# Chapter 15
# Economic Modeling and the Management of Exotic Annual *Bromus* Species: Accounting for Ecosystem Dynamics, Ecological Thresholds, and Spatial Interdependencies

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**Abstract** This chapter describes how economic models can inform management of exotic annual *Bromus* species on rangelands in the Western United States. It surveys published studies that develop bio-economic models of the management of *Bromus* species and other exotic annual invasive grasses, focusing on the challenges of representing the complex dynamics of rangeland ecosystems within tractable models of economic decision-making. The discussion starts with elements that are common to most economic models of *Bromus* management, then turns to contributions from the literature that have developed bio-economic models that capture three salient features of *Bromus* invasion: the dynamics of *Bromus* invasion, ecological thresholds related to *Bromus*, and spatial interdependencies in biophysical and human systems. The chapter synthesizes insights gained from this literature for managing *Bromus* in the Western United States, including insights on where to direct *Bromus* management resources on the landscape to achieve the greatest benefit given limited funds for management and on how to improve the design of policies that encourage socially efficient *Bromus* management by private land managers. The chapter concludes by identifying key areas where further research into the economics of *Bromus* management is needed.

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## 15.1 Introduction

Public and private land managers regularly make decisions that influence the prevalence and spread of exotic annual *Bromus* species (*Bromus* hereafter) and other exotic annual invasive grasses on semiarid rangelands in the Western United States. Ranchers affect *Bromus* through weed control efforts and livestock management (inappropriate livestock grazing can reduce the ability of native plants to compete with *Bromus*). Public land management agencies affect *Bromus* through weed management; post-wildfire rehabilitation; education, outreach, and incentive programs that target land managers; and regulation of the activities of ranchers and other private entities that operate on public land. Understanding how public and private land managers make decisions, and how their decisions are influenced by the financial and ecological constraints they face, is essential for designing policies and regulations that encourage private managers to effectively manage *Bromus* invasions, as well as for determining the efficient use of limited resources available to public agencies for *Bromus* management. This chapter surveys published economic studies that have developed and used integrated ecological and economic models (henceforth, bio-economic models) to analyze public and private decision-making on semiarid rangelands affected by *Bromus* and other exotic annual invasive grasses and discusses the implications of these studies for the management of *Bromus* on rangelands in the Western United States.

The chapter focuses on simulation and optimization bio-economic models that take into account one of three attributes of *Bromus* invasions that pose particular challenges to economic analysis: the temporal dynamics of invasion, ecological thresholds, and spatial interdependencies in biophysical and human systems. All these bio-economic models of *Bromus* grass management include an ecological component to represent how *Bromus* species behave and are likely to respond to management. A primary challenge when developing bio-economic models is to balance the competing imperatives of (1) accurately representing the ecology of a *Bromus* invasion while (2) precisely and parsimoniously describing the elements of the economic decision problem. Ultimately, a modeler chooses which aspects of the complex ecology of *Bromus* invasion are necessary to include in the model—and what aspects can be safely ignored—to address a specific management or policy question. (For the studies reviewed in this chapter, the ecological complexity relates to the dynamics of *Bromus* invasion, including movements between stable ecological states separated by thresholds and to the spatial spread of *Bromus*.) Similarly, choices must be made about which aspects of the economic decision problem to include. As discussed in the next section, economic decision problems may include the decision-maker's objective function, constraints on the ability to meet the objective, and uncertainty about future economic and ecological conditions. The discussion examines how previous studies have balanced these competing imperatives in developing bio-economic models that are both ecologically sound and capable of addressing practical management issues related to *Bromus*.

The chapter starts by describing several elements that are common to most of the bio-economic models of *Bromus* management surveyed in this chapter. It then turns to the various approaches these existing models have used to address the dynamics of *Bromus* invasions, ecological thresholds related to *Bromus*, and spatial interdependencies in biophysical and human systems where *Bromus* are present. Next is a summary of insights from the studies reviewed for management and regulation of *Bromus* on semiarid rangelands in the Western United States. The chapter concludes by identifying areas for further research.

## 15.2 Common Bio-Economic Modeling Elements

Most of the bio-economic studies reviewed in this chapter share common elements. At the most basic level is the recognition that economic problems are posed from the perspective of a decision-maker with specific objectives and constraints. The studies reviewed in this chapter consider decisions from two perspectives. First is the perspective of an individual (or firm) whose primary concern is to meet private objectives, which may be to maximize profits from a ranch operation, or to ensure the ecological sustainability of land under his or her stewardship, or a combination of both. Second is the perspective of a "public decision-maker" concerned with a broader range of benefits and costs that accrue to society (where "public" refers not to a particular public agency, such as the Bureau of Land Management, but to the context in which decisions are made, taking into account the full range of social benefits and costs). In studies of *Bromus* management, public decision-makers are typically assumed to balance the costs of *Bromus* control with the full range of costs associated with *Bromus* invasion, which include reduced livestock forage, increased wildfire frequency and costs, and degradation of ecosystem services such as wildlife habitat, biodiversity, carbon sequestration, and hydrologic functions that reduce soil erosion and flooding costs. (See Havstad et al. 2007 for a comprehensive list of ecosystem services from arid rangeland ecosystems.)

The public-good nature of many of the costs of *Bromus* invasion justifies a role for rangeland policy to align incentives of private decision-makers with social management objectives. For example, although many private ranchers may be motivated to earn profits through their ranch operation and also be "good stewards" who protect the ecological health of the land under their management, they are unlikely to take into account all the ways in which their management decisions generate benefits and costs for other segments of society through their effects on *Bromus*. For this reason, many private decision-making models are designed to address how public programs or policies (e.g., cost sharing of rangeland management treatments) can align private incentives with social goals.

The studies reviewed here, as well as in economics in general, use mathematics to define a decision-maker's objective function and the constraints on the decision-maker's ability to maximize this objective. In the case of *Bromus* management, constraints include those imposed by the ecology of semiarid rangeland ecosystems that have been affected by *Bromus*. For example, a land manager's ability to rehabilitate a site dominated by *Bromus* is constrained by the biology of *Bromus* and the biophysical features of the site (e.g., precipitation, elevation, soil characteristics), among other factors. Similarly, a rancher's profits are constrained by cattle herd growth dynamics and forage availability. Constraints such as those imposed by regulations, limits to public land access, effectiveness of rehabilitation treatments and *Bromus* management technologies, and limited budgets are all incorporated into bio-economic models as mathematical relationships.

The objective function in a bio-economic model should represent the decision-making criteria used by the decision-maker being modeled so that the model's predictions comport with reality. Several decision-making criteria are represented in the studies reviewed in this chapter. Objectives of public decision-makers include minimizing the sum of treatment costs and damages from exotic invasive plants (e.g., Olson and Roy 2002; Eiswerth and Johnson 2002; Finnoff et al. 2010; Epanchin-Niell and Wilen 2012) and maximizing the flow of future benefits from controlling an invader, minus management costs (e.g., Polasky 2010). Models of private decision-makers largely focus on ranchers and assume either that the rancher's objective is to maximize the present value of profits from the ranch (e.g., Huffaker and Cooper 1995; Kobayashi et al. 2014) or that the rancher follows a decision heuristic, or rule of thumb, that determines how to adjust stocking rates and management in response to exotic invasive plant encroachment (e.g., Janssen et al. 2004).

