Carnivore-Livestock Conflicts: Effects of Subsidized Predator Control and Economic Correlates on the Sheep Industry

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Abstract: *Despite the importance of carnivores in terrestrial ecosystems, many nations have implemented well-coordinated, state-funded initiatives to remove predators, largely because of conflicts with humans over livestock. Although these control efforts have been successful in terms of the number of carnivores removed, their effects on the viability of the industries they seek to protect are less understood. I assessed the efficacy of long-term efforts by the U.S. government to improve the viability of the sheep industry by reducing predation losses. I used regression analysis and hierarchical partitioning of a 60-year data set to explore associations among changes in sheep numbers and factors such as predator control effort, market prices, and production costs. In addition, I compared trends in the sheep industry in the western United States, where predator control is subsidized and coyotes (*Canis latrans*) are abundant, with trends in eastern states that lack federally subsidized predator control and that were (1) colonized by coyotes before 1950 or (2) colonized by coyotes between 1950 and 1990. Although control efforts were positively correlated with fluctuations in sheep numbers, production costs and market prices explained most of the model variation, with a combined independent contribution of 77%. Trends in sheep numbers in eastern and western states were highly correlated (*r $\geq$ *0.942) independent of the period during which they were colonized by coyotes, indicating either that control has been ineffective at reducing predation losses or that factors other than predation account for the declines in both regions. These results suggest that government-subsidized predator control has failed to prevent the decline in the sheep industry and alternative support mechanisms need to be developed if the goal is to increase sheep production and not simply to kill carnivores.*

Key Words: *Canis latrans*, coyotes, policy evaluation, predation

Conflictos Carnívoros-Ganado: Efectos del Control Subsidiado de Depredadores y Correlaciones Económicas sobre la Industria Ovina

Resumen: *A pesar de la importancia de carnívoros en los ecosistemas terrestres, muchos países han implementado iniciativas bien coordinadas, financiadas por el gobierno, para remover depredadores, principalmente debido a conflictos entre humanos y ganado. Aunque estos esfuerzos de control han sido exitosos en términos del número de carnívoros removidos, sus efectos sobre la viabilidad de las industrias que se busca proteger son poco comprendidos. Evalué la eficacia de los esfuerzos a largo plazo del gobierno de E.U.A. para mejorar la viabilidad de la industria ovina mediante la reducción de pérdidas por depredación. Utilicé análisis de regresión y partición jerárquica de un conjunto de datos de 60 años para explorar asociaciones entre cambios en el número de ovejas y factores como el esfuerzo de control de depredadores, precios de mercado y costos de producción. Adicionalmente comparé las tendencias en la industria ovina en el oeste de Estados Unidos, donde el control de depredadores está subsidiado y los coyotes (*Canis latrans*) son abundantes, con las tendencias en los estados orientales que carecen de control subsidiado federalmente y que fueron (1) colonizados por coyotes antes de 1950 o (2) colonizados por coyotes entre 1950 y 1990. Aunque los esfuerzos de control*

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se correlacionaron positivamente con las fluctuaciones en el número de ovejas, los costos de producción y los precios de mercado explicaron la mayor parte de la variación del modelo, con una contribución independiente combinada de 77%. Las tendencias en el número de ovejas en los estados orientales y occidentales estaban muy correlacionadas ($r \geq 0.942$) independientemente del período en que fueron colonizados por coyotes, lo que indica que el control ha sido ineficiente en la reducción de depredación o que factores, distintos a la depredación, son responsables de las declinaciones en ambas regiones. Estos resultados sugieren que el control subsidiado por el gobierno ha fallado en prevenir la declinación de la industria ovina y que se necesitan desarrollar mecanismos de soporte alternativos si la meta es incrementar la producción de ovejas y no simplemente matar carnívoros.

Palabras Clave: *Canis latrans*, coyotes, depredación, evaluación de política

Introduction

Carnivore conservation and management are of fundamental concern to conservation biologists because of the importance of carnivores in terrestrial ecosystems. Carnivores have the capacity to shape the demography and behavior of prey species (Berger et al. 2001*a*) and limit prey populations, thereby altering community structure (Terborgh 1992; Terborgh et al. 1999; Berger et al. 2001*b*). Interspecific competition and intraguild predation among carnivores influence the behavior and densities of competing species, with resulting complex changes in prey populations (e.g., Palomares & Caro 1999; Linnell & Strand 2000). Because of their large area requirements, carnivores can function as umbrella species in reserve site selection and design (Noss et al. 1996). And because large carnivores act as a draw for tourists, they encourage conservation of protected areas by serving as mechanisms to generate income and provide employment opportunities for rural communities (Sillero-Zubiri et al. 2004).

