SWMA (170 km$^2$) is located in Jackson County, Alabama, in the Cumberland Plateau region. Most of SWMA was logged at the turn of the century, and only the most inaccessible slopes were spared. Agriculture grew in the region during the 1930s under the auspices of federal programs (Hammer 1967). The majority of the current forest vegetation is the result of natural regeneration, with some planted pine plantations on the plateaus and in the valleys. Even today, forested habitat exists only in narrow valleys, on steep hillsides, and on top of the Cumberland Plateau. Most of the lower, flatter areas in larger valleys have been converted to nonnative pasture or row crops.

Some portions of SWMA are owned and managed by the ADCNR Wildlife and Freshwater Fisheries Division (WFFD). Lands owned by WFFD were purchased with federal aid funds for the purposes of wildlife management and public hunting. Other portions are owned and managed by ADCNR Lands Division. Lands Division purchases were made with state funds for their potential contribution to parks, nature preserve, wildlife management, and recreation. Other portions of SWMA are under long-term lease from Alabama Power Company, but management decisions are delegated to WFFD in mitigation for the establishment of the R. L. Harris Dam, which flooded a substantial amount of forest habitat in central Alabama. Each of these entities has a different mandate and approach to wildlife management. The decision in this case was to identify and recommend alternatives for land use and forest management that would benefit greatest conservation need (GCN) species while providing adequate opportunity for hunters.

### Objectives

1. Maintain or enhance populations of species of GCN identified in the Alabama Comprehensive Wildlife Conservation Strategy.
2. Provide hunting opportunities for large and small game, including white-tailed deer, eastern wild turkey (*Meleagris gallopavo*), eastern cottontail (*Sylvilagus floridanus*), northern bobwhite, and gray squirrel (*Sciurus carolinensis*).
3. Provide nonconsumptive recreational opportunities, including hiking, wildflower viewing, wildlife viewing, horseback riding, and primitive camping.

The measurable attribute for the first objective was the average occupancy of four representative nongame species—cerulean warbler (*Dendroica cerulean*), Kentucky warbler (*Oporornis formosus*), worm-eating warbler (*Helmitheros vermivorum*), and wood thrush (*Hylocichla mustelina*)—equally weighted. The measurable attribute for the second objective was the average occupancy of three representative game species—northern bobwhite, wild turkey, and mourning dove (*Zenaida macroura*)—equally weighted. A measurable attribute for the final objective was not developed for the initial analysis.

### Alternatives

The management alternatives considered were combinations of landscape alternatives that increased the amount of nonforested areas, and treatments to forested and nonforested habitat (Fig. 5.6). The management alternatives considered in forested areas included four options.

1. Status quo: maintaining the current landscape and forest management practices.
2. Even-aged forest management with large (~60 ha) or small stands (~20 ha) by clear-cutting, seed tree, or shelter wood techniques.
3. Two-aged forest management system throughout the forest.
4. Uneven-aged management throughout the forest using either group or single-tree selection methods.

In nonforested areas the alternatives included:

1. Status quo: maintaining a mixture of plantings of green fields, row crops, and early successional habitat.
2. Increasing early successional habitats and native warm-season grass meadows.
3. Increasing early successional habitats and native warm-season grass meadows in some areas, and creating oak (*Quercus* spp.) savannah in others.

### Modeling Consequences

As a prototype, areas were mapped that met an agreed-upon minimum area requirement for NOBO populations (404 ha) and cerulean warbler (6,000 ha). The consequences of the management actions were predicted and evaluated in terms of the expected population response by the game and nongame populations of interest. Uncertainties included the effect of management practices on the composition and structure of the vegetative cover and the response of the animal populations to the structure, availability, and distribution of suitable areas. Occupancy (i.e., probability of use by each species) was determined to be an acceptable population response for comparing alternatives. For many species of reptiles, amphibians, birds, and small mammals, recent research provided estimates of the relationship between occupancy and many forest characteristics including composition, structure, and context (Grand et al. 2008). For some game species where occupancy models were not available, expert judgments were elicited to predict wildlife responses. Experts ranked the alternative landscapes with respect to each of the objectives, but it was difficult to predict the effects of forest management on habitat structure and species responses. Therefore a system model employing a Bayesian belief network was developed as a second prototype (Fig. 5.7).