Uncertainty and risk are inherent to *Bromus* invasion and management. Many studies reviewed in this chapter incorporate risk by including stochastic parameters to characterize sources of uncertainty. Studies have used stochastic parameters for rainfall variability and drought (e.g., Janssen et al. 2004; Ritten et al. 2010), wildfire (e.g., Huffaker and Cooper 1995; Epanchin-Niell et al. 2009), the success or failure of management treatments (e.g., Eiswerth and van Kooten 2002; Epanchin-Niell et al. 2009; Taylor et al. 2013a), and market volatility (Karp and Pope 1984; Carande et al. 1995). Some sources of uncertainty are exogenous to the efforts of the decision-maker (e.g., lightning strikes, drought, market variability), while others are at least partially endogenous, in that the decision-maker's actions influence the likelihoods of particular outcomes. The probability of catastrophic wildfire, for example, is a function of fuel loading, which can be managed with fuel removal treatments (Taylor et al. 2013a). Models that include uncertainty and risk produce ranges of outcomes that depend on the realization of stochastic parameters. The determination of which sources of risk to include in a model depends on the management question(s) being considered.

Bio-economic models of private decision-making under risk require two additional assumptions relative to models that do not consider risk. First, models that consider decision-making over time require an assumption to describe how the decision-maker forms expectations about the outcomes of his or her actions given uncertain future ecological and market conditions. Most studies in this review assume that decision-makers have "perfect foresight." Although decision-makers do not know precise outcomes of their actions given uncertainty about future conditions, they do know the range of possible outcomes and the probability that each outcome will occur from any course of action, and they use this knowledge to pursue actions that have the greatest expected value given their objective function and set of constraints. Even though the assumption of perfect foresight is unrealistic, several ranch models that assume perfect foresight generate realistic predictions for cattle stocking rates, average annual profits, and other relevant variables (e.g., Karp and Pope 1984; Passmore and Brown 1991; Carande et al. 1995; Wang and Hacker 1997; Ritten et al. 2010).

The second assumption required by models that analyze private decision-making under risk concerns the decision-maker's attitude toward risk. In particular, the modeler must decide whether to portray the decision-maker as risk averse, risk neutral, or risk loving. A risk-averse decision-maker faced with the option of participating in a lottery versus receiving the expected value of the lottery with certainty would choose the latter, a risk-neutral decision-maker would be indifferent between the two, and a risk-loving decision-maker would prefer to participate in the lottery. The majority of studies of private decision-makers reviewed in this chapter assume a risk-neutral decision-maker (e.g., Huffaker and Cooper 1995; Finnoff et al. 2008; Kobayashi et al. 2014). However, Passmore and Brown (1991) and Carande et al. (1995) find that, faced with uncertain prices for cattle, risk-averse ranchers would maintain lower average annual stocking rates than risk-neutral ranchers to achieve lower but less volatile streams of profits. A finding that greater levels of risk aversion by ranchers can lead to substantial reductions in stocking rates suggests that risk attitudes are also likely to matter for decisions concerning *Bromus* management.

Dynamic economic models generally assume some form of discounting such that future benefits and costs are valued less, and have less weight in decision-making, than benefits and costs that occur today. The appropriate discount rate for economic studies of *Bromus* depends crucially on the decision-maker being modeled. Previous studies that have considered the decision-making of a private rancher or land manager have elected to use the market interest rate to discount future benefits and costs (e.g., Kobayashi et al. 2014). The market rate of interest is used because it reflects the opportunity cost of the funds used for *Bromus* management (i.e., the lost opportunity from not being able to invest the funds used for *Bromus* management elsewhere in the economy). Conversely, when the decision-maker is a public sector agency, previous studies have used the social rate of time preference to discount future benefits and costs (e.g., Taylor et al. 2013a). The social rate of time preference is the rate that society is willing to trade off future consumption for current consumption and is generally lower than the private discount rate. In addition, although all the bio-economic models reviewed in this chapter assume linear discounting (i.e., all future years are discounted using the same discount rate), several previous studies have suggested that nonlinear or hyperbolic discounting (i.e., the near future is discounted at a higher rate than the more distant future) provides a more accurate description of how people evaluate trade-offs between the present and future benefits and costs (Karp 2005). It is likely that the bio-economic models reviewed in this chapter all assume linear discounting in part because it is a straightforward assumption to implement in dynamic economic models.

Finally, the specific management questions addressed in an economic study of *Bromus* species depend in part on the "stage" of invasion being analyzed. Biological invasions generally have four stages: introduction, establishment, spread, and saturation. Because *Bromus*, in particular *Bromus tectorum* L. (cheatgrass or downy brome), is present to some extent in much of its potential nonnative range in the Western United States, the *Bromus* studies reviewed in this chapter focus primarily on the spread and saturation stages of invasion. These studies analyze management issues that include ecological rehabilitation, preventing partially invaded land from transitioning across an ecological threshold to an exotic invasive-dominated ecological state and minimizing the damages from *Bromus* invasion at a site. Nonetheless, in regions where there remain areas of relatively uninvaded rangeland, management strategies such as detection and quarantine, which aim to slow the spread of the invasion across the landscape, are paramount. Hence, several bio-economic models designed to analyze such management strategies also are reviewed.

## 15.3 Economic and Ecological Dynamics

This section reviews how dynamic optimization has been used to analyze the dynamic aspects of *Bromus* management and discusses insights yielded by such studies. Most of the studies reviewed in this chapter incorporate dynamics of natural processes (e.g., species dynamics, climate, and fire) to generate benefits and costs of invasive species management strategies in units that are comparable over time. Management actions may intentionally or unintentionally cause ecological and economic processes to speed up, slow, reverse, or be shifted to move along completely different pathways, depending on the timing of an action and the nature of the dynamic processes that occur within and between ecological and economic systems. Only a few economic studies have used dynamic optimization methods to analyze management of *Bromus* in particular (Kobayashi et al. 2014) or exotic annual invasive grasses more generally (Huffaker and Cooper 1995; Finnoff et al. 2008), but several dynamic bio-economic studies of other exotic invasive species can provide important insights.

It is important to distinguish between dynamic optimization and dynamic simulation models. This section focuses on optimization models, which analyze the behavior of decision-makers whose goal is maximizing (or minimizing) an objective function given one or more constraints. Because optimization models describe the incentives and constraints faced by real-world decision-makers, they are generally preferred over simulation models for most economic analysis. Simulation models are often used for economic analyses of *Bromus* and other exotic annual invasive grasses because ecological thresholds, spatial dynamics, and other factors complicate the mathematical description of the economic decision problem. Although simulation methods are not designed to identify optimal outcomes, they can be used to compare outcomes from different management options and identify those that are more efficient.

### 15.3.1 General Framework for Dynamic Optimization

Dynamic optimization is an approach used to determine which actions from a defined set of possible actions a decision-maker should choose to maximize (or minimize) an objective function over a defined time horizon. Because the decision-maker's chosen actions affect the future trajectory of the entire dynamic system, these actions are referred to as "control variables." Examples of control variables are (1) a private rancher's choice of which series of weed treatments and herd management actions will maximize the present-valued net worth of a ranch operation affected by *Bromus* and (2) a land management agency's choice of the timing of landscape-level treatments to result in a cost-minimizing strategy to maintain an area's resistance to *Bromus* invasion over a 20-year time horizon.

