Human–Wildlife Interactions 6(1):12–29, Spring 2012

Unintended consequences of bovine brucellosis management on demand for elk hunting in northwestern Wyoming

Mandy E. Kauffman,[1] Department of Agricultural and Applied Economics, University of Wyoming, 1000 E. University Avenue, Laramie, WY 82070, USA *mkauffma@uwyo.edu*

Benjamin S. Rashford, Department of Agricultural and Applied Economics, University of Wyoming, 1000 E. University Avenue, Laramie, WY 82070, USA

Dannele E. Peck, Department of Agricultural and Applied Economics, University of Wyoming, 1000 E. University Avenue, Laramie, WY 82070, USA

Abstract: Management strategies proposed to mitigate the risk of brucellosis transmission between elk and cattle (e.g., test-and-slaughter of all elk, elimination of feedgrounds, use of contraceptives) could result in a substantial decrease in elk (*Cervus elaphus nelsoni*) populations. These strategies could impact hunting and outfitting industries through reduced regional elk populations. Loss of hunters, particularly nonresidents, could result in economic losses for the state and hinder elk management. We estimated 2 empirical models using panel data from multiple hunt areas to determine effects of elk population changes on demand for elk hunting licenses in northwest Wyoming. First, we used a fixed-effects logit model to estimate elk hunter success by hunt area as a function of elk density and other characteristics. Second, we estimated demand for elk licenses as a function of license and hunt area characteristics, including hunter success rates and elk populations. With the resulting equation system, we predicted the effects of reduced elk populations on hunter success and elk license demand. Elk population positively affects hunter success and license demand. On average, model results predict that each 10% reduction in elk population would cause a 3.5% decrease in resident elk hunting applicants and a 0.4 to 1.4% decrease in nonresident applicants. In the 7 elk-herd units affected by feedground management, a 50% decrease in elk population could decrease annual license revenues by $83,000 and annual regional expenditures associated with elk hunting by $520,000. These costs should be weighed against potential benefits of brucellosis management, including reduced feedground management costs and reduced costs to cattle producers of brucellosis prevention activities.

Key words: brucellosis, demand, elk, feedgrounds, human–wildlife conflicts, hunting, outfitters

By the early 1900s, much of the elk (*Cervus elaphus nelsoni*) winter range in the Greater Yellowstone National Park area (GYA) had been developed for agricultural and residential uses. Lack of hunting pressure combined with a series of mild winters led to increased elk populations. Subsequent harsh winters revealed insufficient winter range, and, consequently, large numbers of elk starved while attempting to depredate private haystacks (see Thorne and Herriges 1992). Ultimately, the concern for elk populations and the need to prevent depredation of livestock hay stores led to the creation and maintenance of 23 supplemental winter feedgrounds in Wyoming (Leek 1911, Preble 1911, Dean et al. 2004). Elk are fed hay or pelleted alfalfa at feedgrounds during the winter months to deter them from accessing private property, depredating private haystacks, and commingling with cattle. During 2006 in Wyoming, 23,000 elk, roughly 73 to 84% of the surrounding area's elk population, overwintered on feedgrounds (Maichak et al. 2009, Wyoming Game and Fish Department [WGFD] 2009).

Feedgrounds have successfully reduced elk depredation of private haystacks; however, they are costly to operate and increase the potential for disease transmission within and among large, dense elk herds (Thorne 2001, Bienen and Tabor 2006). The high concentration of elk on feedgrounds has likely contributed to the persistence of bovine brucellosis (caused by the bacteria *Brucella abortus*) in the GYA. Infection with *B. abortus* typically causes elk to abort (see Thorne et al. 1978). Although cow elk typically seclude themselves during normal parturition (see Murie et al. 1951), abortions can occur on or near feedlines during late winter or

[1] Current address: Department of Veterinary Sciences, University of Wyoming, Wyoming State Veterinary Laboratory, 1174 Snowy Range Road, Laramie, WY 82070, USA

early spring. The high concentration of elk on feedlines makes contact with abortive materials extremely likely (Cook 1999, Maichak et al. 2009). Reproductive material from an abortive event is directly infectious (see Nicoletti 1980) and may also pose an indirect risk of infection by contaminating the environment for an extended time period. A susceptible animal can, therefore, be exposed by licking, sniffing, or ingesting aborted materials (Cook 1999, Maichak et al. 2009).

The GYA is the only location in the United States where *Brucella abortus* occurs in free-ranging wildlife populations (*Brucella suis* is present in free-ranging feral swine; see Olsen 2010). Among elk wintering on feedgrounds, average seroprevalence (i.e., the proportion of animals with detectable antibodies to the bacteria, although not necessarily actively infected) for brucellosis is 22%, while seroprevalence in nonfeedground GYA elk averages 3.7% (Scurlock and Edwards 2010). While the dense elk populations on feedgrounds have historically been blamed for the persistence of high levels of brucellosis in wild elk populations (see Thorne et al. 1979), increasing seroprevalance is being observed in nearby areas not influenced by feedgrounds (Scurlock and Edwards 2010) but with increasing population size and conditions similar to those on feedgrounds (see Cross et al. 2010).

Brucellosis in GYA elk poses a substantial risk to cattle in the area. Cattle likely face the highest risk of exposure when they graze on feedground sites in spring and early summer. Infected elk may also abort on private land and public grazing allotments surrounding feedgrounds, areas in which cattle often are present during spring (Thorne 2001). If cattle contract brucellosis, individual cattle producers and the state livestock industry are financially impacted due to federal policies to control and eradicate the disease. Estimates of lost livestock sales from a 2004 outbreak range from $3.5 to $27 million (Bittner 2004). Additional brucellosis cases in cattle have occurred since 2004.

Given the economic implications of brucellosis, the search for effective means to control and eradicate it in elk continues. Vaccination for brucellosis in elk and bison (*Bison bison*) remains problematic, due, in part, to incomplete understanding of the species' immune systems (Davis and Elzer 2002). In lieu of effective vaccines for elk (Roffe et al. 2004), the WGFD initiated an experimental test-and-slaughter program in 2006. The pilot program, which concluded in 2010, trapped elk on select feedgrounds, tested adult female elk for antibodies against *B. abortus*, and culled all seropositive females (Figure 1). The program had some success in reducing brucellos seroprevalance in elk captured on selected feedgrounds (Scurlock 2010); however, the cost (>$1.2 million) and the politically unpopular nature of test-and-slaughter limits its suitability for use on a larger regional and temporal scale. Wyoming Game and Fish Department employs several other strategies to mitigate disease risk on feedgrounds, including spatial arrangement of feed (to reduce elk–elk contact), shortening of feeding season, vaccination of elk using strain 19 vaccine, and habitat improvement of elk winter range and reduce elk dependence on feedgrounds (Thorne 2001, Scurlock 2010).

Figure 1. Herd of trapped elk.

Several strategies have been considered for managing brucellosis in the GYA, ranging from doing nothing to removal and replacement of all elk and bison (see Thorne and Kreeger 2002). Many of these management strategies, including removal-and-replacement, test-and-slaughter, elimination of feedgrounds, and control of birth rates through contraception, would likely result in decreased elk populations. Reduced elk populations could, however, also impact the hunting and outfitting industries by reducing available elk tags and elk hunter success rates. These effects could drive elk hunters to seek alternative hunting locations (e.g., other areas of the state or other states entirely). Economic impacts of a decrease in hunter numbers could be significant for the state (see Bishop 2004). Wyoming Game and Fish Department sold >60,000 elk licenses in 2008, generating >$6 million in revenue (WGFD 2009). In 2008, only 17% of elk licenses were issued to nonresidents, but nonresident elk license fees accounted for 73% of elk license revenue (WGFD 2009). Wyoming Game and Fish Department estimates that, in addition to license fees, hunters spent >$38 million in 2008. The average economic gross return per harvested elk (in license fees and hunter expenditures) in 2008 was $1,858 (WGFD 2009).

The objective of this study is to empirically estimate the potential effect of brucellosis management strategies that reduce elk populations on demand for elk hunting in northwestern Wyoming. We estimate 2 econometric models to accomplish this objective: (1) elk hunter success and (2) demand for elk licenses. The first model examines the effect of elk populations on hunter success. The second model estimates the effect of hunter success and other explanatory variables (including elk population) on demand for elk licenses. This model system captures indirect (i.e., less demand due to reduced hunter success) and direct (i.e., less demand due to fewer expected elk encounters) effects of decreased elk population on elk license demand. These models are then used to simulate effects of reduced elk populations on demand for elk licenses.