The Bayes net was used because it provided the means to start with a graphical representation (i.e., influence diagram) of the system, which could be parameterized and converted to a decision model using existing data or expert judgments. Each node in the network represents an important characteristic (i.e., state variable) of the system and the linkages among nodes represent relationships between variables. Uncertainty in the relationships between variables, and uncertainty in the estimates of the variables themselves, was incorporated. Decisions were modeled using the Bayes net by adding a decision node, used to manipulate the state of the system under candidate management actions, and a utility node, which was used to assign stakeholder values to the measurable attributes of each top-level objective (game and nongame species). The relative weights on these objectives were not formally elicited from the decision makers; rather, a range of values was explored to understand how the preferred alternative was affected by the weights.

### Decision Recommendation and Implementation

Analysis using the second prototype suggested that managing forested areas using a two-aged system would achieve the greatest utility. The model was not sensitive to the size of for-

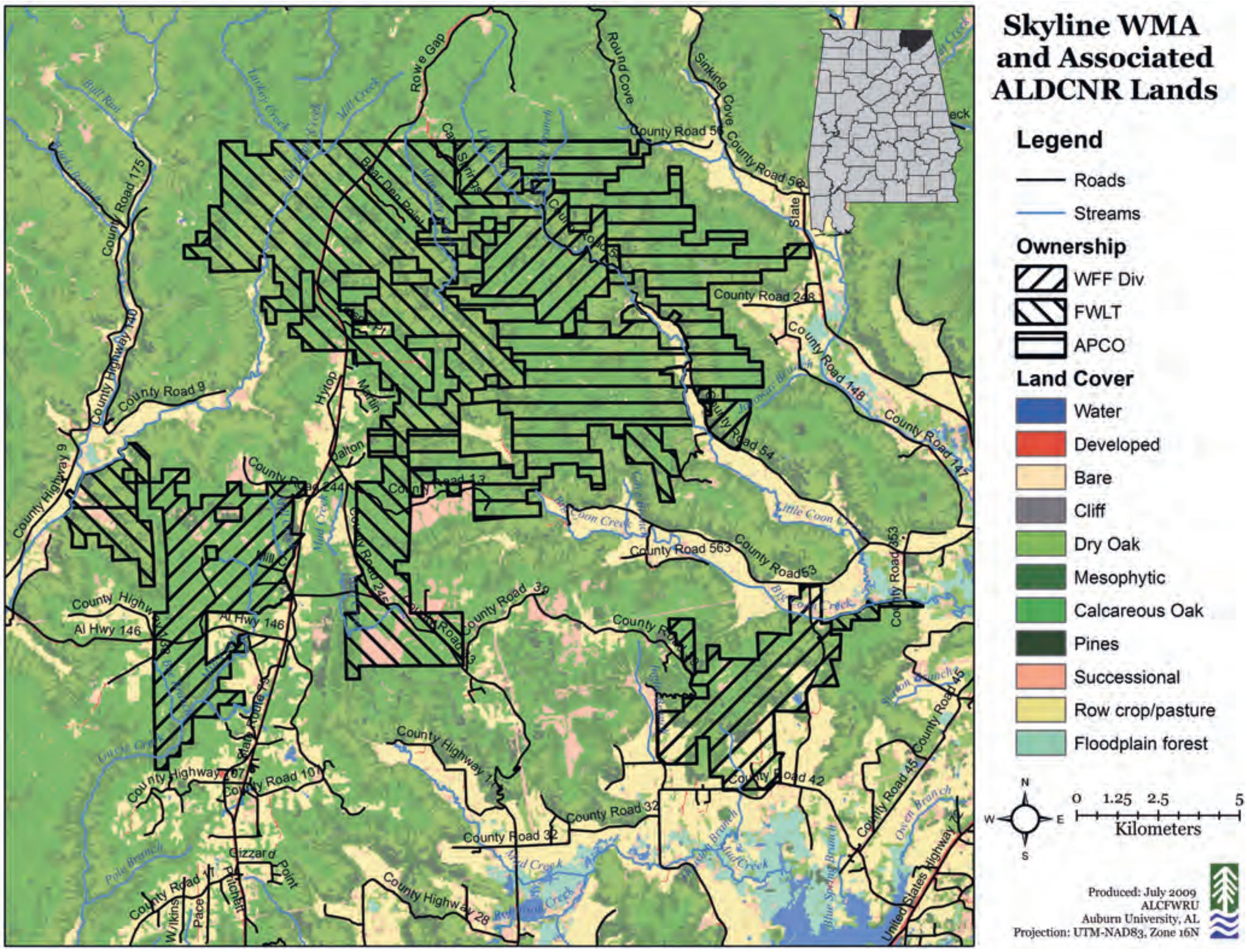


*Figure 5.6.* J. D. Martin Skyline Wildlife Management Area land cover and land ownership boundaries, Jackson County, Alabama.

est stands, nor did it indicate differences in utility between the alternatives for managing nonforested habitat. As of late 2011, the management alternatives had not been implemented, but the SDM process is being applied to develop and evaluate management alternatives for 12 additional wildlife management areas, parks, and nature preserves across the state.