Dynamic optimization models integrate time and system dynamics through state equations, which define how "state variables" change over time as a function of both natural processes and the application of control variables. A state variable describes the level (or quantity) at a given time of a variable that can change over time. Examples of state variables are (1) the size (measured as density or spatial coverage) of a *Bromus* infestation, (2) the stock of forage for livestock, and (3) the size of a herd. A state equation that describes how the size of an invasion evolves over time depends on the natural (or "intrinsic") rate of growth of the species, as well as the influence of human efforts to manage it through control variables. The goal is to choose values for control variables strategically to influence how the state variables evolve over time to either maximize or minimize the decision-maker's objective function. The solution to a dynamic optimization describes the values of all the state variables and control variables at each point along the optimum path and is a function of the starting points of the state variables. For example, the level of a *Bromus* infestation at the start of the management problem would affect the solution to the optimization problem.

Two methods used for solving dynamic constrained optimization problems are optimal control (OC) and stochastic dynamic programming (SDP). OC methods are typically characterized by models that yield mathematical equations broadly characterizing analytical properties of solutions to the optimization problem, thereby allowing one to reach general conclusions. These models often are of the "continuous-time" variety, meaning that the state variables are modeled as changing continuously over time (using differential equations), rather than once every specified period (e.g., once each year), as in a discrete-time model.

In contrast, SDP is a means of numerically solving a constrained optimization problem to provide approximate solutions to systems that do not result in analytical solutions because of their mathematical complexity. In addition, SDP offers a more tractable approach than OC alone for accommodating uncertainty, including uncertainty regarding the performance of control measures, how an infestation evolves in response to natural conditions and management, and the occurrence of fire and other stochastic disturbances. Finally, because SDP models are based on discrete rather than continuous time, parameterizing economic models of *Bromus* for data such as livestock herd size, end-of-year cattle prices, acreage treated, and other parameters that tend to be considered in discrete or annual increments is more straightforward than with the continuous formulations used in OC methods. OC and SDP models applied in the exotic invasive context also typically maximize an objective function over an "infinite time horizon." Alternatively, OC and SDP models may maximize an objective function over a finite time horizon, taking into account what the predicted "terminal value" of a specified state variable will be at the end of that finite time horizon.

### 15.3.2 Cost Minimization Models

Several studies formulate the invasive species management problem as minimizing the sum of the costs of invasion (damages) and management costs. Cost minimization approaches are particularly useful when evaluating alternative management strategies. An example of a cost minimization model is Eiswerth and Johnson (2002), who use an OC model to minimize the sum of damages and management costs following the introduction and establishment of exotic invasive weed and grass species on arid lands. Olson and Roy (2002) similarly use an OC model to minimize the sum of damages and management costs for an invasive species; however, they also model uncertainty in how an infestation grows and spreads over time.

In a useful extension of previous work, Ranjan et al. (2008) use a cost minimization approach to determine optimal combinations of strategies for allocating a fixed pool of financial resources between efforts to prevent introduction of an exotic invasive species into a new location and efforts to mitigate adverse impacts once establishment takes place. Buhle et al. (2005) combine data on population dynamics with control costs to identify the least-cost approaches for preventing *Ocinebrellus inornatus* (Japanese oyster drill), an established aquatic invasive snail, from spreading. Their methods are applicable to exotic annual invasive grass management where (1) managers wish to minimize the total costs of exotic invader control, and (2) it is relevant to ask at what stage of the life cycle of an exotic invader it is most cost-effective for managers to apply a control measure.

### 15.3.3 Ranch Management Models Using Dynamic Optimization

Several studies use SDP methods to analyze the effect of ranch management on rangeland ecosystems (Karp and Pope 1984; Passmore and Brown 1991; Carande et al. 1995; Wang and Hacker 1997; Ritten et al. 2010). These studies are calibrated to quantitatively match observed ranch outcomes and have typically used livestock stocking rates and the intensity of rangeland vegetation treatments as control variables (e.g., Karp and Pope 1984; Kobayashi et al. 2014). Kobayashi et al. (2014) is the only study to date that uses SDP to analyze a rancher's decision-making in the context of exotic annual invasive grasses; their model considers stochastic wildfire and effectiveness of rangeland rehabilitation treatments and incorporates ecological thresholds. Because their model is calibrated to quantitatively match observed ranch outcomes, Kobayashi et al. (2014) are able to analyze whether realistic and specific changes in rangeland policy (e.g., expansion of cost sharing for vegetation treatments) will induce changes in ranch management that translate into empirically meaningful improvements in the economic viability of ranching, rangeland ecological health, and the likelihood that privately managed rangeland will cross an ecological threshold to an annual grass-dominated ecological state.

### *15.3.4 Incorporating Stochastic Processes and Uncertainty into Dynamic Optimization*

Studies that use stochastic dynamic optimization methods must address the issue of how to parameterize the stochastic elements of the problem. Eiswerth and van Kooten (2002) use a discrete-time, infinite-horizon SDP model to identify preferred approaches for managing *Centaurea solstitialis* L. (yellow star thistle), an exotic invasive rangeland weed. The researchers include a random variable in the state equation to capture the stochastic nature by which the size of the infestation evolves over time. To parameterize their stochastic state equation, they use data collected via a survey of weed and plant experts to develop infestation transition probability matrices for each control option under consideration.

Kobayashi et al. (2014) use historical data for wildfire ignitions on rangeland systems distinguished by ecological states to parameterize the probability of stochastic fire events and the role of *Bromus* in crossing ecological thresholds. Other studies based on SDP models that are relevant for *Bromus* management include studies performed in the contexts of cropland weeds (e.g., Pandey and Medd 1991) and invasive species in general (Leung et al. 2002; Bogich and Shea 2008; Polasky 2010).

In another study employing SDP methods potentially applicable to the context of *Bromus*, Hyytiäinen et al. (2013) develop an SDP model to simultaneously examine the optimal magnitudes and timing of prevention, eradication, control, and adaptation for an aquatic exotic invader, *Corbicula fluminea* L. (Asian clam). Such an approach may apply especially well to exotic annual invasive grasses in cases where managers are free to choose among (1) a prevention strategy that stops or delays the invasion at a particular site, (2) a mitigation strategy that focuses on early detection and control of an infestation once established, and (3) an adaptation strategy that seeks to minimize economic losses without controlling the infestation.

In a study modeling *Dreissena polymorpha* L. (zebra mussel), Timar and Phaneuf (2009) use methods that also could be translated to *Bromus*. They estimate the probability of a dispersal event occurring at a given point in time, originating from an infested site and spreading to an uninfested site, to parameterize the likelihood of observing an infestation of zebra mussels as a function of the anthropogenic and natural factors that influence spread. An application or adaptation of this approach to exotic annual invasive grasses would be useful for developing a time- and site-dependent invasion hazard index as a function of (1) variables that indicate naturally occurring threats of invasion to each site (i.e., factors that influence the natural dispersal of seeds) and (2) a human threat variable (e.g., incorporating livestock stocking rates and management practices and rangeland fire prevention and restoration practices).

