Essays on Measuring the Economic Impacts of Keystone Species

By

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Abstract

The first chapter estimates the causal impact of changes in deer abundance on roadway collisions and associated economic losses. I use ordinary least squares and instrumental variables regressions to identify the determinants of county-level police-reported deer-vehicle collisions (DVCs) in Ohio between 2001 and 2013 and Wisconsin between 1998 and 2013. Results show that increases in deer population, vehicle miles traveled, precipitation, and hot temperatures increase the frequency of DVCs while cold temperatures tend to decrease DVCs. Based on these results and the national average economic loss per DVC, the marginal deer causes $83 in economic losses from DVCs each year. Equivalently, 112 additional deer cause one more DVC per year. A one percent reduction in deer abundance in every county in the study area would lead to 195 fewer DVCs and a $1.8 million reduction in DVC losses each year. A 30 percent reduction in the deer population, which would roughly achieve deer population management goals in each state, would lead to about 5,800 fewer DVCs and a $54 million reduction in DVC losses each year. The results suggest that a relatively small decrease in deer abundance yields an economically significant reduction in DVCs.

The second chapter evaluates whether wolves affect the frequency of DVCs through predator-prey interactions. I use ordinary least squares and instrumental variables regressions to identify the determinants of county-level police-reported deer-vehicle collisions (DVCs) in Wisconsin between 1998 and 2010. Results show that wolves reduce DVCs both by decreasing deer populations and causing deer to avoid roads. The population effect dominates in core and secondary wolf habitats, while the behavioral effect dominates in wolf dispersal areas. One additional wolf above the mean reduces DVC losses by $600 to $1800 each year in primary wolf habitat and $156,000 to $375,000 per wolf per year in dispersal areas. By comparison, the

average wolf in Wisconsin causes about $235 per year in verified depredation losses. Overall, wolves are a cost-effective biological control on the economic losses caused by DVCs.

The third chapter assesses the impact of changes in species-specific catch rates on the non-market economic value of the recreational fishing industry in Lake Michigan. I use a discrete choice experiment to estimate per-trip values for Wisconsin resident anglers and Great Lakes Salmon and Trout Stamp holders using a multinomial logit framework. Consistent with intuition, results show that preferences for target species are heterogeneous, and catching more and bigger fish increases the probability of choosing a trip. Using these results, I calculate the non-market value of nine fishing trip configurations that represent historical and potential future conditions in the fishery. The per-trip values confirm that Chinook Salmon remain one of the most valuable species in the lake despite reductions in success rates over recent years. Continued declines in the Chinook Salmon population are likely to cause large economic losses unless fisheries managers can substantially rehabilitate Lake Trout and Walleye populations and/or recruit new anglers to the fishery. If all current Chinook Salmon trips instead targeted Lake Trout, non-market value would decrease by $27 million under current conditions and remain statistically unchanged under improved conditions. Substituting to Walleye would lead to large economic gains, but populations are geographically concentrated and may be inaccessible to many anglers.

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If all my years of schooling have taught me anything, it is that I would not be here without the guidance, support, and generosity of many people—like raising a child, completing graduate school takes a village. I am humbled and overwhelmed by the time and energy that others have invested in my success, and I would like to recognize a few of these extraordinary people here.

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Introduction

Understanding the ways in which fish and wildlife affect the economy is imperative for developing efficient management strategies. Ideally, natural resource managers would adopt policies that maximize net economic benefits; however, in practice it is often difficult to determine the aggregate economic impacts of a species and even more difficult to measure how these impacts would change under alternative management scenarios. Complicating matters further, the individuals who reap the benefits of fish and wildlife often are different than those who suffer the costs. Since both costs and benefits tend to increase with species abundance, stakeholders are likely to have conflicting preferences regarding management goals. There is a need for science-based estimates of the trade-offs between costs and benefits as fish and wildlife populations change.

Healthy fish and wildlife populations are important not only for ecosystems but also for the economy. In 2011, more than 90 million individuals participated in wildlife-related recreation in the United States (U.S. Fish and Wildlife Service and U.S. Census Bureau 2014). Spending on hunting, sport fishing, and wildlife watching generated $362 billion in economic activity (or "gross output") and supported 2.8 million jobs (Caudill 2014; Southwick Associates 2012a, 2012b).[1] As a point of reference, the gross output from wildlife-related recreation is on par with that of oil and gas extraction ($362 billion) and manufacturing of computer and electronic products ($396 billion) (U.S. Bureau of Economic Analysis 2017). Wildlife watching accounts

[1] Unless otherwise noted, all monetary values are converted to 2015 dollars using the Bureau of Labor Statistics' Consumer Price Index. Economic activity includes direct, indirect, and induced spending. This measure is also known as total industrial output or gross output.

for the largest share of gross output (42 percent), followed by sportfishing (33 percent), and hunting (25 percent).

Wildlife-related recreation also generates substantial net economic value.[2] Deer hunting resulted in an estimated $12.1 billion in net economic value or consumer surplus in 2011 ($80 per hunting day) (Aiken 2016; Fuller 2016). The net benefits from away-from-home wildlife watching were of a similar magnitude, at $10.1 billion (about $40 per day) (Aiken 2016; U.S. Fish and Wildlife Service and U.S. Census Bureau 2014). Aggregate net economic value for sport fishing is not readily available, but the average economic value for bass, trout, and walleye trips were all roughly $50 per day (Aiken 2016). All of these figures underestimate total value because they only refer to individuals participating in activities in their home states.