## Case Study Two: Wolf Hunting Management in Montana

Gray wolves in the U.S. northern Rocky Mountains (NRM) were first removed from the endangered species list in February 2008, at which point management authority for wolves passed from the USFWS to the states of Montana and Idaho. Wolf management in each state included setting harvest quotas and seasons. Lessons learned from the first wolf hunting season in Montana in 2009 suggested that Montana Fish, Wildlife and Parks (MFWP) needed to redefine its wolf management units (WMUs) to better allocate hunter opportunity and harvest and to manage wolf numbers. For the 2009 hunting season, MFWP defined three WMUs (Fig. 5.8). Because wolves are primarily located in the mountainous portions of western Montana, managers believed that smaller, redistributed WMUs in that portion of the state would be necessary to manage allocation of hunter opportunity and thus the distribution of harvest across the Montana wolf population. Statutory obligations for effective conservation of a game species and often-contentious public attitudes and expectations regarding wolf management in Montana combined to present a challenging context for deciding on new WMUs. The MFWP thus elected to use a structured process to ensure explicit consideration of all relevant factors affecting the designation of WMUs, and to provide transparency to the public.

Representatives from MFWP—including regional managers, biologists, and wolf specialists—developed the following problem statement:

> MFWP must propose a 2010 wolf harvest strategy that maintains a recovered and connected wolf population, minimizes wolf–livestock conflicts, reduces wolf impacts on low or de-