### *15.3.5 Imperfect Information and Dynamic Optimization in Invasive Species Management*

Most dynamic optimization models assume decision-makers have a rather sophisticated understanding of the ecological conditions on the land that they manage, can observe or monitor changes in ecological conditions without incurring costs, and are aware of the impact of their management actions on future ecological conditions. Several recent studies relax these stringent assumptions to develop models of how decision-makers adapt to imperfect information in the context of making multiple decisions over time. In an application to the exotic invasive rangeland weed *C. solstitialis*, Eiswerth and van Kooten (2007) compare the results of an SDP model to those of a “reinforcement-based, experience-weighted attraction learning model” (for background, see Camerer and Ho 1999; Hanaki et al. 2005), which is a formulation from game theory of a model describing adaptive management. This type of model simulates how a decision-maker incorporates additional information over time as more is learned about the net benefits of alternative management strategies, based on observing outcomes from implementing different strategies in each previous time period. The decision-maker adapts by adjusting the value of selecting a particular management strategy in a given time period based on how well different strategies have worked in the past, thereby allowing for efficient use of management resources over time.

Another approach to modeling how decision-makers handle imperfect information is to assume that a land manager with imperfect knowledge characterizes ecological conditions (and, hence, the level of infestation) into broad categories (e.g., good, fair, poor) that are used along with decision heuristics, or rules of thumb, to make management decisions (e.g., Eiswerth and van Kooten 2002). Such approaches use “fuzzy” methods to model decision-making in the context where ecological conditions and other elements of the problem are classified by the decision-maker into discrete categories, rather than treating these as continuous data. Such approaches must address two aspects of decision-maker subjectivity. First, two managers may label a given infestation differently depending on differences in their experience, knowledge, and judgment. For example, one manager may think of a specific infestation as “minimal,” while another labels it as “moderate” or even “high.” Second, depending on differences in characteristics and human uses of the landscapes at two locations, a manager may classify infestations of similar size and type (e.g., same species, infestation size, and density) as “minimal” at one location but “moderate” at another. As a result, infestations display characteristics associated with fuzzy variables that can be analyzed using fuzzy membership functions (e.g., Zadeh 1965), which are different from conventional probability distributions (Kosko 1992). Other variables in dynamic models of exotic annual invasive grasses or other rangeland exotic invaders (e.g., the intrinsic rate of growth) also may be treated as fuzzy variables. Fuzzy methods offer an approach for dealing with issues related to bounded rationality, which may more realistically represent how private and public actors make decisions regarding *Bromus*. It is important to note that fuzzy methods are not used to represent uncertainty on the part of the economic modeler concerning parameters and other model assumptions; rather, fuzzy methods capture the uncertainty of the decision-maker in the problem that is being modeled.

## 15.4 Ecological Thresholds

An ecological threshold is a critical point at which small changes in one or more ecosystem variables can lead to sudden, extreme changes in ecosystem condition (Holling 1973). More formally, thresholds are boundaries in conditions that lead to alternative stable states. Thresholds are crossed when an ecosystem does not return to the original state via self-organizing processes after stress or disturbance but instead transitions to a new, alternative state that has altered attributes and primary ecological processes (Beisner et al. 2003; Stringham et al. 2003).

Thresholds are a feature of many natural resource management problems, including rangeland management in the presence of *Bromus* and other exotic annual invasive grasses (Stringham et al. 2003). The prevalence of exotic annual invasive grasses can play a role, along with other biotic and abiotic factors (e.g., temperature, moisture regime, large deep-rooted perennial bunchgrasses), in determining whether rangeland ecosystems will transition to an exotic annual invasive grass-dominated state after a disturbance such as wildfire or drought (McIver et al. 2010). In many cases, transitions across thresholds can only be reversed through costly management interventions or are irreversible with current restoration technology. Ecological thresholds are relevant for rangeland policy because desired ecological states (e.g., states dominated by native perennial grasses and sagebrush with a small presence of *Bromus*) and exotic annual invasive grass-dominated states are very different in terms of livestock forage productivity and effects on ecosystem services such as the frequency and severity of wildfires, wildlife habitat for game animals and sensitive species, and the extent of soil erosion (Havstad et al. 2007).

A large and growing literature in economics analyzes the management of ecosystems in the presence of ecological thresholds in a variety of contexts, including eutrophication of freshwater lakes (Carpenter et al. 1999; Naevdal 2001; Brock and Starrett 2003; Mäler et al. 2003), infectious wildlife disease (Horan and Wolf 2005), environmentally sustainable economic development (Common and Perrings 1992), wildlife management (Rondeau 2001), and rangeland management (Perrings and Walker 1997, 2004). Most economic studies that analyze thresholds in terrestrial ecosystems focus on rangeland ecosystems (Huffaker and Cooper 1995; Perrings and Walker 1997, 2004; Anderies et al. 2002; Janssen et al. 2004; Finnoff et al. 2008), likely because an estimated 10–20 % of rangelands worldwide are degraded (Millennium Ecosystem Assessment 2005), and this degradation is often associated with crossing thresholds to undesirable ecological states, including ecological states dominated by exotic invasive plants.

### *15.4.1 Optimization Models and Ecological Thresholds*

Several studies use optimal control (OC) to analyze interactions between ecological thresholds and livestock management in rangeland ecosystems (Huffaker and Cooper 1995; Perrings and Walker 1997, 2004; Anderies et al. 2002; Janssen et al. 2004; Finnoff et al. 2008). Two of these studies—Huffaker and Cooper (1995) and Finnoff et al. (2008)—consider exotic annual invasive grasses. In these models, ecological thresholds arise endogenously as a result of interspecies plant competition and are characterized by the inherent properties of an ecosystem. These studies use OC methods to generate qualitative analytic results that describe generally how economic factors interact with ecological factors to determine whether management will result in crossing of an ecological threshold. Results demonstrate that a combination of economic factors (cattle prices, land management treatment costs, interest rates) and the initial ecosystem condition determine whether it is in the economic best interest of the decision-maker to maintain an ecosystem in a desired ecological state (e.g., a state dominated by native perennial grasses and sagebrush with a small presence of *Bromus*) or to allow it to cross a threshold to a degraded ecological state (e.g., a state dominated by *Bromus* and other exotic annual invasive grasses).

Kobayashi et al. (2014) incorporate ecological thresholds and exotic annual invasive grasses into a stochastic dynamic programming model of a ranch typical of northern Nevada. They use their model to analyze when and if subsidies that offset the cost of rehabilitation treatments and/or improved treatment success rates will result in changes in ranch management that make crossing ecological thresholds to an exotic annual invasive grass-dominated state less likely. The authors find that on rangeland dominated by native perennial grasses and sagebrush, lower treatment costs and improved success rates lead to larger herd sizes and higher profits but do not reduce the likelihood that the ranch will cross an ecological threshold to an exotic annual invasive grass-dominated state. The explanation is that the rancher has sufficient private incentive to maintain the land in the ecological state dominated by native perennial grasses and sagebrush through herd management and periodic vegetation treatments at current treatment costs and success rates. Conversely, on rangeland that has been invaded by exotic annual invasive grasses, lower treatment costs and/or improved treatment success rates cause the rancher to increase the frequency and intensity of restoration treatments, making it less likely that the land will convert to the exotic annual invasive grass-dominated state. These results suggest that subsidies to lower restoration treatment costs are most effective if directed toward ranchers whose land has been invaded by exotic annual invasive grasses but has not yet crossed the ecological threshold to the exotic annual invasive grass-dominated state.