These same characteristics pose conservation challenges. Because carnivores tend to prey on species valued by humans, the presence of mammalian predators can impose economic costs on rural communities through competition with humans over livestock and wild game (Treves & Karanth 2003; Graham et al. 2005). Carnivores are vulnerable to habitat fragmentation because of their large home ranges, and their wide-ranging movements take them outside protected areas, where conflicts may occur (Woodroffe & Ginsberg 1998). And although attacks are relatively rare the potential for large carnivores to kill humans may instill fear, leading to intense persecution (Kruuk 2002). Thus, despite considerable effort to mitigate human-carnivore conflicts and notwithstanding a few notable successes (Swenson et al. 1995; Bangs et al. 1998; Breitenmoser 1998), most species of large carnivore are in decline globally (Weber & Rabinowitz 1996; Woodroffe 2000).

Predator control is one of the oldest, most widespread forms of wildlife management. Killing predators was defined in law as a statutory obligation in Sweden from 1442 to 1864, and in ancient Greece wolves were killed to protect livestock 2500 years ago (Reynolds & Tapper 1996). In response to concern over livestock predation, governments of many countries have implemented predator-control initiatives at a national scale. Examples of predator control on every continent abound and include wild dogs (*Lycaon pictus*, Woodroffe 2001) and jackals (*Canis mesomelas, C. aureus*, Harris & Saunders 1993) in Africa; dholes (*Cuon alpinus*) in Asia (Rangrajan 1998); culpeos (*Pseudalopex culpaeus*) in South America (Novaro 1995); dingos (*Canis lupus dingo*) in Australia (Harris & Saunders 1993); coyotes (*Canis latrans*), wolves (*Canis lupus, C. rufus*), red foxes (*Vulpes vulpes*), mountain lions (*Puma concolor*), bobcats (*Lynx rufus*), and brown bears (*Ursus arctos*) in North America (Reynolds & Tapper 1996); and lynx (*Lynx lynx*), wolverines (*Gulo gulo*), wolves, and brown bears in Europe (Breitenmoser 1998). Although these organized campaigns have threatened persistence of species such as African wild dogs, gray wolves, and red wolves, other species, including foxes, coyotes, jackals, and culpeos, have shown remarkable resilience (Sillero-Zubiri et al. 2004).

Predator-control programs have been enormously successful in terms of the number of carnivores killed. In the United States, federal agents killed more than 286,000 large ($\geq$9 kg) carnivores in 1998 (Wildlife Services 2000). Yet despite the long-standing nature of these programs, their effects on the viability of the industries they seek to protect have received little attention. Although predator control is based on the assumption that a decrease in carnivore abundance will result in a reduction in predation losses (Hone 1994), this view represents a gross oversimplification of the complex trophic structure in which predator-prey interactions occur. Not surprisingly, the relationship between carnivore abundance and predation losses is not unequivocal (Conner et al. 1998; Knowlton et al. 1999).

In North America the situation is perhaps best exemplified by federal efforts to reduce predation on domestic sheep for more than 80 years. Federal subsidies for predator control began in 1915 when Congress appropriated \$125,000 (nominal dollars) to the Bureau of Biological Survey to reduce livestock losses to predators (Dunlap 1988). Today, funding is provided jointly by congressional appropriations and through cooperative agreements with

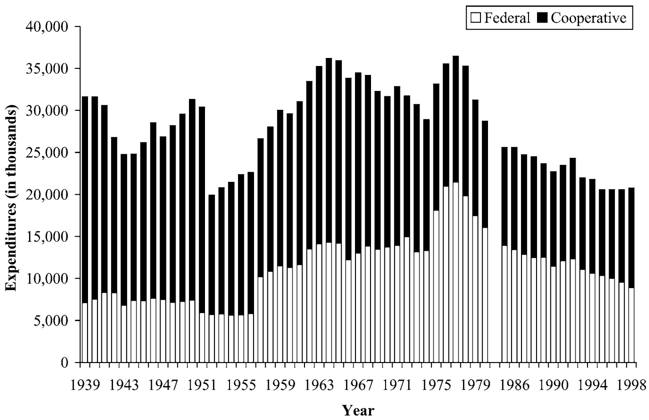


Figure 1. Real annual federal and cooperative expenditures for livestock protection in the 17 western states. Data were unavailable for 1981–1984. Cooperative funding comes from individuals, agencies, and organizations that seek the program's assistance.

state and local governments, livestock associations, and other federal agencies (collectively termed "cooperators") that seek the program's assistance (Cain et al. 1972). Annual funding provided by cooperators has ranged from 40% to 80% of total programmatic expenditures for livestock protection (Fig. 1). Although bobcats, mountain lions, wolves, black bears, and brown bears are killed to protect livestock, coyotes are the principal target and constitute 75% to 95% of the large carnivores removed each year (Fig. 2).