Methods

Study area

The study area encompasses the area within Wyoming, east of Yellowstone National Park, to Sheridan, Wyoming, and south of the park to Interstate 80. The area includes 15 elk herd units, each of which contains 2 to 12 elk hunt areas. Hunting licenses are assigned at the hunt area level, which is also the level that harvest statistics and drawing odds are reported. The study area includes all 23 elk feedgrounds in Wyoming and would, therefore, most likely be affected by brucellosis management strategies. The study area also includes herd units to the east and south of the GYA that do not contain feedgrounds. These units provide additional data variation and represent an area with similar features but an absence of feedground influence. The study area comprised 104,000 square kilometers and supported 40,000 hunters in 2006 (WGFD 1994–2007).

Elk hunter success

Elk hunter success can be characterized as a binary outcome—the hunter is either successful (i.e., harvests an elk) or unsuccessful. Because data on individual hunters are not available, we developed an aggregate model of hunter success by hunt area. We used a logit transformation to ensure that the model's predictions of hunter success rates are constrained between 0 and 1 (i.e., success rate in a given hunt area and year must be between 0 and 100%; see Hosmer and Lemeshow 2000). The logit model of aggregate hunter success rates in hunt area j period t can be expressed as:

$$P_{jt} = \frac{TotalHarvest_{jt}}{TotalHunters_{jt}} = \frac{e^{\beta' X_{jt}}}{1+e^{\beta' X_{jt}}} \qquad (1)$$

where e is the exponential function, X_{jt} is a matrix of explanatory variables by location (j) and year, and β is a vector of parameters to be estimated.

We used 3 primary explanatory variables (X_{jt}) to specify (equation 1): elk density (*ELKDENS;* see Appendix for explanation of variables), number of wolves (*#WOLVES*), and percentage of hunters using a professional outfitter (%*OUT*; Table 1). We calculated elk density by dividing the herd unit population by the total area (km^2). *ELKDENS* scales elk population relative to the size of a herd unit. Elk populations were measured within the boundaries of elk herd units, which contained multiple hunt areas (the unit at which potential hunters select areas). Converting elk population to elk density allowed us to distribute the elk of a herd unit across the appropriate hunt areas, and, thus, better represents the likelihood of hunters encountering an elk. We used 1-year, lagged elk population data to derive elk density because elk are counted after the hunting season, and, thus, the number of animals available during a given hunting season is best reflected by the previous year's population estimate.

Table 1. Summary statistics for variables in the elk hunter success model.

Variable	Mean	Standard deviation	Minimum	Maximum
$TOTALHUNTERS_{jt}$	667.04	514.58	46.00	3,648.00
$TOTALHARVEST_{jt}$	215.95	160.37	4.00	1,183.00
$\mathrm{ELKDENS}_{jt}$	1.20	1.03	0.02	4.12
$ELKDENS^2_{jt}$	2.52	4.10	0.0004	17.01
$ELKDENS_{jt*}\%PUBLIC_{jt}$	0.98	1.15	0.03	4.12
$\#WOLVES_{jt}$	3.37	7.09	0.00	31.00
$\%OUT_{jt}$	0.06	0.09	0.00	0.87

Note: The subscript $_j$ in this case is used interchangeably for hunt area and herd units. See Appendix for explanation of variables.

We also used elk density to create 2 additional explanatory variables. First, we included elk density squared (*ELKDENS*²) to allow the marginal effect of additional elk density to change as the elk density increases (i.e., to allow for a nonlinear relationship between elk density and hunter success). Second, we interacted elk density with the percentage of public land in a hunt area (*ELKDENS* × *%PUBLIC*) to allow the marginal effect of additional elk density to vary with the level of hunter access to elk. Additional elk might not increase hunter success by as much if those elk can move to the relative safety of private lands. Note that elk populations (and, therefore, all variables involving elk densities) are measured at the herd unit level, which encompasses several hunt areas. Thus, our model may not capture the heterogeneity of elk distributions across the finer spatial scale of hunt areas.

We included the number of wolves within each herd unit (*#WOLVES*) to capture behavioral changes of elk that face heightened predation pressure (Creel et al. 2005, Creel and Winnie 2005). These behavioral changes may make elk more difficult to hunt and, therefore, affect hunter success. We used data on wolf-pack locations and number of wolves within each pack (U.S. Fish and Wildlife Service [USFWS], personal communication, 2009) to assign numbers of wolves to individual elk herd units over time.

Lastly, we included the percentage of hunters outfitted (*%OUT*) in each hunt area (Wyoming State Board of Outfitters and Professional Guides 1994–2007). The use of an outfitter may affect hunter success for many reasons, including both the outfitter's knowledge of local elk populations and habits, as well as their ability to use past experience to help identify areas in which hunter success rates are typically higher (see e.g., Schmidt et al. 2007). Outfitters might also facilitate access to private land where hunting pressure is lower. Thus, *%OUT* captures the outfitter effect—the expected increase in hunter success as a result of hunting with a professional guide.

Past research has shown that regional characteristics, such as road density (Cooper et al. 2002) and weather (Batastini 2005), can also influence hunter success. Data are not available, however, in the study region for these characteristics over time and area. We, therefore, used a 1-way, fixed-effects approach to control for unobserved heterogeneity in hunter success across hunt areas. Fixed effects may capture a number of factors that vary across hunt areas, such as percentage of wilderness area (representing differences in terrain and access) and presence or absence of grizzly bears (representing predation pressure or hunter anxiety).

Substituting the data described above into equation 1 resulted in the following final estimable model:

$$P_{jt} = \frac{e^{B_0+\sum_{j=1}^{66} B^j D_j + B_1 ELKDENS_{jt-1} + B_2 ELKDENS^2_{jt-1} + B_3 ELKDENS_{jt-1} * \%PUBLIC_{jt-1} + B_4 \#WOLVES_{jt} + B_5 \%OUT_{jt}}}{1+e^{B_0+\sum_{j=1}^{66} B^j D_j + B_1 ELKDENS_{jt-1} + B_2 ELKDENS^2_{jt-1} + B_3 ELKDENS_{jt-1} * \%PUBLIC_{jt-1} + B_4 \#WOLVES_{jt} + B_5 \%OUT_{jt}}} \quad (2)$$

The final dataset includes 858 observations across 66 hunt areas and 13 years (1994 to 2006). Prior to 1994, data on outfitted hunters were not available. In 2007, a preference points system was instituted in Wyoming. Due to the lack of multiple years of data on licenses assigned through the preference points system, our analysis was limited to 2006 and earlier. Lastly, we used SAS 9.2 (SAS 2008, Cary, N. C.) to estimate the model, and alpha ≤ 0.1 to judge statistical significance.

Marginal effects

Parameter estimates in the logit model are difficult to interpret directly because of the model's nonlinear functional form. We, therefore, calculated marginal effects by hunt area using area specific data averaged over time:

$$\frac{\partial Hunter\ Success}{\partial X_{jk}} = \frac{\partial F(\beta' X_{jk})}{\partial X_{jk}} P_j(1-P_j), \quad (3)$$

where $\frac{\partial F(\beta' X_{jk})}{\partial X_{jk}}$

is the derivative of the logit specification (equation 2) with respect to the variable of interest (X_{jt}) and is the predicted success rate in hunt area j (i.e., the proportion of hunters harvesting an elk given parameter estimates and hunt area characteristics). Marginal effects measure the predicted change in hunter success for a 1-unit change in an explanatory variable, holding all other variables constant. Note that marginal effects in this logit model differ across hunt areas, even though parameter estimates do not. This is because the marginal effects are a function of both parameter estimates and explanatory variables.

Demand for elk licenses

Some background information on how elk licenses are assigned is necessary for understanding our empirical model of elk license demand. Prior to 2007, when a preference points system was instituted, WGFD assigned Wyoming elk-hunting licenses at the hunt area level through a complex draw system (Figure 2). From an initial quota of licenses based on elk population estimates, management objectives, and predicted hunter success rates, 16% of licenses were assigned to nonresident hunters and 84% were assigned to resident hunters. Available licenses first passed through a draw for landowner licenses that comprised a sufficiently low proportion of licenses (3.5% of nonresident and resident licenses assigned in 2006), which we omit in this study.