Many of these benefits, however, are offset by substantial economic costs. Major cost categories include damage to agriculture, forests, and private property as well as the spread of disease. For example, in 2001 (the latest year available) losses from crop and livestock depredation were $1.3 billion (National Agricultural Statistics Service 2002). Farmers most commonly reported deer as the cause of crop damage and coyotes as the cause of livestock damage. Concerns about the possible transmission of diseases from wildlife to livestock, such as brucellosis, also feature prominently in wildlife management debates (Bienen and Tabor 2006). Such diseases can also sometimes spread to humans. For instance, Lyme disease, which is transmitted through deer ticks, infects an estimated 240,000 to 440,000 individuals and causes at least $4 billion in economic costs each year (Adrion et al. 2015; Berry et al. 2017; Levi et al.

[2] Expenditures indicate the economic importance of the sector but not the net economic value because expenditures are a transfer of benefits from consumers to producers. Net economic value or consumer surplus measures the benefit to consumers after accounting for this transfer and is calculated as the difference between what an individual is willing to pay and what they actually pay.

2012). Wildlife-vehicle collisions also represent a serious threat to health and safety and cause more than $9 billion per year in economic losses (Huijser et al. 2008). For many of these issues, mitigation measures are extremely costly and difficult to implement on a large scale. Reducing wildlife abundance is one option to mitigate costs; however, this also likely would reduce economic benefits. Empirical estimates of these tradeoffs are rare.

This study uses econometric techniques to measure the aggregate and marginal economic impacts of three ecologically and economically important species in the United States—white-tailed deer (*Odocoileus virginianus*), gray wolves (*Canis lupus*), and Chinook Salmon (*Oncorhynchus tshawytscha*). The first chapter estimates the causal impact of changes in deer abundance on roadway collisions and associated economic losses. The second chapter evaluates whether wolves affect the frequency of deer-vehicle collisions (DVCs) through changes in deer abundance or behavior. The third chapter assesses the impact of changes in species-specific catch rates on the non-market economic value of recreational fishing in Lake Michigan. In all three cases, I find that relatively small changes in species abundance have large economic impacts. Overall, these results emphasize the importance of economic considerations in developing efficient fish and wildlife management strategies.

Chapter 1. The Causal Impact of Increased Deer Abundance on Vehicle Collisions

1. Introduction

White-tailed deer (*Odocoileus virginianus*) are one of the most economically important species in the United States, generating at least $61 billion in benefits and $15 to $27 billion in costs each year (Table 14).[3] Wildlife managers face a difficult task of balancing the many benefits and costs of deer because both tend to be positively correlated with deer abundance. Presently, it is unknown to what extent reductions in deer abundance mitigate negative economic impacts. This study focuses on deer-vehicle collisions (DVCs), arguably the largest known economic cost of deer.

The social costs of DVCs are enormous. An estimated one million DVCs occur every year in the United States, causing 29,000 human injuries, 200 human fatalities, and $9.2 billion in total economic losses annually (Conover et al. 1995; Huijser et al. 2008).[4] To put this in context, losses from DVCs are more than six times the combined annual expenditures by federal and state agencies to protect endangered and threatened species (Endangered Species Act, $1.4 billion in 2014), eight times what the government spends to clean up the nation's worst hazardous waste sites (Superfund program, $1.1 billion in 2015), and five times the costs of protecting environmentally sensitive farmland (Conservation Reserve Program, $1.7 billion in

[3] Note that benefits minus costs does not represent net economic benefits because many categories include transfers.

[4] Economic losses includes vehicle repair costs, towing and law enforcement services, monetary value of the animal, and carcass removal and disposal (Huijser et al. 2008). It also includes "lost earnings, lost household production, medical costs, emergency services, travel delay, vocational rehabilitation, workplace costs, administrative and legal costs, and pain and lost quality of life" (U.S. Department of Transportation 1994).

2015) (U.S. Fish and Wildlife Service 2014; U.S. Environmental Protection Agency 2016; U.S. Congressional Budget Office 2016). Losses from DVCs were about half of total spending on big game hunting equipment and trip-related expenses in 2011 ($17.8 billion) (U.S. Fish and Wildlife Service and U.S. Census Bureau 2014). Furthermore, the problem has worsened over time—animal-vehicle collisions, 90 percent of which are collisions with deer, increased by an estimated 50 percent nationwide between 1990 and 2004 (Huijser et al. 2008). Losses likely have continued to grow since then as the white-tailed deer population increased from 15 million in 1984 to about 29 million in 2010 (VerCauteren et al. 2011).