Since reaching a peak of 56.2 million animals in 1942, the U.S. sheep industry has declined by >85%, with predation, chiefly by coyotes, cited as the primary cause of this decline (Johnson & Gartner 1975; Gee et al. 1977; Dunlap 1988; House Resources Committee 1996). Whether

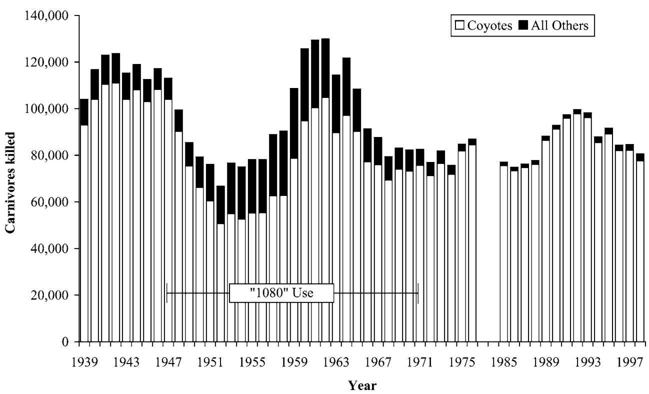


Figure 2. Annual number of carnivores killed by federal predator-control agents (All Others includes black bears, bobcats, wolves, and mountain lions; 1080 Use identifies the period over which the toxicant compound 1080 was used to control predators). Data were unavailable for 1977–1984.

data support the role of predation (Wagner 1972), the perception that carnivores are driving the decline in the sheep industry clearly persists.

If predation losses are the primary factor influencing the economic viability of the U.S. sheep industry and federal predator control has been effective at reducing these losses, then a positive relationship should exist between control efforts and sheep numbers. Alternatively, if predation losses are of secondary importance relative to economic factors, then sheep numbers should decline in years in which market conditions are unfavorable, regardless of any reduction in livestock losses that results from predator control.

I evaluated the extent to which the decline of the U.S. sheep industry is associated with predator control efforts relative to other economic variables that may influence sheep production. In addition, because coyotes were absent from much of the southeastern United States before 1950 (Parker 1995), I used geographical contrasts to explore the relationship between changes in sheep numbers and the presence of potentially depredating carnivores. Analyses such as these are important to conservation for several reasons. First, public perceptions about carnivores can affect the success of recovery efforts and, in some cases, may even halt reintroductions (Mech 1995; Maehr et al. 2001). Second, analyses of long-standing programs that affect ecosystem function allow conservation biologists to recommend changes conducive to the maintenance of biodiversity. Finally, in situations where conventional evaluation methods such as cost-benefit analysis are impractical or ineffective, conservation biologists must advance new ways to develop insights into program efficacy.

Methods

I used historical data from the National Agricultural Statistics Service, Census of Agriculture, Animal and Plant Health Inspection Service, and U.S. Fish and Wildlife Service for the period 1920–1998 to explore factors that might be associated with trends in the U.S. sheep industry (a detailed listing of data sources for all variables is available from the author). When possible, I used information specific to the 17 western states (Table 1) because 97% of federal funding for livestock protection is spent there (U.S. Fish and Wildlife Service 1978). For comparative purposes I adjusted all monetary variables to "real" terms based on the consumer price index (1982–1984 = 100; Bureau of Labor Statistics 2000).

Measuring the Sheep Industry's Response

Producers respond to fluctuations in market prices and productions costs by altering the amount they produce

Table 1. Descriptions, abbreviations, and geographic coverage for explanatory variables used for the analysis of changes in sheep numbers.

Variable	*Abbreviation*
Average lamb price per 100 pounds received by ranchers[a]	lamb
Greatest season average shorn wool price per pound or support price per pound[a]	wool
Average hay price per ton[a]	hay
Average cattle price per 100 pounds received by ranchers[a]	beef
Average hourly wage rate paid to field/livestock workers[a]	wage
Percentage of sheep ranchers aged 65 and over[b]	age
Federal and cooperative dollars spent on livestock protection[b]	control
Binary variable coded "1" for years in which compound 1080 was used to control predators	1080

[a] *Data represent the average for all states.*
[b] *Data are limited to the 17 western U.S. states (Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, North Dakota, New Mexico, Nevada, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming).*

(Koch 1976). Thus, for the dependent variable I calculated the change in the number of breeding sheep and lambs on 1 January of each year as

$$\Delta\text{sheep} = \text{sheep}_t - \text{sheep}_{t-1} = \text{births}_{t-1} - \text{deaths}_{t-1},$$

where sheep_t and sheep_{t-1} are the number of sheep and lambs on 1 January of the current year and prior year, respectively; births_{t-1} is the number of lambs born during the prior year; and deaths_{t-1} includes natural mortality (e.g., weather-related deaths, losses during lambing), culling, disease, accidents, predation, and slaughter of sheep and lambs during the prior year. The difference between births_{t-1} and deaths_{t-1} (Δsheep) represents the change in the sheep industry's productive capacity from one year to the next. Accordingly, all explanatory variables were lagged by one year to correspond to the period during which the associated change in sheep numbers occurred (Pindyk & Rubinfeld 1998).