### 15.4.2 Ecological Resilience

Several of the studies using OC methods mentioned thus far—in particular, Perrings and Walker (1997, 2004), Anderies et al. (2002), and Janssen et al. (2004)—consider the role of ecosystem resilience on the optimal management of a livestock operation in the presence of exotic invasive grasses and ecological thresholds. Consistent with the other chapters in this book, we define resilience as the capacity of an ecosystem to regain its fundamental structure, processes, and functioning when altered by stressors such as increased $CO_2$, nitrogen deposition, and drought and by disturbances including land development and fire (Holling 1973; Allen et al. 2005). Understanding how alternative management strategies influence the resilience of rangeland ecosystems is important because, as Scheffer et al. (2001) write, in rangeland ecosystems "a loss in resilience usually paves the way for a switch to an alternative state."

Anderies et al. (2002) develop a mathematical model to characterize the dynamic interactions among grass, shrubs, fire, and livestock in a setting with stochastic rainfall and ecological thresholds. These authors use their model to explore how ecological, economic, and management factors influence the resilience of a rangeland ecosystem. In a follow-up paper using the same analytical framework, Janssen et al. (2004) develop a methodology to characterize "robust" management strategies that determine when a rancher should reduce sheep stocking densities to allow the ecosystem to maintain ecological resilience. The authors of these studies conclude that economic conditions (such as high livestock prices) can cause ranchers to adopt management strategies (such as high livestock stocking rates) that compromise ecological resilience and make transition across ecological thresholds to degraded states more likely, in the event of disturbances such as drought or wildfire.

### 15.4.3 Computer Simulation Models

An alternative approach for analyzing how ecological thresholds influence the management of exotic annual invasive grasses in rangeland ecosystems is to develop computer simulation models that integrate state-and-transition models (STM) from rangeland ecology with economic models. This approach is used by Epanchin-Niell et al. (2009) and Taylor et al. (2013a). An STM describes an ecosystem as being in one of several alternative states separated by ecological thresholds, where transitions between states are often triggered by disturbances including natural events (e.g., drought, wildfire) and management actions (e.g., grazing, prescribed burns) (Stringham et al. 2003). The STM framework allows for the incorporation of complex ecosystem dynamics into bio-economic simulation models, including the role of ecological disturbances such as wildfire and drought as catalysts for transitions across ecological thresholds to an exotic annual invasive grass-dominated state.

In contrast to studies based on optimization models, simulation models do not analyze a self-interested decision-maker's optimal response to changes in ecological or economic conditions or policy. Rather, simulation models are used to analyze and compare the economic efficiency of alternative management regimes in a setting where the effects of stochastic factors such as wildfire, post-disturbance ecological transition, and treatment success on the distribution of outcomes can be explicitly analyzed.

Bio-economic simulation models that incorporate STMs of exotic annual invasive grasses in rangeland ecosystems have reached several novel management conclusions. Epanchin-Niell et al. (2009) demonstrate that in the sagebrush steppe ecosystem in the Western United States (specifically, the Wyoming big sagebrush community in the Great Basin 8–10-inch precipitation zone), investment in post-wildfire revegetation of degraded sites (i.e., sites with sagebrush and *B. tectorum* but sparse to no perennial bunchgrasses) using either native or nonnative perennial bunchgrasses can reduce long-term fire management costs over a 50-year time horizon by more than enough to offset the costs of treatment. These reductions in fire management costs are accomplished in part by reducing the amount of land that transitions to a state entirely dominated by *B. tectorum*, where wildfires occur more frequently. The study also quantifies the economic and biodiversity trade-offs of revegetating using native versus nonnative perennial bunchgrasses and derives a cost function for the long-term maintenance of native sagebrush steppe vegetation on the landscape via postfire revegetation. Epanchin-Niell et al. (2009) also reach the significant if not surprising conclusion that although greater federal funding levels for post-wildfire restoration in the sagebrush steppe are warranted based on the expected economic returns and biodiversity benefits, this management strategy alone is insufficient to reverse the continued transition of rangelands across thresholds to exotic annual invasive grass-dominated states.

Taylor et al. (2013a) compare the economic efficiency of prevention versus rehabilitation treatments for two rangeland ecosystems (Wyoming sagebrush steppe and mountain big sagebrush ecosystems) affected by invasive grasses. They find that over a 200-year time horizon, prevention treatments applied to contain exotic annual invasive grasses on lands that have not yet become dominated by the invasive grasses yield benefits in terms of expected future wildfire suppression cost savings that are several times greater than the cost of treatment and that the savings in wildfire suppression costs pay for treatment costs within 20 years. Conversely, they find that for systems dominated by exotic annual invasive grasses, the wildfire suppression cost savings associated with rehabilitation are not sufficient to justify the high per acre treatment costs and low restoration success rates. Together, these results suggest that limited budgets for exotic annual invasive grass management are most efficiently directed toward preventing rangeland that has not yet become dominated by *Bromus* from crossing an ecological threshold to *Bromus* dominance.

### *15.4.4 Uncertain Ecological Thresholds*

It is often difficult for experienced rangeland ecologists to determine with certainty whether an ecosystem has crossed a threshold between states (McIver et al. 2010). This uncertainty can be costly because treatment methods that are appropriate before a threshold has been reached may be ineffective, or could even hasten exotic annual invasive grass domination, after the threshold has been crossed. Taylor et al. (2013a) find that the expected economic benefits of restoration-based hazardous fuel reduction treatments on rangelands increase with the land manager's ability to determine whether the land has crossed an ecological threshold related to exotic annual invasive grasses. The increased expected economic benefit of treatment occurs because uncertainty about whether the threshold has been crossed causes land managers to treat land that is not at immediate risk of crossing a threshold to an exotic annual invasive grass-dominated state in the event of wildfire or other disturbance, and hence where treatment could have been delayed at no cost. Further, reduced uncertainty makes it less likely that land managers will treat in areas that have already crossed a threshold to a state where treatment is a disturbance that moves the land to an exotic annual invasive grass-dominated state. In this manner, Taylor et al. (2013a) quantify the economic benefits of rangeland ecology research and outreach that improves accuracy in assessing whether *Bromus*-affected rangeland has crossed a threshold.

## 15.5 Spatial Considerations

The question of how to prioritize among locations is paramount when a fixed set of management resources is to be allocated across a number of locations that have different economic and ecosystem characteristics or when there are strong interdependencies across sites that affect the costs or benefits from investments at each location. Because incorporating spatial interactions into decision models with dynamic ecological and economic processes introduces another level of mathematical complexity, modelers use simplifying assumptions to keep models tractable for practical application. Ultimately, the modeler must decide whether to ignore spatial interdependencies because the benefits from accounting for them are very small or are not important in the particular context or whether the benefits are large and important enough to justify more involved modeling approaches. The existing literature contains a variety of approaches to spatial bio-economic modeling of landscape-level economic decision-making problems that could be adapted to *Bromus* and invaded rangelands. This literature includes spatial models that can facilitate development of management rules of thumb or management strategies to be tested within adaptive management frameworks, to confirm or reject existing intuition about best management strategies, and to identify specific cost-effective management strategies. This section reviews studies that are most relevant for *Bromus* management scenarios.

Two classes of problems involving decision-making that affects multiple sites are relevant for *Bromus* management. In the first class of problems, the level and importance of spillover effects from one site to other sites is minor or relatively unimportant to the management scenarios being considered. In this case, decision problems are linked spatially through the need to allocate a fixed set of management resources across a number of locations with different characteristics (such as different ecological states). Management benefits and costs may also vary across sites because of travel distances, spatial configurations, proximity to residential areas, and presence of critical wildlife habitat or highly valued cultural features. In cases where activities on one site do not generate important changes in the ecological processes and responses to management activities on other sites—that is, where the interactions between locations can be treated as independent—the spatial modeling problem is relatively straightforward.