In the case of residents, licenses remaining after the landowner draw were assigned to resident applicants through a random draw (resident regular elk [RRE]). In the case of nonresidents, licenses that remained after the landowner draw were assigned through either the nonresident regular elk (NRE) or nonresident special elk (NSE) draws. Applicants wishing to participate in the NSE draw paid approximately twice as much as the nonresident regular fee to be included in a separate draw. These licenses were drawn prior to the NRE draw, so NSE applicants had a higher probability of receiving a license.

Any unassigned licenses remaining after the nonresident draws were cycled back into the resident draw system. Applicants for licenses could indicate a first, second, and third choice hunt area. Draw odds were calculated as the number of permits available divided by the number of first choice applicants (applicants indicating the respective hunt area as their first choice). To remain consistent with this system of license assignment, we used the number of first choice applicants to represent demand for licenses in a given hunt area.

Elk-hunting licenses distributed during the study period were specified not only for resident and nonresident use, but also for other characteristics, including temporal (early or late season), spatial (portions of hunt areas), method (archery only), and age or sex (antlered only and any elk). We considered only licenses for any elk or antlered elk to capture hunters most likely to be pursuing trophy elk.

We modeled each draw type (NRE, NSE, and RRE) separately because: (1) attempts to pool draw types created an unwieldy panel within a panel data structure that precluded many common econometric techniques; and (2) licenses under each draw type are essentially separate goods because individuals were purchasing the right to enter different draws (Sun et al. 2005). Separate models also made it easier to examine potential differences among the 3 populations of hunters and license draw types.

When individual-level data are available, recreation demand models often focus on socioeconomic variables to characterize differences in demand between demographic groups (Loomis and Walsh 1997). Due to the aggregate nature of the data available for Wyoming hunters (e.g., draw odds at the hunt area level), it was not possible to analyze individual hunters' characteristics. We, therefore, modeled aggregate demand over time by hunt area and focused on explanatory variables believed to influence differences in demand across time and space (e.g., Sandrey et al. 1983, Nickerson 1990, Batastini 2005; Table 2).

To construct a usable panel data set for each draw type, we combined multiple licenses in a hunt area for a given year. Specifically, we summed the number of first choice applicants ($\#FIRSTCHOICEAPPS_{jt}$) across different licenses (i.e., antlered and any elk) for each hunt area to generate a measure of license demand. Letting j = 1,..,J denote hunt areas and t = 1,…,T denote time, the basic model for each draw type (NSE, NRE, RRE) is:

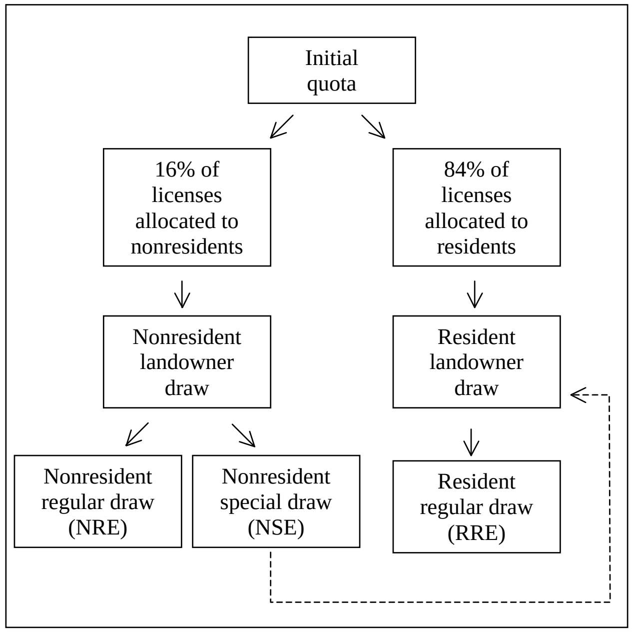

Figure 2. Wyoming elk license drawing system prior to 2007.

$$\begin{aligned}&\#FIRSTCHOICEAPPS_{jt}\\ &= \beta_0 + \beta_1 PERMITS_{jt} + \beta_2 ELKPOP_{jt} + \beta_3 ELKPOP_{jt-1} + \\ &\beta_4 BULL:SPIKE_{jt-1} + \beta_5 SUCCESS_{jt-1} + \beta_6 \#WOLVES_{j} \\ &\beta_7 OWNPRICE_{jt} + \beta_8 SUBPRICE_{jt} + \beta_9 \#INCOME_{jt} + \\ &\beta_{10} TREND_{jt} + \sum_{J=1}^{J-1} \beta_j D_j + \varepsilon_{jt}\end{aligned} \tag{4}$$

where βs are parameters to be estimated, and the remaining terms are explanatory variables, which are described below and summarized in Table 2.

We included the total number of permits available ($PERMITS_{jt}$) to capture potential congestion effects. Highly congested areas may be more or less desirable to applicants, depending on individual preferences (e.g., Heberlein et al. 1982, Frey et al. 2003), thereby influencing license demand. Availability of permits and knowledge of previous draw odds may offer insight into potential site congestion. Prospective hunters are able to see this information in their application packet prior to applying for a hunting license.

Wyoming Game and Fish Department calculated hunt area draw odds by dividing the number of licenses available by the number of first-choice applicants. Previous demand models of lottery-rationed licenses have included draw-odds as an explanatory variable (e.g., Scrogin et al. 2000). We used a weighted average of the lagged draw odds ($DRAWODDS_{jt}$-1), where the weights correspond to the proportion of total licenses available that each type comprises, as a measure of hunters' knowledge about their odds of drawing a license. Draw-odds may represent a variety of hunter perceptions. They could proxy for opportunity cost (i.e., applying in an area with low odds foregoes the opportunity to apply in an area with higher odds). Draw odds may also provide information about an area's desirability, and, thus, may be a measure of site quality. An area with very high draw-odds (close to 100%), for example, may indicate low applicant interest in that area, which may suggest that the area has undesirable features (e.g., small elk or poor access).

Measures of site quality often are used to characterize the desirability of a location or activity (Loomis and Walsh 1997). Because

Table 2. Summary statistics for variables in the elk license demand models.

Variable[a]	Mean	Standard deviation	Minimum	Maximum
Nonresident regular (NRE) model				
$\#FIRSTCHOICECAPPS_{jt}$	118.93	109.91	3.00	1,022.00
$PERMITS_{jt}$	17.34	20.23	1.00	168.00
$DRAWODDS_{jt-1}$	0.19	0.17	0.002	1.00
$ELKPOP_{jt-1}$	6,408.72	3,953.34	1,900.00	18,825.00
$BULL{:}SPIKE_{jt-1}$	5.94	4.65	1.17	27.68
$SUCCESS_{jt-1}$	0.41	0.14	0.14	0.92
$\#WOLVES_{jt-1}$	3.05	6.90	0.00	31.00
$OWNPRICE_{t}$	469.07	23.79	435.12	511.63
$SUBPRICE_{t}$	751.08	96.51	657.92	938.00
$INCOME_{t}$	72,728.72	3,230.91	66,414.85	76,601.29
Nonresident special (NSE) model				
$\#FIRSTCHOICECAPPS_{jt}$	43.94	34.76	0.00	222.00
$PERMITS_{jt}$	11.96	14.50	1.00	125.00
$DRAWODDS_{jt-1}$	0.35	0.27	0.01	1.00
$ELKPOP_{jt-1}$	6,459.71	3,984.10	1,900.00	18,825.00
$BULL{:}SPIKE_{jt-1}$	5.93	4.66	1.17	27.68
$SUCCESS_{jt-1}$	0.42	0.14	0.14	0.92
$\#WOLVES_{jt-1}$	3.05	6.90	0.00	31.00
$OWNPRICE_{t}$	750.60	96.26	657.92	938.00
$SUBPRICE_{t}$	468.86	23.87	435.12	511.63
$INCOME_{t}$	73,669.11	3,271.62	64,414.85	76,601.29
Resident regular (RRE) model				
$\#FIRSTCHOICECAPPS_{jt}$	285.97	219.97	0.00	1080.00
$PERMITS_{jt}$	149.84	161.91	3.00	1,302.00
$DRAWODDS_{jt-1}$	0.55	0.32	0.04	1.00
$ELKPOP_{jt-1}$	6,413.40	3,931.15	1,900.00	18,825.00
$BULL{:}SPIKE_{jt-1}$	5.92	4.64	1.17	27.68
$SUCCESS_{jt-1}$	0.41	0.14	0.14	0.92
$\#WOLVES_{jt-1}$	3.01	6.86	0.00	31.00
$OWNPRICE_{t}$	40.64	3.08	34.81	44.77
$INCOME_{t}$	73,663.94	3,277.16	66,514.85	76,601.29

[a]See Appendix for explanation of variable names.

spatial heterogeneity (i.e., differences across hunt areas) is the primary source of variability in our data, we used several measures of site quality. Lagged elk population ($ELKPOP_{jt}$-1) reflects the effect of elk population size on demand for licenses. We used lagged elk population because elk are counted after the hunting season, and, thus, last year's population best reflects game availability in the current hunting season. We also included the ratio of bull to spike elk (bull = male elk >2 years; spike = male elk <2 years) from the previous year ($BULL{:}SPIKE_{jt}$-1) to reflect perceived quality (presence or frequency of trophy bulls) in the local elk population (see Manfredo et al. 2004).