Explanatory Variables

I included hay prices and wage rates paid to livestock workers because they affect profitability through their effect on production costs. Lamb and wool prices were included because they directly affect producers' incomes. In 1954 the National Wool Act was enacted to support the price of wool and encourage domestic production (U.S. Fish and Wildlife Service 1978). The act set a minimum price (termed support price) for wool, with payments made when the support price exceeded the national average price received by producers (U.S. Fish and Wildlife Service 1978). Thus, for the wool variable I obtained both market and support prices and used the higher of the two figures for each year to represent the effective price received by producers. Lamb and wool prices were treated as exogenous variables because (1) the dependent variable was only proximately related to lamb prices through its constraint on the industry's capacity to produce lambs, (2) in most years wool prices were set by the federal government (i.e., the support price) independent of the amount of wool produced, and (3) the United States produces only a small fraction of the world's sheep supply (i.e., ∼2%); hence changes in domestic production have a minimal effect on world prices of lamb and wool.

A rancher's decision to use available inputs (e.g., hay, labor) to produce sheep necessarily means these resources are not available to produce an alternative product. Many ranchers jointly produce cattle and sheep (Pearson 1975; Gee et al. 1977) because joint production permits greater range utilization, diversification of income and risk, and the flexibility to vary the mix of sheep and cattle in accordance with changing prices (U.S. Fish and Wildlife Service 1978). Thus I included beef prices in the analysis because ranchers may shift from sheep to cattle production in years when beef prices are relatively higher. Sheep numbers might also decline if ranchers cease production because of retirement (Gee et al. 1977). Thus I included the proportion of sheep ranchers nearing retirement age (i.e., the percentage of ranchers aged 65 or over). Because data on rancher age were available only for 1940, 1945, 1950, 1959, 1964, 1969, 1974, 1978, 1982, 1987, 1992, and 1997, I used linear interpolation (Zar 1999) to estimate values for the intervening years.

Measuring Predator Control Effort

Federal predator control potentially affects profitability, and hence production decisions, in two ways. First, subsidized control may decrease production costs by reducing the amount that ranchers must spend privately on animal husbandry and predator control (Dunlap 1988). Second, if predation losses are reduced as a consequence of subsidized control, then the number of lambs available for sale increases resulting in higher revenues.

Basing control effort on the number of carnivores removed is intuitively appealing because the assumption of an inverse relationship between carnivore abundance and predation losses is the foundation for predator control (Hone 1994). Although the actual relationship is likely to be tenuous given the number of factors that influence carnivore densities (Cain et al. 1972), this should not be construed as a limitation of the variable per se. Rather it underscores potential deficiencies in the premise on which predator-control efforts are based and the real-world environment in which the federal program operates.

The number of carnivores killed by federal control agents is available for most years between 1916 and 1998, but figures may not have been reliably and consistently reported. Estimates of the number of predators killed are subject to differential probabilities of carcass detection associated with changes in the control methods (i.e., poisoned animals may leave the area, making carcass recovery more difficult; Wagner 1972), and shifts in public perception of predator control may encourage over- or underreporting (Cain et al. 1972; Dunlap 1988). The reported harvest of coyotes by federal control agents decreased by >40% between the late 1940s and the early 1950s concomitant with the introduction of sodium monoflouroacetate (also known as compound 1080), a highly toxic, canid-selective poison (Fig. 2; Wagner 1972). Estimates of coyote abundance during the same period indicate that coyote populations may have declined by as much as 50% in states where compound 1080 was used extensively (Wagner 1972), suggesting that the actual coyote harvest was considerably higher than the reported totals.

Conversely, reliable data on federal funding for livestock protection are readily available for most years between 1939 and 1998, and these figures should provide an index of changes in control effort over time. Although the relationship between expenditures and predator-control effort is not known precisely, the presumption of an inverse relationship between predation losses and expenditures has been used to substantiate the need for sustained federal funding for predator control (U.S. Fish and Wildlife Service 1978). Thus it seems reasonable to assume that control efforts were greater in years with higher real expenditures.

The assumption of a positive relationship between expenditures and control effort is violated, however, if programmatic changes necessitate the adoption of more expensive, less effective predator-control techniques. For instance, although compound 1080 was viewed by ranchers and federal control agents as one of the most effective and economical methods for depressing coyote populations (Cain et al. 1972; Johnson & Gartner 1975; U.S. Fish and Wildlife Service 1978), the use of poisonous baits for predator control was banned in 1972 because of concerns about misuse and the magnitude of nontarget kills (Buys 1975; Dunlap 1988). To account for this change in control technology, I included a binary variable coded "1" for years (1948–1971) in which compound 1080 was used to control predators.

Data Analysis

I used three complementary approaches to assess the extent to which trends in the sheep industry appeared to be associated with livestock predation. First, I used multiple regression to evaluate 16 models, and ranked them according to Akaike's information criterion adjusted for small samples (AIC_c, Table 2; Burnham & Anderson 2002). I tested a global model that included all the explanatory variables and reduced models specific to market-related variables and predator-control effort. In addition, I tested models that successively omitted wool prices, beef prices, and use of compound 1080 because results of previous studies suggest these variables might be least important (Wagner 1972; Gee et al. 1977; U.S. Department of Agriculture 2000).