The second class of problems involves situations where it is not reasonable to ignore spatial interdependencies between locations. Spatial interdependencies in biophysical systems occur when underlying dynamics are interdependent across sites, such as through the spread of exotic invasive species, spread of wildfire, and habitat linkages. Management actions at one location could affect adjacent sites through these biophysical interdependencies. Similarly, spatial interdependencies in human systems arise from the choices made by a manager in one area influencing the effectiveness of options available to a manager in an adjacent area. For example, treating a *Bromus* monoculture in one location may reduce fire risk to adjoining locations, thereby altering expectations regarding habitat, and thus management decision-making, on these adjacent lands.

### 15.5.1 Management Efforts across Space with Resource Constraints

If the assumption of spatial independence is reasonable, the returns from a fixed amount of resources to invest in rehabilitation treatment are maximized across a heterogeneous landscape by targeting effort first to the site with the highest benefit–cost ratio from treatment, then moving sequentially among sites in decreasing order of the benefit–cost ratios until the budget is exhausted or the costs outweigh benefits (Broadman et al. 2006; Pearce et al. 2006; Boyd et al. 2012). The practical issue is how to assess benefits and costs of treatment to account for varying levels of effort and alternative suites of management actions for each location. For large landscapes, the process of measuring benefit–cost ratios for relevant ranges of treatments for every individual site is likely to be impractical for most landscape-level management scenarios. An alternative approach to simplify the process is to identify a set of site attributes (using ecology and other criteria) that allow for classification of all sites into a smaller number of site "types." The sets of attributes can be used to estimate a standard unit area benefit–cost ratio for each type. The standardized benefit–cost ratios are then applied to all sites matching each type. Furthermore, the attributes for site types are ready for subsequent policy and programmatic decisions. This approach requires consideration of the relationship between definitions of site type attributes and the delineation of actual sites, and how attributes can be defined to facilitate application to different regions.

The development and application of standardized benefit–cost ratios per unit area by landscape type is practical where minor spatial interdependencies and unique features for specific sites can be taken into account after the fact, during the decision process. This approach may be particularly useful for allocating rehabilitation treatments across sites to prevent rangeland from transitioning to an exotic annual invasive grass-dominated state. Taylor et al. (2013a) use benefit–cost ratios (where benefits of treatment are measured as wildfire suppression cost savings) and the assumption of independence of locations to evaluate which *Bromus*-influenced ecological states should be prioritized for restoration-based fuel treatment. They quantify benefits and costs and quantify the differences in returns on treatment between lands where exotic annual invasive grasses are present but not yet a dominant component of the understory versus lands that have already crossed an ecological threshold and require rehabilitation treatments.

Similar intuition applies when deciding among locations for investing in postfire restoration. Epanchin-Niell et al. (2009) demonstrate that returns from postfire restoration of degraded sagebrush and exotic annual grass-dominated sites are greatest on sites with higher restoration success rates (e.g., due to soil type, climate), lower costs (e.g., due to terrain, accessibility), greater benefits from preventing a transition to an exotic annual invasive grass-dominated state (e.g., due to averting high fire suppression costs near developed areas), and in close proximity to high-valued natural resources at risk (e.g., sage grouse habitat). While each of these attributes contributes to greater "bang for the buck" from rehabilitation, all else equal, in practical application these attributes are present in various combinations at different sites across a landscape. Studies such as this suggest which attributes (restoration success rate, fire suppression cost, at-risk resources) are most useful for developing a classification system of "types" for standardized benefit–cost ratios.

In addition to rehabilitation treatments, spatial prioritization is important for decisions about optimal locations for monitoring effort using a fixed set of monitoring resources. For example, studies of exotic invasive plants (Hauser and McCarthy 2009) and exotic invasive forest pests (Epanchin-Niell et al. 2012, 2014) have developed approaches to cost-effectively allocate monitoring resources across sites that vary in the likelihood of exotic invasive introduction, ecosystem values at risk, and monitoring costs. These could be adapted to design cost-effective survey and control strategies for new incursions of *Bromus*.

### *15.5.2 Spatial Interdependency of Biophysical Processes*

Spatial interdependencies in exotic annual invasive grass management exist where interconnected biophysical processes cause management effort at one location to influence benefits and costs or management outcomes at other locations. Invasions generally begin with introductions into limited locations, which then spread over time through reproduction and dispersal. Damages increase over time as more area is affected. Interdependencies can result when controls applied at one location affect the rate of spread at other locations. In the extreme, eradication of an invasive species from a single key area could prevent spread and damage across a much larger area. A review of studies that integrate ecology and economics to analyze optimal management of the geographic spread of established invasions (Epanchin-Niell and Hastings 2010) finds that models used to incorporate spatial interdependencies to represent the spread of invasive species are generally of two main types: spatially implicit models predict the total invaded area over time without considering specific invaded area locations, and spatially explicit models take into account the details of specific locations. These models use optimization as well as simulation approaches to compare management strategies.

Spatially implicit models can be used to determine cost-effective levels of effort for controlling invasions in cases where it is not necessary to model precise locations for where controls should be targeted. The general findings of the studies reviewed in Epanchin-Niell and Hastings (2010) are fairly intuitive: features that have the greatest influence on whether control is cost-effective include the speed of an invasion's spread, the potential size of area that could be affected, the degree of potential damages, and control cost. Features that increase the likelihood that eradication is an optimal strategy include invasions being small when detected and reintroduction being unlikely and/or infrequent. Although these generalized findings confirm intuition, many of the spatially implicit studies reviewed by Epanchin-Niell and Hastings (2010) provide modeling approaches that can be parameterized (calibrated) for application to specific management contexts and locations, thereby yielding quantitative results for critical management questions, such as how much to invest in control effort, whether the economics support pursuing an eradication strategy, and whether it is more cost-effective to strive for containment or slow the spread of an infestation. Some of the spatially implicit models most applicable to informing *Bromus* management are described in Sect. 15.3.

A spatially explicit modeling approach is necessary when a problem requires determining precisely which combination of specific locations is optimal for applications of controls to minimize the costs of exotic annual invasive grass spread. Models that use spatially explicit methods to account for spatial interdependencies generally reduce computational challenges by making simplifying assumptions about the underlying ecological and economic processes (Epanchin-Niell and Hastings 2010). They nonetheless provide important guidance about where, when, and how much to apply controls across heterogeneous landscapes—guidance that often cannot come from intuition or experience alone. For example, Cacho et al. (2010)

and Cacho and Hester (2011) use simulation models to compare decision heuristics about where to search for and control a reproducing and dispersing weed to minimize the area of the weed's spread, subject to an effort constraint. Their spatial-dynamic model showed, for a hypothetical weed invasion, how cost-effective search strategies change in response to increases in annual budgets: as budgets increase, strategies shift first to sampling sites more intensively, then to increasing the duration of the control program, and finally to applying repeat control treatments to found infestations.