Locations with significant wolf activity may be less desirable to hunters because of fears of encountering wolves or a perception that wolves negatively impact the local elk population (Batastini 2005, WGFD 2007*a*). We, therefore, included the number of wolves in the herd unit during the previous year (*#WOLVESjt-1*) to capture their influences on perceived site quality. We used data on wolf-pack locations and the number of wolves within each pack (USFWS 2009) to assign numbers of wolves to elk herd units. All three of the aforementioned site-quality variables were measured at the herd-unit level, and, as such, multiple hunt areas within the same herd unit have the same values in a given year.

We used income (*INCOME*) in 2006 dollars to test the hypothesis that as income increases, people have more money to spend on recreational activities, such as hunting. We used the median income of the "fourth fifth" (U.S. Census Bureau 2010) of all races to remain consistent with previous findings that the $50,000 to $90,000 income bracket had the highest participation in hunting (USFWS 2006). Travel time and cost also often are used to gauge the expense an individual incurred while undertaking a recreational activity. However, such approaches require knowledge of both home location and specific travel site for a recreation participant (Loomis and Walsh 1997). These data were not available for Wyoming elk hunters; therefore, we did not consider travel time and cost in our demand model. In lieu of travel time and cost data, we used the price of an elk license for the relevant draw type ($OWNPRICE_{jt}$) in 2006 dollars to capture changes in hunting expenditures over time. We considered including average gasoline and outfitter prices by year, but they caused severe multicollinearity problems with other time-variant variables.

Recreation demand models also typically include the price of substitute goods, which in this case would be comparable recreational activities. If another site or activity becomes more desirable or less costly, individuals may choose the other site or activity (Loomis and Walsh 1997). Elk hunts in other states are possible substitutes for Wyoming elk hunters but were not considered in this analysis due to differences in licensing systems between states (e.g. specific licenses set aside for outfitters or use of preference points systems), which makes it difficult to identify data on substitute licenses. In lieu of better substitute goods data, we defined the substitute good as a different draw type for the same Wyoming elk hunt. In the nonresident models, the substitute price was, therefore, the price of a license through the alternate draw in 2006 dollars. For example, in the case of the NRE draw, the substitute price ($SUBPRICE_t$) is the price of an elk license through the NSE draw in year t, $SUBPRICE_t$ does not exist in the RRE model because there is only 1 resident draw type.

Lastly, we included time-trend and hunt-area dummy variables to control for other unobserved spatial and temporal heterogeneity. The time trend captures unobserved characteristics that consistently increase or decrease over time, such as population growth and changing attitudes toward hunting. By controlling for unobserved temporal factors, the trend should also improve the precision of parameter estimates for the other time-variant explanatory variables. Hunt-area dummy variables capture unobserved characteristics that differ among hunt areas (e.g., terrain, habitat quality, and access) and potentially influence demand, but adequate data were not readily available. These dummy variables imply that the demand model (equation 4) is a standard, fixed-effects model. F-tests of each draw type model indicate the fixed effects are significant (NRE, F-value = 16.93; NSE, F-value = 5.12; RRE, F-value = 28.53; $P \leq 0.01$), and, therefore, the fixed effects model is appropriate (Greene 1997).

We used the data described above to estimate the license demand model (equation 4) for each draw type (NRE, NSE, RRE). Variables for each draw type were identical except for the exclusion of a substitute price in the RRE model because there is no obvious substitute draw type for the resident regular elk license. We used data from 1994 to 2006 to be consistent with the hunter success model. The final models contain 450 observations for the NRE model, 449 observations for NSE, and 455 observations for RRE.

Simulating the effect of brucellosis management on elk license demand

For the final stage of our modeling effort, we simulated the effect of decreased elk populations (a plausible outcome of brucellosis management) on elk license demand. We investigated a gradient of elk population changes because no scientific study has estimated the potential effect of alternative brucellosis management strategies on elk populations in the GYA; informal predictions of the effects of feedground closure ranged from 10 to 50%. Additionally, seroprevalence on feedgrounds ranged from 9 to 42% (Scurlock and Edwards 2010); thus, a test-and-slaughter program that effectively removed all seropositive elk would also have impacts in the 10 to 50% range. Our simulation proceeds as follows:

1. assume a change in elk populations (e.g., 10% reduction from the average population in each herd unit);
2. use "new" elk population to calculate elk density in each hunt area; and
3. use parameter estimates and "new" elk density in equation 2 to predict hunter success by hunt area;
4. use "new" elk population and predicted hunter success in equation 4 to predict elk license demand by hunt area.

We repeated this process for each license draw type and elk population decreases of 10, 20, 30, 40, and 50% from the herd unit's average population over the study period. This range likely encompasses the effects of many of the proposed brucellosis management strategies. Within each draw type, we compared the average simulated number of applicants given decreased elk populations (the average was taken over all hunt areas in all years) to the average predicted number of applicants given no change in elk populations. We used average values as a starting point rather than a particular year to ensure the inclusion of more hunt areas and avoid the possibility of using a year with unrepresentative elk population data. We reported results as the percentage change in average applicants rather than the absolute change in number of applicants to facilitate interpretation and comparison across draw types.

Results

Elk hunter success

Results from the multivariable hunter success model are generally as expected (Table 3). The model fits the data well with a likelihood ratio test statistic of 21,474 (Pr > χ^2 = 0.0001; the likelihood ratio test compares a restricted intercept only model to the full estimated model). Significance of this test indicates rejection of the null hypothesis that all slope parameters equal zero. Because the success model uses aggregate measures of hunter success rather than individual observations, we cannot estimate the percentage of observations correctly predicted. Graphically, however, the model appears to accurately predict hunter success across space (data not shown). Most importantly, errors in prediction do not appear to be biased systematically.

Table 3. Parameter estimates for the elk hunter success model.

Variable[a]	Estimate[b]
INTERCEPT	-0.098**
$ELKDENS_{jt}$	0.117**
$ELKDENS_{jt}^2$	0.015***
$ELKDENS_{jt}$* $\%PUBLIC_{jt}$	-0.144**
$\%OUT_{jt}$	0.747***
$\#WOLVES_{jt}$	-0.004***

[a] See Appendix for explanation of variables' names.
[b] Because hunter success model is estimated with a logit model (see equation 4), parameter estimates generally cannot be interpreted without first converting them to marginal effects (see Table 4). The signs and statistical significance of parameter estimates are the same as those for the marginal effects.
* indicates $P \leq 0.10$; ** indicates $P \leq 0.05$; *** indicates $P \leq 0.01$.

Parameter estimates from the hunter success model indicate positive and significant associations to elk density ($P \leq 0.05$) and elk density squared ($P \leq 0.01$). The marginal effect of *ELKDENS* (Table 4) implies that a 1-unit increase in elk density (i.e., an increase of 1 elk/km^2) is associated with a 1% increase in hunter success. Using average hunter success across all hunt areas, a 1-unit increase in elk density in each hunt area and the associated 1% increase in odds of hunter success in each hunt area, implies an estimated 5 additional elk harvested within the entire study area. The proportion of hunters using an outfitter (*%OUT*) is also positively and significantly ($P \leq 0.01$) associated with hunter success. The marginal effect on

Table 4. Marginal effects (ME) for the hunter success model, as averaged over all hunt areas and years

Statistic	ME *ELKDENS*	ME *%OUT*	ME *#WOLVES*
Minimum	0.00027	0.09974	-0.00108
Maximum	0.03493	0.18669	-0.00058
Average	0.01171	0.16289	-0.00095
Variance	0.00013	0.00050	1.67689E-08

Table 5. Parameter estimates for the elk license demand models.