With time series data the residuals from ordinary least squares are usually correlated over time. This reduces the

Table 2. Structure and ranking of models used to estimate annual changes in sheep numbers in the western United States.

Model no.	*Model structure*[a]	*Rank*	K[b]	AIC_c	ΔAIC_c
1	global model: lamb, wool, hay, wage, beef, age, control, 1080	14	11	1655.56	7.54
2	lamb, wool, hay, wage, beef, age, control	9	10	1652.54	4.52
3	lamb, hay, wage, beef, age, control, 1080	11	10	1653.30	5.28
4	lamb, hay, wage, beef, control, 1080	15	9	1655.65	7.63
5	lamb, hay, wage, age, control, 1080	5	9	1650.73	2.71
6	lamb, wool, hay, wage, age, control	4	9	1650.22	2.20
7	lamb, wool, hay, wage, beef, age	13	9	1654.82	6.80
8	lamb, wool, hay, wage, beef	12	8	1654.04	6.02
9	lamb, wool, hay, wage, age	8	8	1652.34	4.32
10	lamb, hay, wage, control, 1080	10	8	1652.93	4.91
11	lamb, hay, wage, age, control	1	8	1648.02	0.00
12	lamb, hay, wage, control	7	7	1651.44	3.42
13	lamb, hay, wage, 1080	6	7	1651.21	3.19
14	lamb, hay, wage, age	3	7	1649.85	1.83
15	lamb, hay, wage	2	6	1649.52	1.50
16	control, 1080	16	5	1673.91	25.89

[a] *Variables are defined in Table 1.*
[b] *Number of estimable parameters includes intercept, residual variance, and estimate of first-order autoregressive correlation of the residuals.*

efficiency of the parameter estimates and results in biased estimates of the standard errors (SAS Institute 1999). Because preliminary analyses indicated that the error term exhibited positive first-order autocorrelation (DW = 1.02, $p < 0.001$), I used an autoregressive error model to identify factors associated with changes in sheep numbers (AUTOREG procedure, SAS Institute 1999). This method corrects for autocorrelation in the error term by augmenting the regression model with an autoregressive model for the random error (SAS Institute 1999).

Second, I used hierarchical partitioning to determine the relative importance of each explanatory variable to fluctuations in sheep numbers (Chevan & Sutherland 1991; MacNally 2000; MacNally & Walsh 2004). In contrast to regression techniques in which a single best model is typically sought, hierarchical partitioning is an all-models approach, wherein the contribution of each explanatory variable is averaged over all possible models in which the variable appears. This method can be used to distinguish variables with high independent correlations for the dependent variable from those deemed "significant" because of multicolinearity (MacNally 2000).

Finally, because coyotes are perceived to be the primary predator of sheep, I classified states in the eastern United States into two groups based on the period during which coyote colonization occurred (Parker 1995). I then used simple linear regression to compare trends in sheep numbers in the 17 western states with (1) trends in eastern states (Arkansas, Indiana, Illinois, Iowa, Louisiana, Ohio, Maine, Michigan, Minnesota, Missouri, New Jersey, New York, Wisconsin) colonized by coyotes before 1950 and (2) trends in eastern states (Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia) colonized between 1950 and 1990. Because sheep numbers for many of the eastern states were reported aggregately beginning in 1979, this analysis was based on data for the period 1920–1978.

Results

The most parsimonious model (model 11, lowest AIC_c) included parameters for lamb prices, hay prices, wage rates, rancher age, control effort, and an estimate of the first-order autoregressive correlation of the errors (Table 2). Changes in sheep numbers were positively correlated with lamb prices, control efforts, and rancher age, and negatively correlated with hay prices and wage rates (Table 3). Two additional models were within two ΔAIC_c units of the best-approximating model (Burnham & Anderson 2002). These are model 14 ($\Delta AIC_c = 1.83$), which omitted the variable for control effort, and model 15 ($\Delta AIC_c = 1.50$), which omitted the variables for control effort and rancher age (Table 2). The best model correctly predicted 73% of changes in sheep numbers ($r = 0.855$).

Table 3. Summary of best-approximating regression model used to estimate annual changes in sheep numbers.