Previous research links DVCs to several broad categories of variables, including exposure, engineering features of roads, landscape characteristics, and deer or driver behavior. Consistent with intuition, DVCs tend to be more frequent with higher deer population (DeNicola and Williams 2008; Hussain et al. 2007; Knapp, Khattak, and Oakasa 2005) and traffic volume (Farrell and Tappe 2007; McShea et al. 2008; Meyer and Ahmed 2004). DVCs also are more frequent on roads with higher posted speed limits (Found and Boyce 2011; Ng, Nielson, and St Clair 2008; Sudharsan, Riley, and Campa III 2009) and with shorter or obstructed lines of sight (Bashore, Tzilkowski, and Bellis 1985; Meyer and Ahmed 2004). DVCs generally peak in November during the mating season or “rut,” with most collisions occurring at dawn and dusk throughout the year (Allen and McCullough 1976; Finder, Roseberry, and Woolf 1999; Hothorn et al. 2015). DVCs also tend to occur more frequently in diverse and fragmented landscapes (Finder, Roseberry, and Woolf 1999; Found and Boyce 2011; Mckee and Cochran 2012). The effect of urban (Gkritza, Baird, and Hans 2010; Nielsen, Anderson, and Grund 2003; Farrell and Tappe 2007; Mckee and Cochran 2012), forest (Bashore, Tzilkowski, and Bellis 1985; Meyer and Ahmed 2004; Found and Boyce 2011; Grovenburg et al. 2008), and agricultural land cover

(Hubbard, Danielson, and Schmitz 2000; Iverson and Iverson 1999; Mckee and Cochran 2012) on DVCs is less clear cut, with some studies finding positive impacts and some finding negative impacts.

Most previous research focuses on identifying the characteristics of "hotspots," or areas with especially high DVCs (Bashore, Tzilkowski, and Bellis 1985; Biggs et al. 2004; Finder, Roseberry, and Woolf 1999; Found and Boyce 2011; Nielsen, Anderson, and Grund 2003; Romin and Bissonette 1996). Understanding these characteristics can help traffic safety engineers target mitigation strategies (e.g. fences and deer warning signs) and design safer roads. Results from these studies tend not to be generalizable, however, because the models are designed to be highly predictive of the study area rather than identify causal relationships. In addition, the required data are expensive and difficult to collect. Thus, these studies tend to measure independent variables in small buffer areas along the roadside edge, usually for a small number of sites.

This paper investigates the relationship between deer abundance and DVCs at a broader spatial scale. This is important because location-specific interventions could displace DVCs to different areas, and research focused on specific locations will fail to capture these effects. Also, it is very difficult to estimate deer population in a small road-side buffer; a larger unit of analysis can allow the researcher to control for deer population. A handful of previous studies measure how county-level characteristics affect the frequency of DVCs. The findings from these studies are generally in line with the hotspot literature. In addition, all studies found that DVCs increase in response to higher deer abundance (Hussain et al. 2007; Knapp, Khattak, and Oakasa 2005; Mysterud 2004; Seiler 2004; Schwabe et al. 2002). Rolandsen et al. (2011) find similar results for moose and moose-vehicle collisions in Norway.

These existing county-level studies provide a foundation for identifying the most important determinants of DVCs at a broad geographic scale; however, several data and methodological limitations may introduce undesirable properties of coefficient estimates. Small sample sizes (N=9, T=1 and N=5, T=34, respectively in Iverson and Iverson 1999 and Mysterud 2004), imprecisely measured covariates (in Schwabe et al. 2002; Mysterud 2004; Seiler 2004; Hussain et al. 2007; Rolandsen et al. 2011), replication of data values across years as proxies for missing values (in Hussain et al. 2007), and inclusion of few covariates (in Schwabe et al. 2002; Mysterud 2004; Knapp, Khattak, and Oakasa 2005) could all contribute to biased or inconsistent coefficient estimates. Lastly, most of these studies pooled data across time for spatial analysis and across counties for time series analysis; only one study used panel data methods (Rolandsen et al. 2011).

This paper builds on the existing DVC literature in three fundamental ways. First, it develops a unique panel dataset, covering 88 Ohio counties between 2001 and 2013 and 63 Wisconsin counties. Such data allows controls for time-invariant, unobserved county characteristics. Second, the analysis includes covariates that contribute to overall vehicle collisions but have not been investigated previously as factors in DVCs, namely precipitation and temperature. Lastly, it uses an instrumental variables approach to reduce the impact of measurement error and reverse causality on coefficient estimates.

These results also contribute to the literature that measures the economic impacts of vehicle collisions more broadly. Economists have investigated many factors that influence traffic safety, such as mandatory seat-belt laws and speed limits (Michener and Tighe 1992), drunk driving (Levitt and Porter 2001), fuel economy standards (Jacobsen 2011), vehicle size (Li 2012), and Daylight Saving Time (Smith 2016). Most prior studies focus on fatal collisions, which are critical to understand because mitigating such collisions prevents the loss of human life (as well as large economic losses). However, fatal collisions only account for 0.2 percent of all collisions (Blincoe et al. 2015). Research on the remaining 99 plus percent of collisions could illuminate strategies to minimize the impacts of crashes on a large segment of the population. Deer-vehicle collisions (DVCs) constitute 7 percent of all vehicle collisions and 24 percent of single-vehicle collisions (Huijser et al. 2008; National Highway Traffic Safety Administration 2008).

The rest of this Chapter proceeds as follows. Sections 2 and 3 describes the conceptual model and estimation methods, respectively. Section 4 outlines data sources. Section 5 highlights the main results. Sections 6 and 7 include a discussion of findings and concluding remarks, respectively. Section 8 includes all tables and figures.

2. Conceptual Model

Previous research identifies several categories of variables that determine the frequency and location of DVCs, namely exposure, landscape characteristics, engineering features of roads, and deer or driver behavior (see Introduction). I am not aware of any previous studies that investigate the impact of weather on DVCs, although in-line visibility and road surface conditions affect the risk of any vehicle collision.