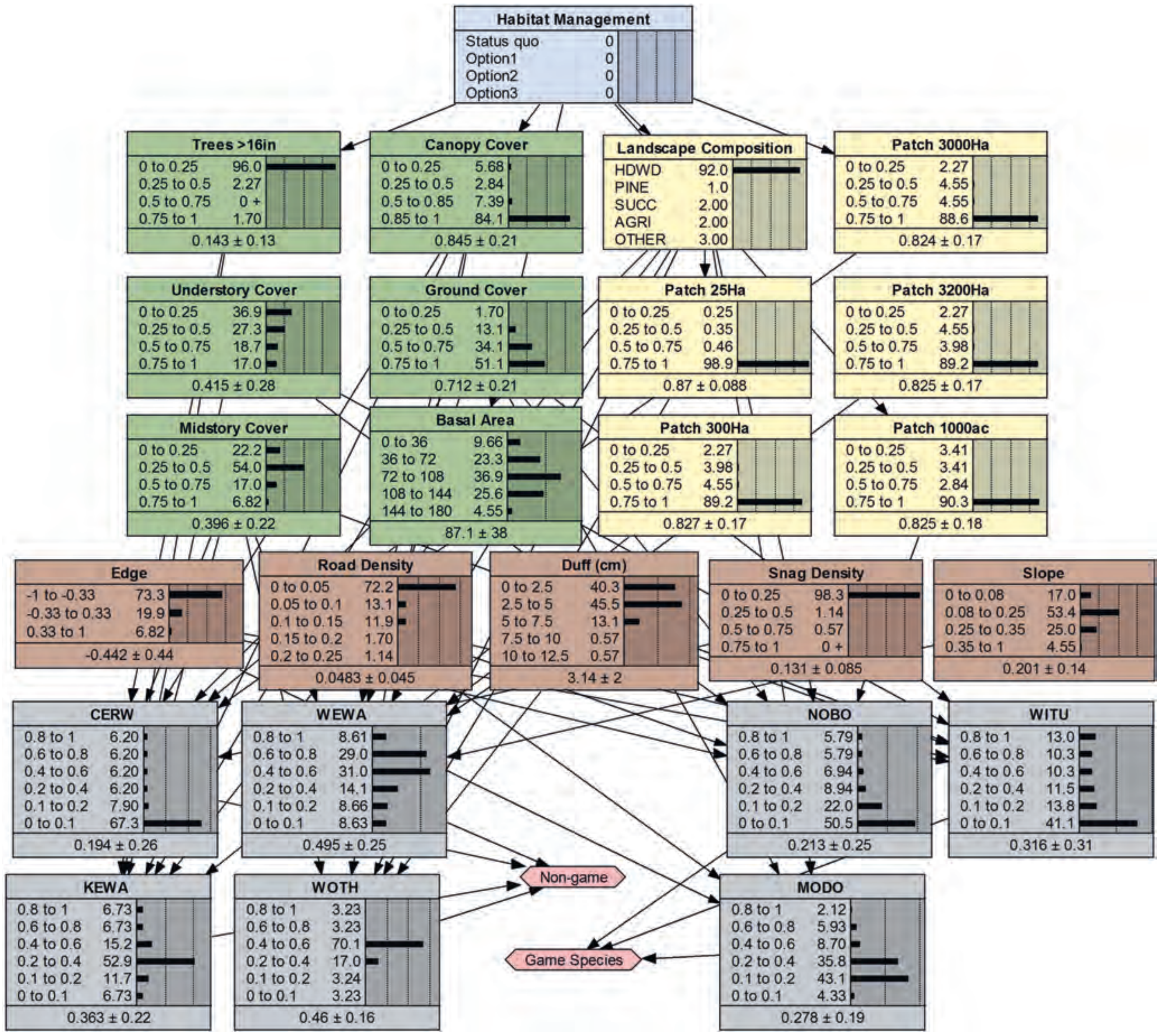


*Figure 5.7.* Bayes decision network for evaluating management alternatives for the J. D. Martin Skyline Wildlife Management Area, Jackson County, Alabama. The decision network (prototype 2) includes nodes that represent the decision (blue), habitat structure (green), land cover (yellow), physical characteristics (brown), species responses (gray), and utilities (red).

clining ungulate populations and ungulate hunting opportunities, and effectively communicates to all parties the relevance and credibility of the harvest while acknowledging the diversity of values among those parties.

The group developed a set of fundamental, process, and strategic objectives.

*Fundamental objectives:*

1. Maintain positive and effective working relationships with
   a) livestock producers,
   b) hunters, and
   c) other stakeholders.
2. Reduce wolf impacts on big game populations.
3. Reduce wolf impacts on livestock.
4. Maintain hunter opportunity for ungulates.
5. Maintain a viable and connected wolf population in Montana.
6. Maintain hunter opportunity for wolves.

*Process objectives:*

7. Enhance open and effective communication to better inform decisions.
8. Learn and improve as we go.

*Strategic objectives:*

9. Increase broad public acceptance of harvest and hunter opportunity as part of wolf conservation.
10. Gain and maintain authority for the state of Montana to manage wolves.