Variable	*Parameter estimate*	t	*Probability*
Intercept	−1,597,147	−0.73	0.467
Lamb	19,753	3.36	0.002
Hay	−25,894	−4.81	<0.001
Wage	−545,552	−3.43	0.001
Age	21,484,221	2.40	0.020
Control	0.0690	2.06	0.045
Ar1*	−0.5232	−4.24	<0.001

**Estimate of the first-order autoregressive correlation of the errors.*

Although control expenditures were positively correlated ($t = 2.06$, $p = 0.05$) with fluctuations in sheep numbers, hierarchical partitioning showed that the combined effect of changes in production costs (hay prices and wage rates) and lamb prices explained most of the model variation, with a combined independent contribution of 77% (Fig. 3). Hay prices alone had an independent contribution of 56%, with wage rates and lamb prices contributing 11% and 10%, respectively (Fig. 3). In contrast, funding spent on predator control had little effect on changes in sheep numbers, with an independent contribution of just 6% (Fig. 3). The use of compound 1080 to control predators also had an independent contribution of 6% (Fig. 3); the sign on the coefficient, however, was unexpectedly negative ($t = -0.28$, $p = 0.78$). Beef and wool prices had independent contributions of 2% and 1%, respectively.

Geographical and temporal differences in coyote colonization patterns enabled comparisons of relative changes in the sheep industry among regions. Trends in sheep numbers in the western United States were strongly correlated ($r = 0.986$, $p < 0.001$) with trends in eastern states colonized by coyotes before 1950 (Fig. 4a) and with trends in eastern states colonized by coyotes between 1950 and 1990 (Fig. 4b; $r = 0.942$, $p < 0.001$).

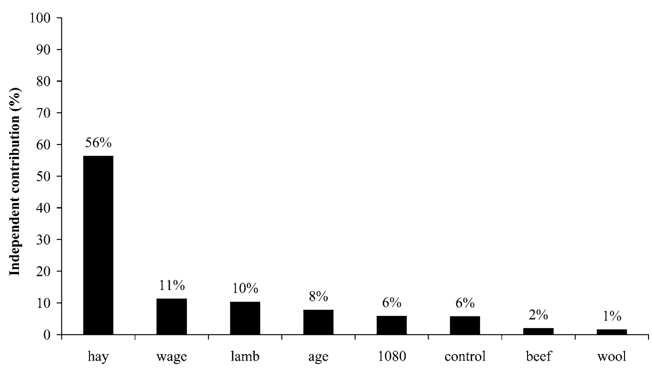
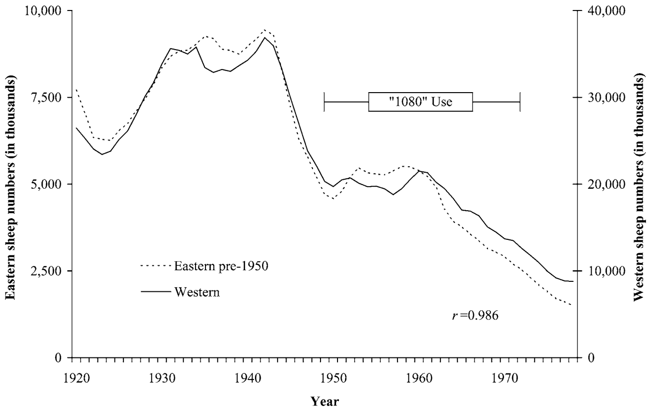


Figure 3. Distribution of independent contributions of the eight explanatory variables (Table 1) to changes in sheep numbers determined by hierarchical partitioning.



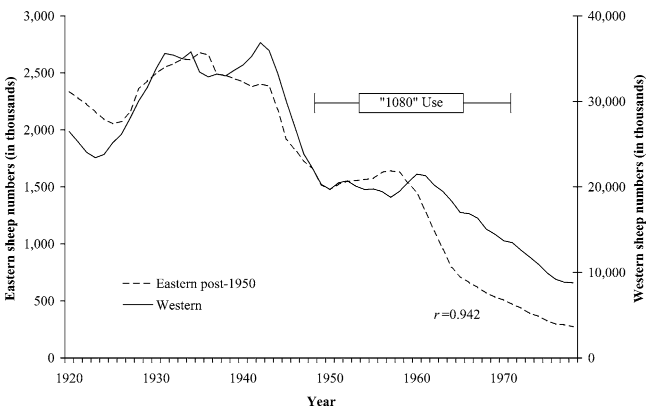


Figure 4. Correlation in trends in sheep numbers in the western United States: (a) eastern states colonized by coyotes before 1950; (b) eastern states colonized by coyotes after 1950.

Discussion

Effects of Carnivore Removal on the Sheep Industry

That control efforts have had little effect on trends in the sheep industry is remarkable given the enduring nature of the program, the considerable resources devoted to carnivore removal (about $1.6 billion in real dollars between 1939 and 1998), the number of carnivores removed, and the frequent assertion that federal control of predators is necessary to maintain the sheep industry (Buys 1975; Johnson & Gartner 1975; U.S. Department of Agriculture 1993). If predation losses are the primary cause of the sheep industry's decline, then control, as practiced, has not been successful at reducing predation losses to the level necessary to make sheep ranching economically viable. Either the reduction in carnivore abundance has not been sufficient to produce effective results or the relationship between carnivore removal and predation losses is tenuous (Wagner 1972; Graham et al. 2005). Alternatively, control efforts may be highly effective at reducing predation losses, but the financial effect of losses may be secondary to other economic considerations. For instance, Gee (1977) reports that for a large percentage of producers, lamb and wool production is not profitable even in the absence of predation losses.