Five categories of variables define the conceptual model

$$DVC_{it} = \boldsymbol{\alpha}'\boldsymbol{Exposure}_{it} + \boldsymbol{\beta}'_1\boldsymbol{Weather}_{it} + \boldsymbol{\beta}'_2\boldsymbol{Landcover}_{it} + \boldsymbol{\beta}'_3\boldsymbol{Engineering}_{it} + \boldsymbol{\beta}'_4\boldsymbol{Behavior}_{it} + u_{it}$$

where $Exposure_{it}$ is a matrix of variables that determine the likelihood of a deer and driver encountering each other in county i at time t, namely deer population and annual vehicle miles traveled (VMT); deer population is the main variable of interest. $Weather_{it}$ contains variables that affect in-line visibility and road surface conditions, such as rain and snow. $Landcover_{it}$ contains variables that affect deer foraging or roadside visibility, such as dominant landscape type and diversity. $Engineering_{it}$ contains variables that influence driver reaction times or the likelihood of a deer crossing, such as speed limit, number of lanes, and in-line visibility. $Behavior_{it}$ contains variables that measure deer and driver behavior, such as rutting, seasonal migration, driver experience, or impaired driving. Lastly, u_{it} is the random error.

Deer population and annual VMT (the total number of miles driven by all residents in a county and year) are the most important exposure variables in previous studies. This finding is intuitive—the more deer there are near roads and the further people are driving, the more likely the two will meet. The model includes both variables.

Forest, farmland, and urban areas are the most important land cover types for predicting DVCs. The model includes forest and farmland (measured in acres), but not urban areas. In the study area, these three categories account for almost all land cover and therefore are highly inversely correlated. Landscape diversity also is important in site level studies. However, this variable likely is a proxy for deer population because deer tend to prefer more heterogeneous landscapes. The model directly controls for deer population, so landscape diversity is redundant and excluded from the model.

Precipitation likely is the most important weather-related determinant of DVCs. Rain and snow create slippery road conditions that could increase the probability of a crash, even if drivers compensate by driving more slowly. Years with very large amounts of rain or snow could have a smaller effect on DVCs because drivers gain experience with poor conditions or a larger effect because drivers become desensitized to the risks of inclement weather. The model includes data on total precipitation. Snow cover data were not available for the full study period. The number of days with minimum temperature below 32 degrees Fahrenheit (°F) is an indicator for years with potentially more snowfall and ice.

High temperatures conceivably could impact DVCs through heat stress of drivers or deer. Heat may increase driver irritability and reaction times, which would tend to increase collisions. Leard and Roth (2015) found the effect of temperatures on vehicle collisions is highest for temperatures above 80°F. In contrast, heat stress may cause deer to decrease activity or seek thermal cover, which would tend to reduce DVCs. Parker and Robbins (1984) found that for mule deer (*Odocoileus hemionus hemionus*) the upper critical temperature (the point at which heat gain is greater than heat dissipation) is 77°F. The model includes the number of days in the year with maximum temperature over 80°F is an indicator of heat stress.

Road characteristics can influence DVCs through effects on driver reaction times and road conditions in adverse weather; some features also seem to deter deer from crossing roads. The most common engineering features included in previous DVC studies are posted speed limit, number of lanes, infrastructure mileage, slope, visibility, and presence of lane dividers (Clevenger et al. 2015; Farrell and Tappe 2007; Lao et al. 2011; Gkritza et al. 2014; Hubbard, Danielson, and Schmitz 2000; Mckee and Cochran 2012; Meyer and Ahmed 2004; Sudharsan, Riley, and Campa III 2009; Ng, Nielson, and St Clair 2008). I assume that these and all other engineering factors (deer warning signs, fencing, road curvature, roadside topography, etc.) are fixed over time within counties during the study period. This assumption is likely realistic at a broad geographic scale such as the county-level.

Deer behavior has a large effect on DVCs. Across the United States, DVCs generally peak in November, which coincides with both the rut (breeding behavior) and the firearm hunting season. Bucks are less wary and move more during the rut, leading to more frequent road crossings (Allen and McCullough 1976). I assume rutting behavior is constant conditional on deer population and habitat type. I do not include harvest as a covariate because harvest is highly correlated with deer density. In fact, harvest is used often as a proxy for deer population in the DVC literature (Farrell and Tappe 2007; McCaffery 1973; Mysterud 2004; Schwabe et al. 2002; Seiler 2004; Sudharsan et al. 2005) and is the basis for the common “sex-age-kill” method of estimating deer population (Millspaugh et al. 2009).

It is important to note that the model estimates the effects of deer population on DVCs *net* of drivers adapting. For example, drivers may avoid driving in DVC hotspots or during dawn and dusk in November. The estimates will not reflect the economic costs of these avoidance behaviors, but allowing drivers to adapt is a more realistic model of the causal impact of deer population on DVCs. Other aspects of driver behavior may be important, such as speed or driving while impaired. I assume these factors are either fixed over time or reflect broader socio-economic conditions that equally impact all counties in the study area.