Variable	Nonresident regular (NRE)	Nonresident special (NSE)	Resident regular (RRE)
INTERCEPT	-71.798	85.331	-285.30
$PERMITS_{jt}$	2.447***	1.437***	0.539***
$DRAWODDS_{jt-1}$	-21.298**	-3.560	-121.176***
$ELKPOP_{jt-1}$	0.002*	0.0001	0.005**
$BULL:SPIKE_{jt-1}$	1.532***	0.844***	1.402
$SUCCESS_{jt-1}$	70.689***	11.700**	133.383***
$\#WOLVES_{jt-1}$	-0.058	0.230	-1.826***
$OWNPRICE_{t}$	-0.561***	-0.092***	-1.752*
$SUBPRICE_{t}$	0.145***	0.148***	na[a]
$INCOME_{t}$	0.004***	-0.001	0.006
$TREND_{t}$	-2.966**	0.384	3.592***

[a] Substitute price does not exist in the RRE model as there is no alternate license type.
* Indicates $P \leq 0.10$; ** indicates $P \leq 0.05$; *** indicates $P \leq 0.01$.

%OUT of 0.16 implies that a 1% increase in the proportion of hunters using an outfitter increases hunter success by 16%.

Results indicate negative and significant associations to $ELKDENS_{jt} \times \%PUBLIC_{jt}$ ($P \leq 0.05$) and to the number of wolves ($P \leq 0.01$). Though statistically significant, the marginal effect of wolves is relatively small. The estimated marginal effect indicates that 1 additional wolf in a herd unit is associated with a decrease in hunter success of <0.01%. Results also indicate that there is variability in hunter success across hunt areas. The fixed-effects estimates are largely significant (60 of 65 fixed effects are significant with $P \leq 0.05$) and vary considerably in sign and magnitude.

Demand for elk licenses

The elk license demand models fit the data well, with adjusted R^2 of 0.96, 0.92, and 0.96 for the NRE, NSE, and RRE models, respectively. Signs and significance of parameter estimates are generally consistent across license demand models (Table 5). *PERMITS* ($P < 0.01$) and *SUCCESSt-1* ($P \leq 0.01$ for NRE and RRE; $P \leq 0.05$ for NSE) are positively associated with demand for all 3 draw types. *ELKPOP* is positive for all 3 draw types, but significant for only NRE ($P \leq 0.1$) and RRE ($P \leq 0.05$). *BULLSPIKE* is positive for all 3 draw types, but significant ($P \leq 0.01$) only for NRE and NSE. *OWNPRICE* is negative and significant for all 3 draw types ($P \leq 0.01$ for NRE and NSE, $P \leq 0.1$ for RRE). *SUBPRICE* is positive and significant ($P \leq 0.01$) for both NRE and NSE draw types (no *SUBPRICE* in RRE model). *DRAWODDS* is negative for all draw types, but significant only for NRE ($P \leq 0.05$) and RRE ($P \leq 0.01$). *INCOME* is positive and significant for NRE ($P \leq 0.01$), negative and insignificant for NSE, and positive and insignificant for RRE. *#WOLVES* is negative and significant for RRE ($P \leq 0.01$), but is insignificant in both nonresident license demand models. *TREND* is negative and significant for NRE ($P \leq 0.05$), positive and insignificant for NSE, and positive and significant for RRE ($P \leq 0.01$). Of the 39 hunt-area fixed effects, 30 are significant in the NRE model, 22 are significant in the NSE model, and 26 are significant in the RRE model ($P \leq 0.10$).

Effect of brucellosis management on elk license demand

Simulations of reductions in elk populations indicate a range of impacts to license demand and differences in hunter response across license types (Table 6). For all license types, applicants decreased systematically for larger decreases in elk populations. Smallest decreases in license demand are predicted in the NSE model with <2% reduction in demand (9 applicants) given a 50% decrease in area elk populations. Resident hunters (RRE) were most responsive, with

Table 6. Percentage change in average predicted applicants (decrease in average predicted applicants) within feedground hunt areas[b] due to alternative percentage decreases in elk populations resulting from feedground closure.

	Average applicants (1994–2006)	Elk population				
		10% decrease	20% decrease	30% decrease	40% decrease	50% decrease
NRE[a]	1,561	-1.4% (-22)	-2.9% (-45)	-4.2% (-66)	-5.7% (-87)	-7.0% (-109)
NSE	510	-0.4% (-2)	-0.7% (-4)	-1.1% (-6)	-1.4% (-7)	-1.7% (-9)
RRE	2,918	-3.5% (-102)	-7.1% (-207)	-10.7% (-312)	-14.2% (-414)	-17.7% (-516)

[a] NRE = nonresident regular elk license; NSE = nonresident special elk license; RRE = resident regular elk license.
[b] 27 hunt areas within 7 herd units.

applicants falling 3.5 to 17.7% as elk populations are decreased by 10 to 50%.

Discussion

Elk hunter success

Elk density (*ELKDENS*) is positively associated with hunter success, which is consistent with expectations that a hunter in an area with higher elk density, and, hence, a better chance of encountering elk, is more likely to be successful. This is consistent with findings of Reardon et al. (1978) and Cooper et al. (2002) who both document positive associations between big game density and hunter success. The coefficient on *ELKDENS2* also is positive, suggesting that hunter success increases at an increasing rate with elk density. Although one might eventually expect diminishing marginal returns to elk density, this might occur at densities much higher than those observed in the study data.

The positive association between hunter success and the proportion of outfitted hunters (*%OUT*) reflects the outfitter effect: hunters with an outfitter increase their chances of successfully harvesting an animal. This result is consistent with past literature on a variety of big game species that indicates positive effects (i.e., greater harvest success and trophy quality) for hunters using professional guides (e.g., Schmidt et al. 2007). Prospective hunters would certainly expect this result, otherwise, they might pay an outfitter much less for their services. Additionally, the positive effect of outfitters suggests that increasing the proportion of outfitted hunters (e.g., by issuing more nonresident licenses) may be a means of increasing harvest and meeting elk population objectives in overpopulated hunt areas. It also suggests that 1 response of hunters to lower populations could be to hire an outfitter and, thereby, offset some of the negative effects on harvest success of population decreases.

The negative association between hunter success and wolf populations may reflect elk behavioral changes. Elk alter their behavior in response to predation pressure by moving into more timbered areas and breaking into smaller groups (Creel et al. 2005, Creel and Winnie 2005). These behavioral changes may make elk more difficult for hunters to successfully harvest. More research is needed, however, to parse the varied effects of wolves, terrain, and other factors, on hunter success.

Demand for elk licenses

The 3 elk license-demand models generally match our *a priori* expectations for hunter behavior. Demand for licenses through each draw type is positively associated with the number of permits available, suggesting that hunters perceive permit availability as an indicator of elk availability. The previous year's total hunter success rate (*SUCCESS*) also positively influences demand for licenses through each draw type. This is consistent with findings from other studies that have identified a positive association between previous harvest or hunter success and demand for hunts (see Miller and Hay 1981, Nickerson 1990, Brown and Connelly 1994, Buschena et al. 2001) and indicates that hunters prefer areas where they are more likely to be successful.

The effects of license prices (*OWNPRICE*) are also consistent with economic theory and findings of other studies (see Sun et al. 2005, Poudyal et al. 2008). Increases in license prices decreases the number of applicants (i.e., license demand is downward sloping). Additionally, nonresidents respond predictably to the price of substitutes (i.e., when the price of nonresident special licenses increase, applicants substitute to the nonresident regular license).

The previous year's draw-odds negatively influence demand for licenses through all 3 draw types, although the effect is insignificant for NSE applicants. Draw-odds may reflect the desirability of hunting particular areas through revealed preferences of other hunters. Other studies have also found that hunters prefer longshots (i.e., areas with low draw odds; Scrogin et al. 2000). Thus, as draw-odds increase, approaching certainty of drawing a license, the associated perception of how desirable the area is may decrease. Low draw-odds may also represent areas with fewer licenses available per potential hunter and, therefore, less opportunity for undesirably high hunter densities (Boxall 1994).