Despite differences in the distribution of coyotes, sheep numbers in the eastern and western United States declined at comparable rates. The strong correlation ($r \geq 0.942$) in trends, independent of geographical and temporal differences in coyote colonization patterns, suggests that factors other than predation must be primarily responsible for the declines in areas that are ecologically disparate.

Although attention continues to focus on reducing predation losses, fluctuations in sheep numbers appear largely related to changing market conditions. Rising production costs and declining commodity prices have reduced or eliminated the profitability of many sheep-ranching enterprises. Between 1939 and 1998, when the sheep industry declined by >85%, real wage rates rose by 141% (from $2.91 to $7.02/hour). Over that same period market prices for lamb fell 23% (from $94.31 to $72.30/cwt), whereas wool prices decreased 82% (from $3.26 to $0.60/lb).

Although hay prices in 1998 were actually 26% lower than in 1939 ($113.87 vs. $84.60/ton), periodic, short-term price increases associated with steep declines in sheep numbers also occurred. For instance, between 1966 and 1976 a 44% increase in hay prices was associated with a concomitant 44% decrease in sheep numbers. The effect of increases in hay prices can perhaps best be understood within the context of drought conditions. During periods of drought hay production declines, leading to a sharp increase in prices at the same time that production of natural forage decreases. Under these circumstance ranchers must provide more supplemental feed. To avoid this many ranchers respond by thinning their herds or selling their operations outright (Austen et al. 2002; Salt Lake Tribune 2003). When conditions eventually improve, ranchers who have ceased production are unlikely to resume their operations because of poor overall economic prospects associated with sheep ranching.

The increase in wage rates over the past 70 years has also precipitated changes in husbandry practices. Sheep were commonly tended by herders during the first half of the twentieth century; today, many flocks roam unattended (Linnell & Brøseth 2002; Sillero-Zubiri et al. 2004). This change has increased the vulnerability of sheep to predation (Treves et al. 2002) and shifted the financial burden from producers, who are solely responsible for production costs, to taxpayers, who subsidize control of predators.

Although the substantial decline in wool prices between 1939 and 1998 should have affected the profitability of sheep ranching, wool prices explained little of the variability (1%) in sheep numbers. This seemingly contradictory result might be explained by the lesser role of wool production in the United States. Whereas wool is an important export in Australia and New Zealand (Witherell

1969), lamb sales represent the principal source of income for U.S. sheep producers (Whipple & Menkhaus 1989). Thus, changes in wool prices alone may be insufficient to motivate ranchers to either commence or abandon sheep production. Wool support payments to ranchers were discontinued in 1996 on grounds that the subsidy had failed to increase the domestic wool supply (U.S. Department of Agriculture 2000).

The negative relationship between the use of compound 1080 and changes in sheep numbers was unanticipated. Since the ban on compound 1080 in 1972, sheep ranchers have advocated strongly for a return to its use (Johnson & Gartner 1975; Terrill 1988). If, however, compound 1080 was as effective at reducing predation losses as proponents claim, it seems incongruous that sheep numbers declined by 63% during the period in which it was used (Figs. 4a & 4b). Wagner (1972) suggests that compound 1080 did effectively suppress coyote populations by as much as 50% between 1948 and 1955 in states where it was used extensively. No corresponding decrease in total sheep losses, however, was evident (Wagner 1972).

Ecological Effects of Carnivore Removal

Species-specific effects of predator control have long been recognized. For instance, the extinction of the Tasmanian wolf (*Thylacinus cynocephalus*) has been attributed to eradication by sheep farmers in the 1920s and 1930s (Paddle 2000). Brown bears and gray wolves were extirpated from Britain by the 1700s and suffered widespread regional extinctions throughout Europe (1800s) and the United States (early 1900s; Kruuk 2002). African wild dogs now occur in only 40% of the countries in which they were formally distributed because of persecution (Woodroffe et al. 2004).

Despite the long-standing nature of predator-control programs, ecosystem- and community-level effects have been assessed on a limited basis. Three case studies are notable. First, changes in the abundance of red foxes and coyotes were linked, in part, to the extirpation of gray wolves, with concomitant implications for duck mortality and nesting success (Sovada et al. 1995). Second, following the localized extinction of wolves and brown bears, food-web dynamics were altered, resulting in an irruption of moose (*Alces alces*) and a subsequent decrease in avian Neotropical migrants (Berger et al. 2001*b*). Finally, the loss of the native Iberian lynx (*Felis pardina*) facilitates increased predation by Egyptian mongooses (*Herpestes ichneumon*) on native rabbits (*Oryctolagus cuniculus*), the latter being a species preferred by human hunters (Palomares et al. 1995).