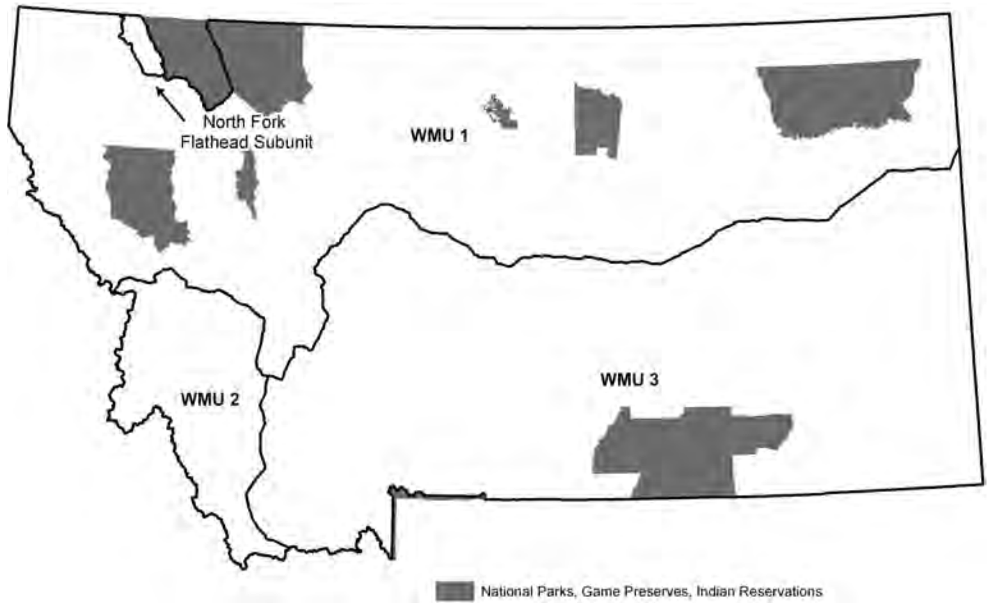


*Figure 5.8.* Wolf management units (WMUs) in Montana, hunting season 2009.

The group developed five management alternatives to address the set of fundamental objectives. The number and distribution of WMUs affect how finely the state can control the distribution of wolf harvest, which in turn affects wolf density and distribution, and the various impacts associated with wolf density. The alternatives focused on the arrangement of WMUs. The first alternative represented the status quo, retaining the same three WMUs used during the 2009 hunting season. The remaining four options represented alternative ways of dividing Montana into WMUs.

Alternative 2. Fifteen WMUs, with eastern Montana incorporated into western units.
Alternative 3. Fourteen WMUs, with eastern Montana incorporated into western units.
Alternative 4. Thirteen WMUs, with eastern Montana incorporated into western units.
Alternative 5. Fifteen WMUs, with eastern Montana having its own management unit not incorporated into western units.

The measurable attributes for each fundamental objective were expressed on a constructed scale that ranged from zero (i.e., poor outcome) to one (i.e., ideal outcome). Two fundamental objectives (numbers 5 and 6 above) were not scored, because the group did not believe their consequences varied among the management alternatives and thus did not affect the decision. One of the strategic objectives (number 9 above) was viewed as critical enough to the decision that it was also scored. A panel of experts composed of wildlife managers, biologists, and wolf specialists from MFWP were asked to score individually each alternative against each objective. An average score for each response was taken across experts (Table 5.4).

The status quo (alternative 1) ranked high among alternatives for maintaining relationships with livestock producers, hunters, and other stakeholders, and for public acceptance, but ranked relatively low for reducing impacts to big game and livestock while maintaining a sustainable ungulate harvest (Table 5.4). Alternative 2 scored relatively low for maintaining relationships but moderately well for reducing impacts of wolves, public acceptance, and maintaining sustainable ungulate harvest. Alternatives 3 and 4 scored comparably across all objectives. Alternative 5 was judged to have strong benefits for reducing impacts to big game and maintaining sustainable ungulate harvests, but would have the strongest negative impacts among alternatives on maintaining relationships with stakeholders and public opinion.

Inspection of the consequence table shows that alternative 3 dominates alternatives 2, 4, and 5, because it scores as well or better than those other alternatives on all objectives. Thus alternatives 2, 4, and 5 can be removed from further consideration, leaving only alternatives 1 and 3 as viable candidates.

At this point, formal multicriteria decision analysis could be used to place weights on the objectives to develop a composite score for each alternative. But the panel chose instead to proceed qualitatively on the basis that identification of dominated alternatives and redundant objectives provided a cognitively accessible trade-off. The group decided alternative 3 (Fig. 5.9) was most likely to satisfy the fundamental objectives for setting WMUs for the 2010 hunting season. This was because the relative benefits of maintaining relationships with hunters, reducing impacts, and maintaining sustainable ungulate populations in alternative 3 outweighed the slight advantages in maintaining relationships with livestock producers and stakeholders and public acceptance offered by alternative 1.