Demand for licenses through all draw types was positively influenced by elk population, which is consistent with findings from other studies that identified positive associations between measures of animal abundance and demand for hunts (Miller 1982, Boxall 1994). The effect of elk population is insignificant, however, for NSE applicants. Hunters applying through the NSE draw are likely to hunt with an outfitter, and may, therefore, be less sensitive than other hunters to small changes in elk population. Additionally, NSE applicants may be more likely than NRE applicants to apply for licenses in areas with high elk populations because they can afford the higher cost of outfitted hunts in these particularly desirable areas. This self-selection among NSE applicants is reflected in lower relative variability of elk populations in the areas targeted by these hunters.

The ratio of mature bulls to young bulls (*BULL:SPIKE*) in the population positively influences demand for licenses through all 3 draw types, which is consistent with the idea that hunters prefer areas with higher quality trophies. Scrogin et al. (2000) found a positive association between the number of bulls and the demand for elk licenses. Buschena et al. (2001) identified a positive association between measures of bull quality (e.g., bull:cow ratio, number of recent Boone and Crockett scoring bulls harvested) and value of elk hunts. Hunters applying through the NSE draw were quite sensitive to *BULL:SPIKE*. This is consistent with our belief that hunters applying through the NSE draw are willing to pay more for the opportunity to hunt elk; they demonstrate this willingness by paying almost double the regular fee to enter the NSE draw) and are, therefore, more likely to be pursuing trophy bulls.

Our results indicate that wolves (*#WOLVES*) have a negative influence on demand for resident licenses, but no statistically significant effect on the demand for nonresident licenses. The latter may stem from the likelihood of nonresidents being outfitted and, hence, being less sensitive to the effects of wolves on elk behavior. When compared to the nonresident models, it appears that resident hunters may be more sensitive to the actual or perceived effects of wolves, perhaps because they can more easily substitute to other areas (both based on their license types and knowledge of the region). This is consistent with findings of Batastini (2005) that some general license hunters may avoid areas with wolves. It might also suggest that the effect of wolves on elk population is largely captured through the elk population variable. Cow:calf ratios have declined in the 8 herd units occupied by wolves, as well as in other herd units not occupied by wolves. Four of the elk herd units with wolves have experienced sufficient enough declines that the populations are no longer a stable population and cannot support hunting and in some cases (WGFD 2007*a*). Such drastic population effects are likely to redistribute resident hunters to other hunt areas. Alternatively, the number of wolves may simply be picking up attractive hunt area attributes, such as wilderness, remoteness, or proximity to Yellowstone National Park.

Income has the positive effect expected in the NRE model (see Floyd and Lee 2002, Poudyal et al. 2008), but is insignificant in the NSE and RRE models. This could reflect that hunters applying through the special draw (NSE), which is twice as expensive as the regular draw, are wealthy enough not to be affected by changes in income. Alternatively, the measure of income used in this model (median income of the fourth fifth of all races) may not reflect the appropriate income category or pattern of income variability through time for this subset of hunters. The insignificance of income in the resident regular model likely reflects the relatively low price of resident elk licenses, which averaged $41 over the study period.

Hunt-area dummy variables ranged in size, with >50% of these fixed effects significant in all 3 of the models. These variables are likely picking up hunt-area characteristics, such as access and suitable habitat (see Buschena et al. 2001, Poudyal et al. 2008) that affect demand for elk licenses and are not captured by our other explanatory variables. The significance of fixed effects in our model demonstrates the importance of controlling for unobserved regional heterogeneity when attempting to correlate species and landscape characteristics to measures of hunting demand.

Effect of brucellosis management on elk license demand

Simulation results accounting for the direct (change in demand) and indirect (change in hunter success) effects of elk population changes indicate significant differences across applicants applying through each draw type. Resident hunters are most responsive to decreases in elk population, which may reflect their ease of relocating to other hunt areas, both within and outside the study area. Resident hunters are likely more familiar with potential hunting sites and might therefore be more willing to transfer their hunting experience to another site. Alternately, potential resident hunters may choose not to participate in hunting at all if they perceive insufficient elk populations. Nonresident hunters, in contrast, may simply wish to experience an elk hunt even if the probability of success is relatively low (see Manfredo et al. 2004).

Nonresident special elk license applicants are least responsive to changes in elk population. This is consistent with our expectation that hunters applying through the NSE draw are less likely to be affected by changes in elk population size. These hunters are likely to be outfitted and might perceive that the outfitter effect should mitigate changes in elk populations. Additionally, their use of a particular outfitter (perhaps the same one used in the past and to whom they feel some loyalty) might limit their choice to the few specific areas in which the outfitter operates.

Nonresident regular elk applicants' responses to decreased elk populations fall somewhere in between the 2 other groups. Perhaps NRE applicants are less likely than the NSE applicants to hunt with an outfitter, in which case, they are less rigidly bound to a subset of hunt areas in which their preferred outfitter operates. Nonresident regular elk applicants who participate in unguided hunts will not benefit from the expertise of a guide, and, therefore, should be more sensitive to changes in elk populations. Due to lack of familiarity with the area (assuming their participation in out-of-state elk hunts is relatively infrequent) we should expect NRE applicants to be less sensitive than RRE applicants to changes in elk population.

If we consider only hunt areas within the 7 herd units containing feedgrounds, we can estimate the potential loss of applicants to the 3 draw types from a change in elk populations (Table 6). If we assume that all applicants lost in response to decreasing elk populations would have drawn a license, the impacts reported in Table 6 are economically significant. In 2006, the price of a nonresident license was $881 through the NSE draw and $481 through the NRE draw. The price of a license through the RRE draw in 2006 was $43. In 2008, WGFD sold >60,000 elk licenses, which generated >$6 million in license revenues, and approximately 6.3 times that ($38 million) in other hunter expenditures (e.g., hiring guides, staying at local motels and lodges, purchasing food and other goods). If a 50% decrease in elk population occurred, the decrease in WGFD license revenue alone would be nearly $83,000. However, the loss of hunters would have ramifications beyond license revenue alone; losses to the region's economy could be much higher (6.3 × 83,000 = $520,000).

These losses to the hunting or outfitting industry and regional economies are small relative to the estimated $3.5 to $7 million in losses associated with a recent brucellosis outbreak (Bittner 2004). However, impacts to the hunting or outfitting industry could persist for many years. There is also no guarantee that reducing elk populations would result in a significant reduction of the risk of brucellosis transmission from elk to cattle (Xie and Horan 2009). Further epidemiological studies are needed to quantify the benefits of brucellosis management strategies. Findings from these epidemiological studies should be evaluated alongside estimates of management strategy costs (including unintended impacts to hunting or outfitting) to inform decisions regarding which, if any, management strategies should be implemented.

The results of our analysis indicate that different subgroups of hunters (nonresident regular elk license applicants, nonresident special elk license applicants, and resident regular elk license applicants) respond differently to elk population changes. A quantitative estimate of elk hunter motivations for choosing a hunt area when applying through the 3 draw types can help WGFD and other stakeholders better understand potential consequences brucellosis management strategies. Results of the analysis indicate that a change in brucellosis management could result in a considerable loss of applicants for Wyoming elk licenses. Elk population decreases would also last multiple years, which implies additive losses over time.

Nationwide, hunting participation for many wildlife species is declining. Measures of hunter recruitment and retention indicate that young hunters are not being recruited into hunting, and older hunters are no longer hunting due to time constraints and shifting priorities (Enck et al. 2000). Hunters who participate only sporadically in the sport are more likely to dissociate from hunting entirely, resulting in a loss to the hunting community (Enck et al. 1993). A decrease in active hunters reduces the ability of wildlife management agencies to manage wildlife populations and decreases revenues from license sales and excise taxes. This reduces funds available for myriad programs, including nongame or endangered species management and habitat improvement (Enck et al. 2000). A better understanding of the factors that influence demand for hunting may enable agencies to take proactive measures to recruit and retain hunters in the face of proposed brucellosis management strategies.

Regardless of adaptive management by WGFD, our results suggest that the impact of brucellosis management (that reduces elk populations) on hunting demand and the associated income of WGFD and rural communities could be significant. Our results may also be consistent for other factors affecting elk populations or density, such as displacement from energy development or changes in the predator community. Potential impacts on hunting demand should, therefore, be considered when policymakers debate alternative brucellosis policies, or other policies likely to affect elk populations.