That conservation biologists have not been more outspoken about ecological effects of organized predator control may stem from perceptions that control efforts do not threaten the viability of species that are frequent targets. Although it is evident that species such as coyotes, dingos, culpeos, and red foxes can sustain high rates of mortality, these case studies underscore the extent to which predator control may compromise ecosystem dynamics and biological diversity. Still, further efforts to document ecological effects such as trophic cascades may be compromised by a lack of baselines against which to measure the effects of perturbations (Berger & Wehausen 1991) because few systems support food webs that remain intact (Croll et al. 2005). Given that predator control has been practiced continuously in some systems for well over a century, the substantial effects that changes in predator populations have had on systems may remain largely unexplored.

Program Evaluation from a Conservation Perspective

The evaluation of conservation and restoration programs is highly relevant to planning and informed decision making, but few programs seriously analyze efficiency, success, and failure (Reading & Miller 1994; Kleiman et al. 2000). Although numerous programs affect landscape-level resources, long-term data sets are rarely available to offer insights. The federal predator-control program is exceptional because of its duration (more than 80 years) and the availability of coincident information and, critically, because options for evaluation are unlikely to change even if additional data become available.

Several lessons may derive from evaluations of program efficiency, some economic, others ecological. First, reticence to accept results will always exist among some sectors of society. In the case of carnivore removal, the cost to design appropriate field studies is so prohibitive that large-scale efforts are not likely to be undertaken. In the absence of such studies, it cannot be said with absolute certainty that carnivore removal fails to facilitate sheep production.

Second, when evaluation costs are high relative to annual operating costs, policy makers may opt to simply maintain the status quo rather than implement controversial changes. But when the ecological costs associated with a program are of concern, the need for objective analyses to determine whether the program's benefits justify its continued existence is heightened. Despite the long-standing nature of many predator-control programs, the extent to which carnivore removal reduces predation losses remains equivocal (Cain et al. 1972; Wagner 1972) and, at least for North America, is based largely on a handful of studies that have produced contradictory results (Balser 1974; O'Gara et al. 1983; Conner et al. 1998; Mitchell et al. 2004).

Third, taxpayer-subsidized control programs help perpetuate public perception of carnivores as widespread livestock killers. Public misperception may hinder conservation of threatened species through direct persecution of carnivores or resistance to reintroduction efforts. For instance, although recovery of Mexican gray wolves (*Canis lupus baileyi*) was supported by a majority (77%) of Arizona residents statewide, 58% of survey respondents living in and around the potential reintroduction site opposed the reintroduction, with concerns about livestock losses most often cited as the reason for their opposition (Schoenecker & Shaw 1997). Additionally, the initial release of 11 Mexican gray wolves into the wolf recovery area on the Arizona-New Mexico border failed after five of the animals were illegally shot, another was missing and presumed dead, and the remaining five were recaptured to prevent further mortality (U.S. Fish and Wildlife Service 1998; Oakleaf et al. 2005).

Finally, the need for unified approaches to problem solving remains paramount. Examples of government programs that operate with discordant objectives abound. The sanctioned killing of predators by Wildlife Services and the concurrent reintroduction of grizzly bears, gray wolves, and red wolves by the U.S. Fish and Wildlife Service at a cost that exceeds millions of dollars is one such case (Mattson & Craighead 1994).

The management of grazing-related issues is another example. Habitat alterations associated with livestock grazing may increase lagomorph and rodent abundance (Miller et al. 1996), but increases in prey availability may also facilitate higher densities of carnivores (Berger & Wehausen 1991; Knowlton & Gese 1995) and ultimately lead to elevated rates of livestock predation (Mech 1995). Acknowledging these interrelationships and subsequently developing integrated approaches would be more efficient than addressing each component of the system independently (Miller et al. 1994). Although conservation biologists recognize the need to address issues from an ecosystem perspective (Brussard 1991), the organization of federal programs into a cohesive approach continues to present a substantive challenge.

Program evaluation is crucial for the sake of improved efficiency and to assess whether a program's goals remain consistent with public values. The federal predator-control program was conceived in an era in which public perception of carnivores was characterized by fear and hatred (Dunlap 1988). Today, carnivores are valued as members of intact ecosystems, and increasing interest is placed on biodiversity and wildlands rather than resource extraction and commodity production, at least on U.S. public lands (Berger & Berger 2001). That the decline of the sheep industry has been associated most closely with unfavorable market conditions rather than predation losses casts doubt on the value of continued carnivore control, except perhaps at a very local scale. Given the importance of carnivores in terrestrial ecosystems (Terborgh et al. 1999), the ecological consequences associated with their removal (Berger et al. 2001*b*), and the failure of subsidized predator control to produce tangible results for either livestock producers or the U.S. public, continued, widespread efforts to reduce carnivore numbers appear contrary to public interest. From both an economic and a public policy perspective, taxpayer dollars might be better spent to support sheep producers through direct cash payments or some other form of subsidy if the goal is to increase sheep and wool production and not merely to kill carnivores.

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