The SDM approach allowed decision makers to see the structure of the problem and the major trade-offs among the alternatives; those insights alone were enough to allow the decision to proceed. The decision was presented in July 2010 as a recommendation to the MFWP commission, which adopted it; the SDM process and product were considered clear assets

Krausman, Paul R., and James W. Cain III, eds. Wildlife Management and Conservation: Contemporary Principles and Practices. pp. 51-72.

*Table 5.4.* Consequence table for case study 2, wolf hunting management in Montana

| Fundamental objective | Measurable attribute | Preferred direction | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|---|---|
| | | **Maintain relationships** | | | | | |
| Livestock producer | Perception 0 to 1 | Maximize | **0.83** | *0.54* | 0.66 | 0.66 | 0.63 |
| Stakeholders | Perception 0 to 1 | Maximize | **0.69** | 0.60 | 0.66 | 0.66 | *0.34* |
| Hunters | Perception 0 to 1 | Maximize | 0.80 | *0.57* | **0.83** | 0.77 | 0.60 |
| | | **Reduce impacts** | | | | | |
| Big game | Ungulate populations at or near objectives Yes (1) / no (0) | Maximize | *0.60* | **1.00** | **1.00** | 0.80 | **1.00** |
| Livestock | Reduction in the number of livestock confirmed injured or killed by wolves 0 to 1 | Maximize | *0.56* | 0.72 | **0.80** | **0.80** | 0.76 |
| Sustainable ungulate harvest | Quota in every WMU for foreseeable future Yes (1) / no (0) | Maximize | *0.60* | **1.00** | **1.00** | 0.80 | **1.00** |
| Public acceptance | Perception 0 to 1 | Maximize | **0.80** | 0.72 | 0.74 | 0.74 | *0.37* |

Consequences for each alternative were elicited individually, then averaged over a group of wildlife managers, biologists, and wolf specialists from Montana Fish, Wildlife and Parks. For each objective, the alternative that was predicted to perform best is indicated by boldface, moderately performing alternatives are in regular type, and the alternative predicted to perform worst is indicated by italics. Alternative 3 dominates all alternatives except alternative 1, which performs relatively well for maintaining relationships but poorest among the alternatives for reducing impacts and maintaining sustainable ungulate harvests.

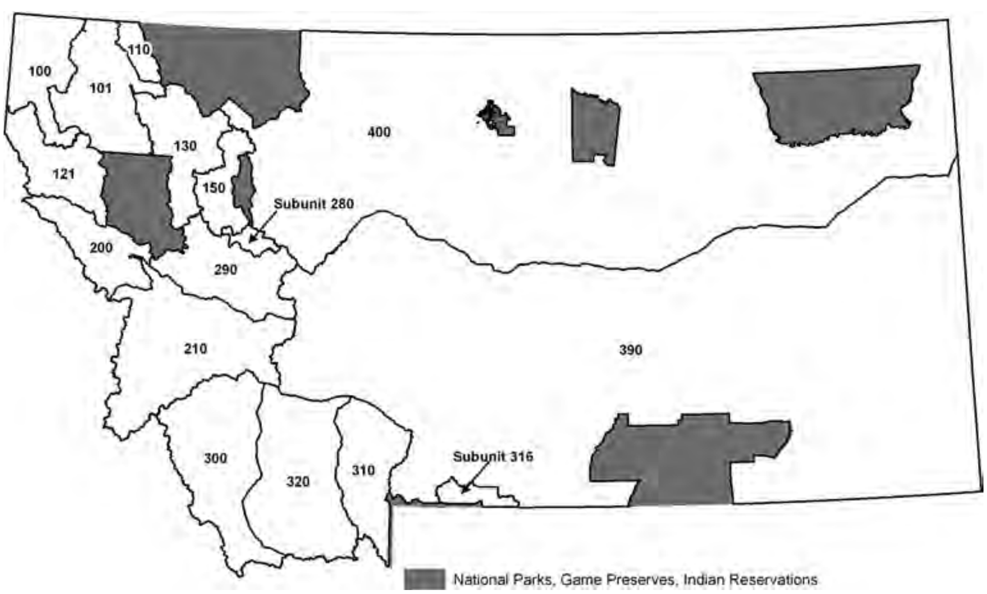


*Figure 5.9.* Wolf management units adopted for implementation in the 2011 hunting season by the Montana Fish, Wildlife and Parks Commission.

in the public presentation and review of the proposed season structure. The 2010 wolf hunting season was not implemented, however, because wolves in the NRM were returned to the endangered species list by court order in August 2010. With the legislated removal of wolves in the NRM from the endangered species list in May 2011, management of wolves under the 2010 WMUs was implemented in 2011 with minor adjustments.