Results of this analysis raise many additional questions. Future research could simulate changes in other variables included in our models to assess potential hunter response. For example, we assume that NSE applicants are pursuing trophy bulls, but it may be worthwhile to examine more closely their responses to elk quality measures, rather than quantity measures. Additionally, some brucellosis management strategies could have significant effects on elk demographics (e.g., test-and-slaughter removes only females), which could have differential effect on license demand. It might also be worthwhile to use information on elk seasonal ranges to develop finer scale spatial measures of the elk population data. Further, future analyses should attempt to construct price and quality measures for substitute hunting opportunities outside the study area and attempt to incorporate the dynamic system of license availability along with the newer preference points draw system.

Acknowledgments

We thank Wyoming Game and Fish Department (especially R. Rothwell, R. Schilowsky, A. Pelto, and J. Cole) for providing both data and explanations of WGFD policies. We also thank the U.S. Fish and Wildlife Service for providing wolf-pack location data. We thank A. Duckworth and J. Flagg at the Wyoming Outfitter and Guides Association for providing us with data on outfitted hunters in Wyoming. This research was funded by Wyoming Wildlife-Livestock Disease Research Partnership.

Literature cited

Batastini, J. 2005. The impact of wolves on the "market" for elk hunting in Montana: hunter adjustment and game agency response. Thesis, Montana State University, Bozeman, Montana, USA.

Bienen, L., and G. Tabor. 2006. Applying an ecosystem approach to brucellosis control: can an old conflict between wildlife and agriculture be successfully managed? Frontiers in Ecology and Environment 4:319–327.

Bishop, R. C. 2004. The economic impact of chronic wasting disease (CWD) in Wisconsin. Human Dimensions of Wildlife 9:181–192.

Bittner, A. 2004. An overview of the economic impacts associated with mandatory brucellosis testing in Wyoming cattle. Wyoming Department of Administration and Information, Economic Analysis Division, Cheyenne, Wyoming, USA.

Boxall, P. 1994. The economic value of lottery-rationed recreational hunting. Canadian Journal of Agricultural Economics 43:119–131.

Brown, T. L., and N. A. Connelly. 1994. Predicting demand for big game and small game hunting licenses: the New York experience. Wildlife Society Bulletin 22:172–178.

Buschena, D. E., T. L. Anderson, and J. L. Leonard. 2001. Valuing non-marketed goods: the case of elk permit lotteries. Journal of Environmental Economics and Management 41:33–43.

Cook, W. E. 1999. Brucellosis in elk: studies of epizootiology and control. Dissertation, University of Wyoming, Laramie, Wyoming, USA.

Cooper, A. B., J. C. Pinheiro, J. W. Unsworth, and R. Hilborn. 2002. Predicting hunter success rates from elk and hunter abundance, season structure, and habitat. Wildlife Society Bulletin 30:1068–1077.

Creel, S., and J. A. Winnie Jr. 2005. Responses of elk herd size to fine-scale spatial and temporal variation in the risk of predation by wolves. Animal Behaviour 69:1181–1189.

Creel, S., J. A. Winnie Jr., B. Maxwell, K. Hamlin, and M. Creel. 2005. Elk alter habitat selection as an antipredator response to wolves. Ecology 86:3387–3397.

Cross, P. C., E. K. Cole, A. P. Dobson, W. H. Edwards, K. L. Hamlin, G. Luikart, A. D. Middleton, B. M. Scurlock, and P. J. White. 2010. Probable causes of increasing brucellosis in free-ranging elk of the Greater Yellowstone Ecosystem. Ecological Applications 20:278–288.

Davis, D. S., and P. H. Elzer. 2002. Brucella vaccines in wildlife. Veterinary Microbiology 90:533–544.

Dean, R., M. Gocke, B. Holz, S. Kilpatrick, T. Kreeger, B. Scurlock, S. Smith, E. T. Thorne and S. Werbelow. 2004. Elk feedgrounds in Wyoming, Wyoming Game and Fish Department, Wyoming, USA, <http://gf.state.wy.us/downloads/pdf/elkfg83004.pdf>. Accessed October 20, 2011.

Greene, W. H. 1997. Econometric analysis. Prentice Hall, Upper Saddle River, New Jersey, USA.

Enck, J. W., D. J. Decker, and T. L. Brown. 2000. Status of hunter recruitment and retention in the United States. Wildlife Society Bulletin 28:817–824.

Enck, J. W., B. L. Swift, and D. J. Decker. 1993. Reasons for decline in duck hunting: insights from New York. Wildlife Society Bulletin 21:10–21.

Floyd, M. F., and I. Lee. 2002. Who buys fishing and hunting licenses in Texas? Results from a statewide household survey. Human Dimensions of Wildlife 7:91–106.

Frey, S. N., M. R. Conover, J. S. Borgo, and T. A. Messmer. 2003. Factors influencing pheasant hunter harvest and satisfaction. Human Dimensions of Wildlife 8:277–286.

Greene, W. H. 1997. Econometric analysis. Prentice Hall, upper Saddle River, New Jersey, USA.

Heberlein, T. A., J. N. Trent, and R. M. Baumgartner. 1982. The influence of hunter density on firearm deer hunters' satisfaction: a field experiment. Transactions of the North American Wildlife and Natural Resources Conference 47:665–675.

Hosmer, D. W., and S. Lemeshow. 2000. Applied logistic regression. Wiley, Hoboken, New Jersey, USA.

Leek, S. N. 1911. The starving elk of Wyoming. Stephen Leek papers, box 1, short stories, American Heritage Center, University of Wyoming, Laramie, Wyoming, USA.

Loomis, J. B., and R. G. Walsh. 1997. Recreation, economic decisions: comparing benefits and costs. Venture, State College, Pennsylvania, USA.

Maichak, E. J., B. M. Scurlock, J. D. Rogerson, L. L. Meadows, A. E. Barbknecht, W. H. Edwards, and P. C. Cross. 2009. Effects of management, behavior, and scavenging on risk of brucellosis transmission in elk of western Wyoming. Journal of Wildlife Diseases 45:398–410.

Manfredo, M. J., P. J. Fix, T. L. Teel, J. Smeltzer, and R. Kahn. 2004. Assessing demand for big-game hunting opportunities: applying the multiple-satisfaction concept. Wildlife Society Bulletin 32:1147–1155.

Miller, J. R. 1982. Game availability and hunter participation: a study of Washington elk hunting. Annals of Regional Science 16:73–94.

Miller, J. R., and M. J. Hay. 1981. Determinants of hunter participation: duck hunting in the Mississippi Flyway. American Journal of Agricultural Economics 63:677–684.

Murie, O. J. 1951. The elk of North America. Stackpole, Harrisburg, Pennsylvania, USA.

Nickerson, P. H. 1990. Demand for the regulation of recreation: the case of elk and deer hunting in Washington state. Land Economics 66:437–447

Nicoletti, P. 1980. The epidemiology of bovine brucellosis. Advances in Veterinary Science and Comparative Medicine 24:70–98.

Olsen, S. C. 2010. Brucellosis in the United States: role and significance of wildlife reservoirs. Vaccine, 28S: F73–F76.

Poudyal, N., S. H. Cho, and J. M. Bowker. 2008. Demand for resident hunting in the southeastern United States. Human Dimensions of Wildlife 13:158–174.

Preble, E. A. 1911. Report on condition of elk in Jackson Hole, Wyoming, in 1911. U.S. Department of Agriculture, Biological Survey, Bulletin No. 40. Washington, D.C., USA.

Reardon, P. O., L. B. Merrill, and C. A. Taylor Jr. 1978. White-tailed deer preferences and hunter success under various grazing systems. Journal of Range Management 31:40–42.

Roffe, T. J., L. C. Jones, K. Coffin, M. L. Drew, S. J. Sweeney, S. D. Hagius, P. H. Elzer, and D. Davis. 2004. Efficacy of single calfhood vaccination of elk with *Brucella abortus* strain 19. Journal of Wildlife Management 68:830–836.

Sandrey, R. A., S. T. Buccola, and W. G. Brown. 1983. Pricing policies for antlerless elk hunting permits. Land Economics 59:432–443.