With the assumptions outlined above, the final conceptual model is as follows

$$DVC_{it} = \alpha_1 DeerPop_{it} + \alpha_2 VMT_{it} + \beta_1 Precip_{it} + \beta_2 DaysBelow32F_{it} + \beta_3 DaysAbove80F_{it} + \beta_4 Forest_{it} + \beta_5 Farm_{it} + \theta_i + \delta_t + u_{it}$$

where for county i at time t, $DeerPop_{it}$ is the prehunt deer population, VMT_{it} is annual vehicle miles traveled, $Precip_{it}$ is total annual precipitation, $DaysBelow32F_{it}$ is the number of days in the year with a minimum temperature below 32°F, $DaysAbove80F_{it}$ is the number of days in the year with a maximum temperature above 80°F, $Forest_{it}$ is the number of forested acres, $Farm_{it}$ is the number of acres of farmland, θ_i is a vector of county effects, δ_t is a vector of year dummy variables that account for secular changes in DVCs, and u_{it} is the idiosyncratic error.

The estimated model assumes DVCs are impacted not by the numerical change in deer, but by percentage change. As such, all variables are log-transformed prior to estimation.[5] In addition, the log transformation helps to scale effects across counties that have very different levels of deer and VMT. The final estimated model is as follows

$$\ln(DVC_{it}) = \alpha_1 \ln(DeerPop_{it}) + \alpha_2 \ln(VMT_{it}) + \beta_1 \ln(Precip_{it}) + \beta_2 \ln(DaysBelow32F_{it}) + \beta_3 \ln(DaysAbove80F_{it}) + \beta_4 \ln(Forest_{it}) + \beta_5 \ln(Farm_{it}) + \theta_i + \delta_t + u_{it}.$$

3. Estimation Methods

Fixed effects v. Random effects

Assumptions about the nature of the county effect θ_i determine the most appropriate estimation strategy. Candidate estimation methods include pooled ordinary least squares (OLS), random effects, and fixed effects. For pooled OLS to yield consistent coefficient estimates, the composite error term $v_{it} = \theta_i + u_{it}$ cannot be correlated with any of the explanatory variables and must not be serially correlated. This requirement is unlikely to hold because, at a minimum, as the idiosyncratic errors u_{it} for a given county likely are correlated over time. Random effects require that the county effect be uncorrelated with all explanatory variables in all periods, or $E[\theta_i|\boldsymbol{x}_i] = 0$. This requirement is also unlikely to hold. For example, road density is unobserved and mostly time-invariant and so would be captured by the county effect. Road density is likely negatively correlated with both deer population and forest cover because road infrastructure tends to correlate with more heavily-developed areas. As such, including the county effect in the

[5] In the data set, there were no county-years with zero values.

composite error term leads to omitted variables bias. Therefore, a fixed effects specification is preferred.

Even though fixed effects mitigate potential omitted variables bias from time-invariant, unobserved variables, the coefficient estimates may still be biased and inconsistent because of time-variant, systematic measurement error and potential reverse causality. An instrumental variables approach can mitigate these problems.

Measurement Error

The dependent variable, the number of police-reported DVCs in a county-year, underestimates the true number of DVCs because some crashes do not meet reporting thresholds,[6] motorists may not report the crash, or police may not have the time or resources to attend the scene. Underreporting may be positively correlated with deer population. As the deer population increases, more collisions likely occur; more frequent DVCs increase the resource burden on the responsible agency, thus increasing the probability that a DVC is not reported. Consider the true model $DVC^* = \alpha_1 DeerPop^* + \boldsymbol{x}'\boldsymbol{\beta} + v$, with $DVC = DVC^* + e$ being the measurement error equation, $\boldsymbol{x}' = (x_1, x_2, \dots x_{k-1})$, and $\boldsymbol{\beta} = (\beta_1, \beta_2, \dots \beta_{k-1})'$. In the estimable equation $DVC = \alpha_1 DeerPop^* + \boldsymbol{x}'\boldsymbol{\beta} + e + v$, the error $u = e + v$ is negatively correlated with $DeerPop^*$ under the assumptions described above. This correlation results in inconsistent estimates of all coefficients and a downward bias on α_1.

Deer abundance is also measured with error. The Wisconsin Department of Natural Resources (WDR) used the sex-age-kill (SAK) method to estimate the size of the deer population

[6] A crash is "reportable" by police in Ohio and Wisconsin only if it meets one of the following three criteria: 1) injury or fatality of a person, 2) damages of $1,000 or more to property owned by any one person, or for Wisconsin only 3) damages of $200 or more to government property except motor vehicles (National Highway Traffic Safety Administration n.d.).

for the period of this study. This method is less accurate for smaller populations (Millspaugh et al. 2009). Let $DeerPop = DeerPop^{*} + \epsilon$ be the measurement error equation for deer population. The estimable equation then becomes $DVC = \alpha_1 DeerPop + \boldsymbol{x}'\boldsymbol{\beta} + e - \alpha_1\epsilon + v$. With the SAK data, it is likely that $E[\epsilon|DeerPop^{*}] = 0$ and $Cov(DeerPop^{*}, \epsilon) \neq 0$ for reasons noted above. Therefore, the error $u = e - \alpha_1\epsilon + v$ is correlated with observed deer population $DeerPop$. This results in inconsistent and biased estimates of all coefficients, including α_1.

Simultaneity and Reversed Causality

The goal of the model is to identify the causal effect of changes in deer population on DVCs, but wildlife managers set deer population goals and harvest quotas partly based on "social carrying capacity" or resident's tolerance for deer damage (Ohio Department of Natural Resources n.d.; Wisconsin Department of Natural Resources 1998). For example, managers may not allow the deer population to get large in areas with a high potential for DVCs or where drivers have experienced high DVCs and advocated for stricter deer control. As such, DVCs may affect the population of deer through management decisions. If the model does not account for this relationship, coefficient estimates will be biased.