Although there was a pressing need to make a recommendation for 2010, this decision can be revisited each year, creating an opportunity to improve the analysis and to reduce uncertainty over time. Future iterations of this process might address three topics: developing better measurable attributes for the objectives, founded on natural scales that are tied to monitoring systems; reinstating the omitted fundamental objectives, which may be more relevant in subsequent years; and analyzing wolf monitoring data over time to evaluate the efficacy of the wolf hunting program.

## Case Study Three: Adaptive Harvest Management of Waterfowl in North America

Each year, the USFWS sets harvest regulations for waterfowl based on population and habitat conditions. The USFWS has sole regulatory responsibility for this decision under the Migratory Bird Treaty Act (16 USC 703–712), and a number of

NEPA compliance documents govern the regulations-setting process (USFWS 1988). But the USFWS recognizes important management partnerships with the states and flyways, and has established a formal collaborative structure for garnering input from these partners. In 1995, a prescriptive decision-theoretic approach to setting harvest regulations for midcontinent mallards (*Anas platyrhynchos*) was established (Nichols et al. 1995, Johnson et al. 1997). Referred to as adaptive harvest management (AHM), this process recognizes the dynamic nature of the resource, the recurrent nature of the decisions, and the role that uncertainty plays in impeding decision making. Because mallards are the most abundant duck species in the midcontinent, AHM also serves as the framework around which regulations for hunting of other duck species is centered.

There are multiple objectives that AHM seeks to achieve: to maximize annual harvest of mallards, to maintain a sustainable level of harvest, to maintain the population size close to or higher than the North American Waterfowl Management Plan (NAWMP) goal, and to prevent closed seasons, except in extreme circumstances. These multiple—and competing—objectives have been combined into a single objective function. The objective of AHM is to maximize

$$\sum_{t=0}^{\infty} H_t \min\left(\frac{\hat{N}_{t+1}}{8.5}, 1\right)$$

where $H_t$ is the annual harvest, $\hat{N}_{t+1}$ is the predicted breeding population size in the next year, and 8.5 is the NAWMP goal for midcontinent mallards (in millions). The minimization within the objective function devalues the harvest whenever the population size is predicted to be below the NAWMP goal. Summing the harvest over an infinite time horizon ensures sustainability; the only way to maximize a long-term cumulative harvest is to keep the population extant.

The alternatives are chosen from a small set of regulatory packages: closed, restrictive, moderate, and liberal seasons, which differ in the length of the season and the daily bag limit. The closed season is only permitted when the midcontinent mallard population size falls below 5.5 million. For each of the regulatory packages, an expected harvest rate has been estimated.

The consequences of the different packages are evaluated through predictive models of mallard population dynamics. These models take three input values: two state variables (mallard breeding population size and the number of ponds in prairie Canada) and one decision variable (the regulatory package). They predict two quantities: the expected harvest, $H_t$, and the breeding population size in the subsequent year, $\hat{N}_{t+1}$ (Runge et al. 2002). One of the motivations for an adaptive management approach was intense disagreement that arose out of uncertainty about the population dynamics. There is uncertainty about the degree of density dependence in recruitment (weak versus strong density dependence), and uncertainty about the effect of harvest mortality on annual mortality (additive versus compensatory harvest mortality); in combination, these uncertainties are captured in four alternative population models. This uncertainty matters; the four alternative models lead to very different harvest strategies, and the resolution of the uncertainty has a significant value of information (Johnson et al. 2002).