Schmidt, J. I., J. M. Ver Hoef, and R. T. Bowyer. 2007. Antler size of Alaskan moose *Alces alces gigas*: effects of population density, hunter harvest and use of guides. Wildlife Biology 13:53–65.

Scrogin, D., R. P. Berrens, and A. K. Bohara. 2000. Policy changes and the demand for lottery-rationed big game licenses. Journal of Agricultural and Resource Economics 25:501–519.

Scurlock, B. 2010. Brucellosis management update. Presentation at brucellosis coordination team meeting, April 20, 2010, Pinedale, Wyoming, USA.

Scurlock, B. M. 2010. Pinedale elk herd unit test-and-slaughter pilot project report, year four: Muddy, Fall and Scab Creek feedgrounds, 2009. Wyoming Game and Fish Department, Cheyenne, Wyoming, USA.

Scurlock, B. M., and W. H. Edwards. 2010. Status of brucellosis in free-ranging elk and bison in Wyoming. Journal of Wildlife Diseases 46:442–449.

Sun, L., C. van Kooten, and G. M. Voss. 2005. Demand for wildlife hunting in British Columbia. Canadian Journal of Agricultural Economics 53: 25–46.

Thorne, E. T. 2001. Brucellosis. Pages 372–395 *in* E. S. Williams and I. K. Barker, editors. Infectious diseases of wild mammals. Iowa State University Press, Ames, Iowa, USA.

Thorne, E. T., and J. D. Herriges Jr. 1992. Brucellosis, wildlife and conflicts in the Greater Yellowstone area. Transactions of the North American Wildlife and Natural Resources Conference 57:453–635.

Thorne, E. T., and T. Kreeger. 2002. Management options for the resolution of brucellosis in the GYA. Pages 19–23 *in* M. S. Boyce and L. O. Hayden-Wing, editors. Brucellosis in elk and bison in the Greater Yellowstone area. Wyoming Game and Fish Department, Cheyenne, Wyoming, USA.

Thorne, E. T., J. K. Morton, F. M. Blunt, and H. A. Dawson. 1978. Brucellosis in elk: clinical effects and means of transmission as determined through artificial infections. Journal of Wildlife Diseases 14:280–291.

Thorne, E. T., J. K Morton, and W. C. Ray. 1979. Brucellosis: its effect and impact on elk in western Wyoming. Pages 212–220 *in* E. T. Thorne, J. K. Morton, and W. C. Ray. North American elk: ecology, behavior and management. University of Wyoming Press, Laramie, Wyoming, USA.

U.S. Census Bureau. 2008. Historical income tables—households. U.S. Census Bureau, USA. <http://www.census.gov/hhes/www/income/data/historical/household/index.html>. Accessed October 20, 2011.

U.S. Fish and Wildlife Service. 2006. National survey of fishing, hunting, and wildlife-associated recreation, U.S. Fish and Wildlife Service, USA, <http://www.census.gov/prod/2008pubs/fhw06-nat.pdf>. Accessed September 19, 2010.

Wyoming Game and Fish Department. 1994–2006. NRE, NSE, and RRE demand indices. Wyoming Game and Fish Department, Cheyenne, Wyoming, USA.

Wyoming Game and Fish Department. 1994–2007. Annual report of big game harvest. Wyoming Game and Fish Department, Cheyenne, Wyoming, USA.

Wyoming Game and Fish Department. 2007*a*. An assessment of changes in elk calf recruitment relative to wolf reestablishment in northwest Wyoming. Wyoming Game and Fish Department, Cheyenne, Wyoming, USA, <http://gf.state.wy.us/downloads/pdf/FinalElkCCRatios3023-07.pdf>. Accessed October 28, 2011.

Wyoming Game and Fish Department. 2007*b*. Job completion report compilations for 1975–2007: Afton, Clarks Fork, Cody, Fall Creek, Gooseberry, Green River, Hoback, Jackson, Medicine Lodge, North Bighorn, Pinedale, Piney, South Bighorn, South Wind River, West Green River and Wiggins Fork. Wyoming Game and Fish Department, Cheyenne, Wyoming, USA.

Wyoming Game and Fish Department. 2009. Annual report. Wyoming Game and Fish Department, Cheyenne, Wyoming, USA, <http://gf.state.wy.us/downloads/pdf/annualreports/2009/2009AnnualReport_final.pdf>. Accessed October 28, 2011.

Wyoming State Board of Outfitters and Professional Guides. 1994–2007. Outfitter's annual reports. Wyoming State Board of Outfitters and Professional Guides, Cheyenne, Wyoming, USA.

Xie, F., and R. D. Horan. 2009. Disease and behavioral dynamics for brucellosis control in elk and cattle in the Greater Yellowstone area. Journal of Agricultural and Resource Economics 34:11–33.

MANDY E. KAUFFMAN is a Ph.D. student in the Department of Veterinary Sciences at the University of Wyoming. She earned a B.S. degree in fisheries and wildlife from Michigan State University in 2005 and an M.S. degree in agricultural and applied economics from the University of Wyoming in 2010. Her research interests include wildlife–domestic animal disease management and human–wildlife conflict. She enjoys spending her free time running trails with her dogs when the Wyoming weather permits.

BENJAMIN S. RASHFORD is an assistant professor in the Department of Agricultural and Applied Economics at the University of Wyoming. He holds B.S. and M.S. degrees in economics from the University of Wyoming and a Ph.D. degree in agricultural and resource economics from Oregon State University. His research focuses on the economics of wildlife management and habitat conservation. Current interests include the economics of wildlife-livestock disease, the effect of climate change on land use and wildlife habitat, and the tradeoff between wind energy production and sage grouse conservation.

DANNELE E. PECK is an assistant professor of agricultural and applied economics at the University of Wyoming. She received a B.S. degree in wildlife biology and an M.S. degree in agricultural economics from the University of Wyoming, and a Ph.D. degree in agricultural and resource economics from Oregon State University. Her areas of expertise include animal health economics, water resource economics, and decision-making under uncertainty. She enjoys fly-fishing, outdoor photography, and traveling abroad.

Appendix

Key to variables

Table 1. Variable names and description for the elk hunter success model.

Variable name	Description
$TOTALHUNTERS_{jt}$	Total number of elk hunters in hunt area *j* and year *t*
$TOTALHARVEST_{jt}$	Total number of elk harvested in hunt area *j* and year *t*
$ELKDENS_{jt}$	#elk/km^2 in herd unit *j* and year *t*
$ELKDENS^2_{jt}$	Squared elk density in herd unit *j* and year *t*
$ELKDENS_{jt*}\%PUBLIC_{jt}$	#elk/km^2 in herd unit *j**% public land in hunt area *j* and year *t*
$\#WOLVES_{jt}$	# wolves in herd unit *j* and year *t*
$\%OUT_{jt}$	% of hunters employing a guide in hunt area *j* and year *t*
Dj	Dummy variable representing hunt area *j*

Note: The subscript j in this case is used interchangeably for hunt area and herd units.

Table 2: Variable names and descriptions for elk license demand models.

Variable name	Description
$\#FIRSTCHOICECAPPS_{jt}$	# of first choice applicants for antlered/any elk licenses through respective draw type in hunt area *j* in year *t*
$PERMITS_{jt}$	# of antlered/any elk licenses available through respective draw type in hunt area *j* in year *t*
$DRAWODDS_{jt-1}$	Weighted average of 1-year lagged draw odds for antlered/any elk licenses through respective d
$ELKPOP_{jt-1}$	1-year lagged elk population in herd unit *j* and year *t*
$BULL:SPIKE_{jt-1}$	1-year lagged ratio of bull (>2yrs) to spike (<2yrs) elk in herd unit *j* and year *t*
$SUCCESS_{jt-1}$	1-year lagged total elk hunter success in hunt area *j* and year *t*
$\#WOLVES_{jt-1}$	1-year lagged number of wolves in herd unit *j* and year *t*
$OWNPRICE_t$	Price of applying for a license of a particular draw type in year *t*
$SUBPRICE_t$	Price of applying for a license of an alternate draw type in year *t* (an option that does not exist in the resident model)
$INCOME_t$	Median income of the fourth fifth of all races in year *t*
$TREND_t$	Time trend with an annual time-step
D_j	Dummy variable representing hunt area *j*

Note: The subscript j in this case is used interchangeably for hunt area and herd units.