Consider the following system of structural equations, ignoring the measurement error described above

$$DVC = \alpha_1 DeerPop + \boldsymbol{z_1}'\boldsymbol{\beta_1} + u_1 \tag{1}$$

$$DeerPop = \alpha_2 DVC + \boldsymbol{z_2}'\boldsymbol{\beta_2} + u_2 \tag{2}$$

Equation (1) contains the coefficients of interest, particularly α_1. Assume $E[\boldsymbol{z_1}u_i] = E[\boldsymbol{z_2}u_i] = \boldsymbol{0}$ for $i = 1,2$. Consistent estimation of α_1 using OLS requires that $Cov(DeerPop, u_1) = 0$. Plugging (1) into (2) and assuming $\alpha_2\alpha_1 \neq 1$ yields the reduced form equation for deer population

$$DeerPop = \boldsymbol{z_1}'\boldsymbol{\pi_1} + \boldsymbol{z_2}'\boldsymbol{\pi_2} + r_2 \tag{3}$$

where $\boldsymbol{\pi_1} = \frac{\alpha_2}{1-\alpha_2\alpha_1}\boldsymbol{\beta_1}$, $\boldsymbol{\pi_2} = \frac{1}{1-\alpha_2\alpha_1}\boldsymbol{\beta_2}$, and $r_2 = \frac{\alpha_2 u_1 + u_2}{1-\alpha_2\alpha_1}$. Equation (3) is a projection and can be estimated using OLS because $E[\boldsymbol{z}r_2] = 0$ by assumption. $Cov(\text{DeerPop}, u_1) \neq 0$ because $Cov(r_2, u_1) \neq 0$; therefore, OLS estimates will be biased and inconsistent for (1), the equation of interest.

Signing the simultaneity bias is difficult in multiple linear regression, but simplifying the model can provide suggestive results (Wooldridge 2013). After dropping $\boldsymbol{z_1}$from (1), $Cov(DeerPop, u_1) = Cov(DeerPop, r_2) = \frac{\alpha_2}{1-\alpha_2\alpha_1}\sigma_1^2$ where $Var(u_1) = \sigma_1^2 > 0$. I hypothesize that $\alpha_2\alpha_1 < 0$ and $\alpha_2 < 0$. Therefore the estimator for $\alpha_1$is likely biased downward, ignoring any interactions between measurement error and simultaneity.

However, any simultaneity bias likely will be small because of the timing of harvest decisions. In the study area, deer harvest quotas are usually proposed in February and finalized between April and June for the following November to January harvest season (Ohio Department of Natural Resources 2017a; Wisconsin Department of Natural Resources 2001). In this study, period t covers July 1 to June 30 of the following year, and deer population is measured in October (see Data section for more details). Therefore, the harvest quota setting process that occurs in period t (e.g. February 2014) affects harvest and posthunt population in period $t + 1$ (e.g. November 2014). In other words, contemporaneous DVCs do not affect contemporaneous deer population through the management mechanism.

Instrument Choice

An instrumental variables approach can eliminate the effects of both measurement error and simultaneity on coefficient estimates. Recall the structural equations (1) and (2), where

$u_1 = e - \alpha_1\epsilon + v_1, u_2 = \epsilon - \alpha_2 e + v_2, E[u_1] = E[u_2] = 0, E[\boldsymbol{z}u_1] = E[\boldsymbol{z}u_2] = 0$, and $Cov(DeerPop, u_1) \neq 0$. Instrumental variables (or two-stage least squares for over-identified models) can consistently estimate the parameters in (1) if the following two restrictions hold. First, the exclusion restriction requires that at least one element of $\boldsymbol{z_2}$ is excluded from (1); these variables are the excluded instruments, or "instruments" for brevity henceforth. Second, the validity restriction requires that the coefficients on the instruments jointly do not equal zero in the reduced form for deer population. In other words, an exogenous variable or set of variables is an appropriate instrument if it affects DVCs only through impacts on deer population, controlling for all other exogenous variables in the structural equations.

Indicators of lagged winter severity and lagged deer population are candidate instruments. Both are reliable predictors of changes in deer population levels (Wisconsin Department of Natural Resources 2001). In the study area, deer conceive in October to November and give birth the following May to June. Severe conditions in the winter during gestation can negatively impact the health of pregnant does and reduce fawn survival and recruitment the following spring due to poor maternal health (Figure 1). Severe weather can also lead to starvation. Exposure to temperatures less than 0°F and snow deeper than 18 inches are important thresholds beyond which the metabolic rate of deer increases and the likelihood of population impacts increases (Hegel et al. 2010). I use the annual number of days with minimum temperature below 0°F and total winter precipitation as indicators of winter severity in the model. Ideally the model would include snow depth, but data are not available for the full study period at the required geographic scale. Lagged winter severity also is highly likely to satisfy the exclusion restriction. It is difficult to identify pathways through which last year's weather could affect contemporaneous DVCs directly.

Lagged deer population is probably a stronger instrument than weather because deer populations are determined by density dependent growth (Bowyer et al. 2014), but lagged deer population may not strictly satisfy the exclusion restriction. For example, if drivers saw numerous deer near the road or if they hit a deer last year, they may undertake more avoidance behaviors this year that tend to reduce DVCs. However, persistent behavioral change seems unlikely. For example, seasonal wildlife warning signs are not effective at reducing DVCs (Huijser et al. 2009); historical indications of high deer population probably have even less effect. Twice-lagged deer population is even less likely to induce contemporaneous behavioral changes than once-lagged deer population because it would require even more long-lasting behavioral changes.