*Table 5.5.* Optimal regulatory strategy for midcontinent mallards for the 2010 hunting season

| | Ponds | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bpop | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 |
| ≤4.5 | C | C | C | C | C | C | C | C | C | C |
| 4.75–5.75 | R | R | R | R | R | R | R | R | R | R |
| 6 | R | R | R | R | R | R | R | R | M | M |
| 6.25 | R | R | R | R | R | R | M | M | M | L |
| 6.5 | R | R | R | R | M | M | M | L | L | L |
| 6.75 | R | R | R | M | L | L | L | L | L | L |
| 7 | R | M | M | M | L | L | L | L | L | L |
| 7.25 | M | L | L | L | L | L | L | L | L | L |
| 7.5 | L | L | L | L | L | L | L | L | L | L |
| ≥7.75 | L | L | L | L | **L** | L | L | L | L | L |

*Source:* USFWS (2010).

The two state variables are the breeding population size (Bpop, in millions) and the number of ponds in prairie Canada (ponds, in millions). The regulatory packages are closed (C), restrictive (R), moderate (M), and liberal (L). Boldface represents the regulatory prescription for 2010.

The optimal strategy is found each year through passive adaptive stochastic dynamic programming (Williams 1996), which produces a state-dependent harvest strategy that stipulates the optimal regulatory package for any combination of breeding population size and number of ponds (Table 5.5). It is a passive adaptive strategy, in that the optimization does not anticipate the effect of learning on future decisions.

The USFWS, Canadian Wildlife Service, U.S. states, and Canadian provinces collaboratively operate an extensive monitoring program for waterfowl, which includes aerial surveys to estimate abundance and habitat conditions, banding and band-recovery programs for survival and related estimates, and harvest surveys for harvest and reproductive estimates. From the standpoint of adaptation, the key annual monitoring data are the breeding population estimates, because these provide the feedback for evaluating the model uncertainty. The weights on the four models have evolved over time as a result of the observed responses to management (Fig. 5.10); the evidence for the weakly density-dependent model has increased significantly, and the evidence for the additive model has increased slightly. These changes in model weights have been accompanied by an evolution in the harvest strategy over time; thus the annual regulations have adapted to the new information.

The AHM program has undergone some technical adjustments and minor policy modifications over the years since its first implementation, but has largely remained intact. Currently, the waterfowl management community is engaged in a process of double-loop learning, examining the nature of the objectives, alternatives, and models that underlie the regulations setting process (Anderson et al. 2007).

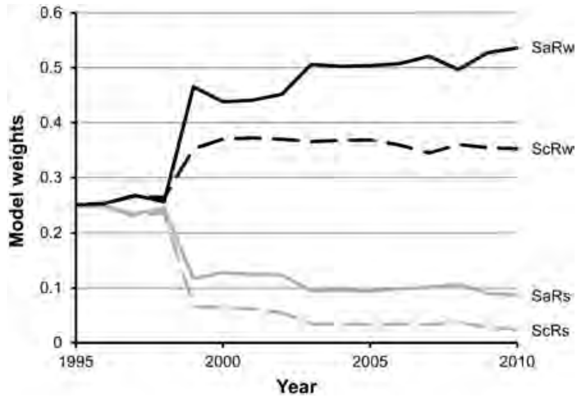


*Figure 5.10.* Weights on alternative predictive models for midcontinent mallard dynamics, 1995–2010 (USFWS 2010). The four models are distinguished by whether the survival model is compensatory (Sc) or additive (Sa), and whether the reproductive model is strongly (Rs) or weakly (Rw) density dependent.

## SUMMARY

Wildlife management is a decision-focused discipline. It needs to integrate traditional wildlife science and social science to identify actions that are most likely to achieve the array of desires society has surrounding wildlife populations. Decision science, a vast field with roots in economics, operations research, and psychology, offers a rich set of tools to help wildlife managers frame, decompose, analyze, and synthesize their decisions. The nature of wildlife management as a decision science has been recognized since the inception of the field, but formal methods of decision analysis have been underused. There is tremendous potential for wildlife management to grow further through the use of formal decision analysis. First, the wildlife science and human dimensions of wildlife disciplines can be readily integrated. Second, decisions can become more efficient. Third, decisions makers can communicate more clearly with stakeholders and the public. Fourth, good, intuitive wildlife managers, by explicitly examining how they make decisions, can translate their art into a science that is readily used by the next generation.

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