Epanchin-Niell and Wilen (2012) develop a model of invasion spread that accounts for how positioning controls at alternative locations affects invasion spread across a landscape and identify optimal spatial-dynamic strategies for controlling invasions. They applied their model to various hypothetical invasions and showed how long-term invasion costs and damages can be reduced by limiting the length of the spreading invasion front through control or strategic use of landscape features, such as by directing the invasion toward mountain ranges or rivers that act as natural barriers. The study also showed that for certain combinations of control costs, damages, and initial invasion conditions, it is optimal to spatially target controls to slow or prevent the spread of an invasion toward high-value resources. In addition to deriving general spatial control strategies that could be applied to managing *Bromus* spread, the spatially explicit modeling approach developed by Epanchin-Niell and Wilen (2012) could be adapted and parameterized to identify the locations, timing, and amount of resources to cost-effectively manage the spread of exotic invasive annual grasses in specific contexts.

### *15.5.3 Coordination of Exotic Annual Invasive Grass Management*

Management outcomes may depend on the actions and incentives of multiple decision-makers in cases where invasions can spread spatially across property, political, and jurisdictional boundaries (Epanchin-Niell et al. 2010; Epanchin-Niell and Wilen 2015). Decisions regarding rangeland restoration, stocking rates, and fuels management at one location can affect the spread of fire or exotic annual invasive grasses to neighboring locations. However, if managers consider the benefits of their management decisions for reducing fire risk or enhancing forage values only on their own property, they generally underinvest in management relative to what is best for society. Several studies have quantified the often large spatial externalities that arise when decision-makers do not fully include all effects of their exotic invasive species management decisions on others (Bhat et al. 1996; Jones et al. 2000; Wilen 2007; Epanchin-Niell and Wilen 2015; Fenichel et al. 2014).

A few studies model how spatial coordination among private managers and public land managers improves exotic invasive species management outcomes through incorporating more comprehensive considerations of costs and damages, increasing efficacy by reducing the rates of local reinvasion, and inducing control by a wider set of managers (Wilen 2007; Fenichel et al. 2014; Epanchin-Niell and Wilen 2015). Some studies consider spatial coordination simply in terms of the timing of management actions across space to improve outcome efficacy by reducing reinvasion; others consider ways in which targeted transfers of management resources across jurisdictional boundaries increase total landscape-level benefits. For example, Epanchin-Niell and Wilen (2015) model the spread of a hypothetical invasive species across a landscape with many managers and compare outcomes in cases where each manager chooses how much to control the invasion on his or her own property, based on individual benefits and costs, versus a coordinated strategy in which landowners farther from the invasion may contribute resources to invasion control to prevent spread onto their properties. The study finds that even highly localized coordination among small groups of landowners can provide large economic benefits relative to independent management, such that strategies that enhance coordination may have large social payoffs. Strategies that could encourage such coordination and improve landscape-wide management of exotic invasive plants include creating weed management areas or similar institutions that facilitate communication among landowners and reduce the transaction costs of coordination, as well as making the distribution of control incentives (e.g., cost-sharing programs) contingent on local coordination of management efforts (Epanchin-Niell et al. 2010; Epanchin-Niell and Wilen 2015).

The magnitude of benefits of coordinated management can be affected by the strength of spatial interdependencies across properties. Taylor et al. (2013b) find that homeowners' wildfire risk is determined in part by their neighbors' decisions to create defensible space on their properties in pinyon-juniper woodland, sagebrush shrublands, and alpine forest communities but not in *Bromus*-dominated grassland communities in Nevada. This result suggests that spatial interdependencies and coordination among neighboring decision-makers related to wildfire are likely to be more important on rangelands where pinyon-juniper or sagebrush is the dominant vegetation than on rangeland dominated by exotic annual invasive grasses. However, this may depend on the specific management actions considered (e.g., restoration, firebreaks, weed control, defensible space creation).

## 15.6 Management Implications

The bio-economic models reviewed in this chapter have numerous implications for *Bromus* management, in two respects. First, the results from studies that quantify the economic benefits from *Bromus* management can inform where and how to direct management resources to achieve the greatest economic benefit given limited funds for management. Second, the bio-economic models developed in some studies can be used to improve the design of programs and policies that encourage socially efficient management of *Bromus* by ranchers and other private land managers. As we discuss above, bio-economic models are unique in their ability to analyze how private decision-makers are likely to adjust their management in response to counterfactual changes in policy and to evaluate how these changes in management will affect the prevalence of *Bromus* and other management outcomes.

Before proceeding, it is worth emphasizing that the bio-economic models reviewed in this chapter have implications for *Bromus* management, even though none were expressly constructed to be used as management tools. An important takeaway from this chapter is that economic studies do not have to be expressly constructed as management tools to produce insights and information that are useful for *Bromus* management.

### *15.6.1 Economically Efficient* **Bromus** *Management*

Existing studies suggest strategies for managing *Bromus* on the landscape to achieve the greatest economic benefit given limited funds for management:

- Research into the long-term benefits and costs of treating *Bromus* on sagebrush rangelands has found benefit–cost ratios of 13 to 1 for preventing rangelands with intact native perennial grass cover from becoming *Bromus* dominated. However, low success rates for rehabilitation treatments cause the expected benefits of rehabilitating lands dominated by *Bromus* to be less than the costs of treatment (Taylor et al. 2013a).
- Taylor et al. (2013a) find that on sagebrush rangelands, the benefits of rehabilitation treatments on land dominated by *Bromus* outweigh the costs of treatment for success rates of 52 % or higher when treatment costs of $165 per acre (2010 dollars) are assumed. This result implies that the rehabilitation treatments will become cost-effective if success rates improve and/or costs decline relative to current levels.
- Epanchin-Niell et al. (2009) find that postfire revegetation treatments on sagebrush shrubland sites that lack the necessary perennial grasses and forbs to recover but have not transitioned to *Bromus*-dominated states can reduce long-term management costs while providing biodiversity benefits. For example, postfire revegetation treatments can reduce fire suppression costs by greater than the cost of treatment.
- Current funding levels from federal land management agencies for post-wildfire restoration are insufficient to reverse the continued transition of rangelands in the Western United States across thresholds to exotic annual invasive grass-dominated states (Epanchin-Niell et al. 2009).
- Kobayashi et al. (2010) find that the general public in Nevada has a higher willingness to pay for preventing conversion of rangelands that are currently dominated by native perennial grass and sagebrush to *Bromus*-dominated states than for rehabilitating lands that are currently in *Bromus*-dominated states. This result suggests that over time, as more rangeland transitions to *Bromus*-dominated states, public support for *Bromus* management could decline.

### 15.6.2 Roles for Incentives and Coordination to Enhance Management

Existing studies suggest how to design public programs and policies to better align private land managers' incentives for *Bromus* management with social goals:

- Kobayashi et al. (2014) find that ranchers operating on rangeland dominated by native perennial grasses and sagebrush have a private incentive to maintain rangeland health through herd management and rehabilitation treatments and that policies to improve the success rates of rehabilitation treatments and lower treatment costs lead to larger herd sizes, more acres receiving treatment, and higher ranch profits but do not affect the long-run ecological condition of the ranch. Conversely, for ranchers operating on rangeland dominated by exotic annual invasive grasses, Kobayashi et al. (2014) find that while it is not optimal for private ranchers to perform rehabilitation treatments, improved success rates or reduced costs could lead them to undertake rehabilitation treatments and that such treatments will improve the long-run ecological health and economic viability of the ranch.
- Kobayashi et al. (2014) demonstrate that market forces, such as high cattle prices, may cause ranchers to place short-term economic gain ahead of the long-run ecological health of their ranches. In particular, high cattle prices may cause ranchers to increase stocking rates, which raises the likelihood that land on the ranch will cross an irreversible ecological threshold to an exotic annual invasive grass-dominated state in the event of a disturbance such as wildfire. This result suggests that in periods of high cattle prices, grazing policies and allotment management plans need to be strictly enforced on public lands to prevent the potential for ecological damage through inappropriate grazing.
- Taylor et al. (2013a) show that uncertainty about whether a sagebrush rangeland ecosystem has crossed an ecological threshold between an ecological state dominated by native perennial grasses and sagebrush and a decadent sagebrush state that will transition to a *Bromus*-dominated state after a disturbance (e.g., wildfire, drought) lowers the expected economic benefits from treatment. This suggests that there may be significant economic benefits to extension and outreach programs that improves the accuracy of land managers' assessments of whether their *Bromus*-affected rangeland has crossed a threshold between ecological states before undertaking *Bromus* treatments.
- Epanchin-Niell and Wilen (2015) demonstrate that coordination of exotic invasive management activities across locations can improve expected outcomes. Public policy can improve the coordination of *Bromus* management across locations by (1) reducing transaction costs of coordinating work across districts, jurisdictions, and agencies; (2) creating and supporting institutions, such as weed management areas, that lower barriers to coordination; and (3) making funds for *Bromus* management contingent on coordination efforts.

## 15.7 Research Needs

This final section of the chapter discusses areas where further research into the economics of *Bromus* is needed. The research needs are divided into two categories: research that relaxes the economic modeling assumptions made in previous studies to better capture land managers' decision-making regarding *Bromus* and research that considers economic features of the *Bromus* management problem that have not previously been analyzed. Despite the growing literature on the economics of exotic invasive plants, relatively few studies have focused specifically on *Bromus*. Targeted studies are needed because, as discussed above, aspects of *Bromus* invasion—such as the fact that eradication is not a realistic management outcome on most invaded sites—are not shared by many of the other invasive plants analyzed in the previous economics literature.

To ensure that future research into the economics of *Bromus* management is of practical value to land managers, policy-makers, and other stakeholders, economists must continue to coordinate their work with rangeland ecologists and other scientists engaged in *Bromus* research, as well as with ranchers, public land managers, and others involved in on-the-ground *Bromus* management. Input from these various sources is vital to ensuring that the complex ecology of *Bromus* invasion is accurately captured in future economic models and that future economic analysis focuses on timely and relevant *Bromus* management issues.

### *15.7.1 Research Needs: Modeling Assumptions*

Further research is needed that relaxes the modeling assumptions made in previous economic studies of *Bromus* management to better capture land managers' decision-making:

- Further research is needed into how land managers' attitudes toward risk influence their decision-making regarding *Bromus* management. Attitudes toward risk are likely to be relevant because managers must balance the upfront costs of management against uncertain future benefits. Further research could explore whether conventional analysis of decision-making under risk based on expected utility theory can explain observed *Bromus* management, as well as the relevance of concepts such as probability weighting and loss aversion emphasized in prospect theory (Kahneman and Tversky 1979).
- Further research is needed that analyzes the decision-making of land managers who have imperfect knowledge of the ecology of *Bromus* and the consequences of management actions to control *Bromus*, to shed light on the extent to which limited knowledge explains observed management (or lack thereof) of *Bromus* on western rangelands.

- Further work is needed that compares the performance of ranch-level models that assume profit maximization and perfect foresight (all the studies reviewed in this chapter, apart from Janssen et al. 2004, make these assumptions) against models that assume alternative decision-making criteria. As Janssen et al. (2004) have argued, given the complex ecology of *Bromus* invasion and uncertainty inherent in *Bromus* management, assuming that ranchers follow a decision heuristic, or rule of thumb, may provide a more realistic description of rancher decision-making than assuming perfect foresight and profit maximization. In addition, previous research has found that ranchers receive compensation from ranching in the form of "consumptive amenities" related to the "ranching lifestyle" (Torell et al. 2005). Evidence of these consumptive amenities suggests that ranchers are motivated by more than solely maximizing profits.

### *15.7.2 Research Needs: Management Issues*

Further research is needed that considers economic features of the *Bromus* management problem that have not yet been analyzed:

- Economic analyses of the benefits and costs of *Bromus* management have focused primarily on the benefits of management in terms of wildfire suppression cost savings (Epanchin-Niell et al. 2009; Taylor et al. 2013a). A full accounting of the benefits and costs of *Bromus* management requires further research to quantify how the economic value of wildlife habitat, forage for livestock, recreation opportunities, erosion control, and other ecosystem goods and services are influenced by *Bromus* invasion.
- Epanchin-Niell et al. (2009) consider how the level of funding for post-wildfire restoration affects the expected amount of land that will cross ecological thresholds to exotic annual invasive plant-dominated states. Further research is needed that explores the relationship between funding for *Bromus* management and long-run ecological conditions on sagebrush rangelands affected by *Bromus*.
- Although existing studies have analyzed the benefits and costs of pre-fire rehabilitation treatments (e.g., Taylor et al. 2013a) and postfire restoration treatments (e.g., Epanchin-Niell et al. 2009) for *Bromus* management, no previous study has jointly analyzed both management options. Such analysis is needed to enhance understanding of the economic trade-offs and complementarities between the two options, given limited public funds for *Bromus* management.
- To date, economic models of *Bromus* management have not accounted for spatial interdependencies related to the *Bromus* propagation and the spatial spread of wildfire. Further research is needed that accounts for these interdependencies to inform how management options, such as rehabilitation, fuel treatments, and firebreaks, can be most cost-effectively located on the landscape to protect natural resources. Further research also is needed to explore how land managers' decision-making is influenced by *Bromus* management on adjacent land, and

whether strategic interactions between neighboring decision-makers can result in inefficiently low levels of *Bromus* management from a societal perspective. Taylor et al. (2013b) find that homeowners' decisions to invest in mitigating wildfire risk on their property are determined in part by their neighbors' wildfire risk mitigation investment decisions in pinyon-juniper woodland, sagebrush, and alpine forest communities but not in grassland communities. This result suggests that spatial interdependencies between neighboring decision-makers related to wildfire are likely to be important on rangelands where pinyon-juniper or sagebrush is the dominant vegetation and *Bromus* is a component of the understory, rather than on *Bromus*-dominated rangeland.

- It has been suggested that land managers adopt "adaptive management" to effectively manage *Bromus*, given the uncertainty inherent in *Bromus* invasions and management (Morghan et al. 2006). Adaptive management involves deliberate learning-by-doing by land managers to compare the effectiveness of alternative *Bromus* management strategies. Although learning models (Camerer and Ho 1999; Hanaki et al. 2005) have been applied to the problem of managing exotic invasive plants (e.g., Eiswerth and van Kooten 2007), further economic research is needed to analyze the economic benefits of adaptive management for *Bromus* and to design programs and policies to encourage adaptive management.
- As discussed in the previous section, the bio-economic models of *Bromus* management reviewed in this chapter were not constructed expressly to inform on-the-ground management. Rather, they were constructed to analyze and better understand a complex problem that involves capturing the incentives and constraints faced by decision-makers managing *Bromus*, while taking into account the complex ecological features of *Bromus* (e.g., dynamics, ecological thresholds, and spatial considerations). An important goal of future research is to tailor and refine these bio-economic models so that they are better suited to provide decision support for land managers deciding how to deal with *Bromus* on their land.

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