The Data section describes data availability in more detail, but it is worth noting here that the independent variables are available for many years prior to the first value of the dependent variable. Therefore, the number of observations does not decline by using lagged variables as instruments.

4. Data

Geographic coverage

I collected data for this study from all 48 coterminous U.S. states. While nearly all states provided vehicle collision data, deer population data was scarcer. Only 12 states responded that they estimate deer populations, and among these only Missouri, Ohio, and Wisconsin provided estimates at the county level.[7] The remaining 9 states provided deer population based on

[7] The estimates for Wisconsin are for deer-management units, which mostly follow county boundaries. I converted these data to a county basis using GIS for consistency (see Data section for further details).

ecological boundaries or other broad geographic regions. It is beyond the scope of this study to convert these data to a county basis. An additional 21 states responded that they do not specifically measure deer abundance. These states provided antlered/buck harvest, which is highly correlated with abundance and is the basis for common deer population estimation methods (Lang and Wood 1976; Millspaugh et al. 2009). However, without additional information about the deer herd, it is not possible to translate harvest to population estimates. Among the three states that provided deer population data at the county level, I ultimately included Ohio and Wisconsin in the final analysis and excluded Missouri because DVCs are much lower in Missouri. In the sample, there was on average about 300 DVCs per county per year in Ohio and Wisconsin versus only 30 in Missouri. A Poisson or negative binomial model would be more appropriate for Missouri because DVCs are so infrequent, whereas standard OLS techniques are appropriate for Ohio and Wisconsin.[8]

Deer-vehicle collisions

The Ohio Department of Public Safety publishes DVCs by month and county in its annual *Traffic Crash Facts* report available online for 2001 to 2015 at the time of data collection for this study (Ohio State Highway Patrol n.d.). The Wisconsin Traffic Operations and Safety Laboratory (TOPS Lab) at the University of Wisconsin-Madison provided all crash reports that police submitted to the Wisconsin Department of Transportation (WDOT) between January 1, 1994 and December 31, 2015 (Wisconsin Traffic Operations and Safety Laboratory 2017). Individual crash records are not available for earlier years.

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[8] I estimated the final model using Missouri data to test this claim. Several coefficient estimates had perverse signs, which supports that the OLS assumptions do not hold.

I aggregated crash data on a midyear basis rather than a calendar year basis. Data for period t cover July 1 to June 30 of the following year (e.g. July 1, 2013 to June 30, 2014 is labeled t = 2013) (Figure 1). This aggregation technique is useful because, as noted previously, winter severity in December through April is an important determinant of the prehunt deer population the following October. This definition of a year allows the winter immediately preceding measurement of the deer population to be a lagged (i.e. exogenous) variable.

I excluded several Wisconsin counties for which I had concerns about data quality. The individual who provided the DVC data for Wisconsin noted anecdotal evidence that police may have stopped attending DVC crash scenes in some counties, except when the crash causes a road hazard, human injury, or fatality (Donald Lyden, personal communication). However, a comprehensive accounting of these changes is not available. To investigate potential breaks in series, I visually inspected the longest time series of DVCs by county available, which WDOT provided for calendar years 1988 through 2013. These data revealed obvious discontinuities in reported DVCs for the following counties and years, with a high number of DVCs in early years and a suddenly and persistently low number of DVCs beginning in the year noted: Trempealeau county 1994 onward, Marinette county 1995 onward, Oconto and Wood counties 1996 onward, Adams and Clark counties 2003 onward, and Pierce and Rock counties 2004 onward. Some of these periods correspond to the election of new sheriffs. Dummy variables for post-break periods could solve the problem if the change in reporting only involved a level shift with the same variation around the mean both pre- and post-break. This assumption is unlikely to hold because the number of DVCs that cause an injury or fatality in a year (the basis for post-break reporting) are infrequent and fairly constant year-to-year. Therefore, I removed these counties from the dataset. I also excluded Menominee County, which is a tribal area that is not required to report

DVCs to WDOT. Overall, I excluded 9 of 72 Wisconsin counties or a grand total of 144 of 1,152 observations.

Deer population

The Ohio Department of Natural Resources (ODNR) provided prehunt deer population by county for 1981 to 2013. The Wisconsin Department of Natural Resources (WDNR) provided posthunt deer population density by Deer Management Unit (DMU) for 1981 to 2013. Population density is defined as the number of deer per square mile of deer range, with deer range defined as "all permanent cover—forest, woodlot, brush-covered land, or marsh—at least ten acres or more in size" (Wisconsin Department of Natural Resources 2001). WDNR also provided us maps showing the DMU boundaries for each of these years and a raster file showing the presence or absence of deer range on a 0.77-km grid in 1993, the last year deer range was measured.

Historically, Wisconsin's DMU boundaries followed roads or other natural features that would be easy for hunters to identify in the field. In 2013, the WDNR revised DMUs to follow primarily county boundaries. At that time, they estimated deer population for the new DMUs for 2002 onward using the procedure described below. I replicated this procedure using the U.S. Census Bureau's Tiger/LINES 2015 county boundaries as a basis, rather than the new DMU boundaries, for 1988 onward. The procedure is as follows: 1) join the deer density data to the DMU map, 2) intersect the DMU map with the deer range map and the 2015 county boundary map, 3) delete all polygons for which deer density is missing; these polygons are parks and other small areas where the WDNR does not measure deer density, 4) delete all polygons outside of deer range, 5) calculate the area in square miles of each remaining polygon, 6) multiply deer density (deer/square mile) by square miles for each polygon to estimate the number of deer in that polygon, 7) sum the calculated number of deer by county.

This procedure assumes that deer are uniformly distributed across the deer range in each DMU. It also assumes that the deer in state parks and other areas for which deer density data is not available is constant over time. This assumption is probably inconsequential because the true variations from the mean in these areas likely constitute a negligible proportion of county estimates.

WDNR defines prehunt population as posthunt population plus 1.15 times deer harvest (Wisconsin Department of Natural Resources 2001). The inflation of harvest by 15 percent is, according to WDNR, “an arbitrary adjustment to account for unretrieved wounding loss, registration non-compliance, illegally harvested deer, etc.” WDNR provided total harvest by county and year, which I used to calculate prehunt deer population according to the WDNR definition.

Vehicle miles traveled

The Ohio Department of Transportation (ODOT) provided daily VMT for all roads for 2001 to 2014. These data are based on average annual daily traffic over the calendar year, January 1 to December 31. I calculated annual VMT by multiplying daily VMT by 365. WDOT provided annual VMT on all roads (local roads, collectors, arterials, expressways, and interstates) by county for 1998 to 2014. WDOT measures VMT over the calendar year, January 1 to December 31.

As noted previously, DVCs are on a midyear basis rather than calendar year basis. I used the average of annual VMT in the two calendar years that overlap the midyear DVC estimates as the midyear estimate of VMT. For example, in the midyear period $t = 2013$, which covers July 1, 2013 to June 30, 2014, annual VMT for calendar year 2013 pertain to the first half of this period while annual VMT for calendar year 2014 pertain to the second half of this period. The midyear VMT estimate for period t = 2013 is the average of VMT for calendar years 2013 and 2014 (Figure 1). Results are robust to using either the earlier or later overlapping calendar year data instead of averaging the two, although the coefficient on VMT is usually somewhat attenuated when using calendar year data, likely due to larger measurement error.

Weather

Daily minimum temperature, maximum temperature, and precipitation (rain plus melted snow) are available online from the PRISM Climate Group at Oregon State University (PRISM) for the United States for January 1, 1982 to November 30, 2015. A PRISM day is defined as 1200 UTC to 1200 UTC (6 a.m. to 6 a.m. Central Standard Time). PRISM labels the observations by their ending day (e.g. a day defined by 6 a.m. January 1 to 6 a.m. January 2 is labeled January 2). The data are provided as 4-kilometer grid raster files. I used ArcGIS and the U.S. Census Bureau's 2015 Tiger/LINES county boundary map to calculate spatially-weighted averages for each variable, county, and day.

I calculated the number of days where the county-average maximum temperature is above 80 degrees Fahrenheit (°F), minimum temperature is below 0°F, and minimum temperature is below 32°F. I also calculated total precipitation (inches) and winter precipitation (inches) (winter is defined as December 1 to April 30). For comparability with the DVC data, estimates are on a midyear basis where period t covers July 1, year t to June 30 year $t+1$ (Figure 1).

As noted in the Conceptual Model section, the number of days with a maximum temperature above 80°F is an indicator of heat stress in both drivers and deer. Total winter precipitation and the number of days with a minimum temperature below 0°F are indicators of winter severity. The number of days with a minimum temperature below 32°F is an indicator of snowy or freezing conditions. Lastly, total precipitation is an indicator of poor road conditions.

Habitat

Annual land use/land cover data for the United States are available online from the U.S. Geological Survey's Earth Resources Observation and Science (EROS) Center, National Assessment of Ecosystem Carbon and Greenhouse Gas Fluxes project for 1992 to 2015. The data are provided as 250-meter grid raster files. Data for 1992 to 2005 are from the baseline historical conditions dataset; data for 2006 to 2015 are from the modeled annual land-cover maps of the B1 scenario dataset. I used this scenario based on the guidance of USGS staff (Terry Sohl, personal communication). I used ArcGIS and the U.S. Census Bureau's 2015 Tiger/LINES county boundary map to calculate the total area for each land cover class, county, and year. "Forest" is the sum of Deciduous Forest, Evergreen Forest, Mixed Forest, Mechanically Disturbed National Forests, Mechanically Disturbed Other Public Lands, and Mechanically Disturbed Private land cover categories. "Farmland" is the sum of Cropland and Hay/Pasture Land.

5. Results

DVCs cause large economic losses in the study area. More than 650,000 police-reported DVCs occurred during the study period, about 26,000 per year on average in Ohio and 19,000 per year in Wisconsin. DVCs were 7 percent and 15 percent of all reported vehicle collisions in Ohio and Wisconsin, respectively. Based on the national rate of under-reporting (3 reported DVCs to 7 unreported DVCs in the most conservative scenario in Huijser et al. 2008), at least two million total DVCs likely occurred during the study period, or about one DVC over the period for every seven currently-licensed drivers in Ohio and every four currently-licensed drivers in Wisconsin (U.S. Department of Transportation 2016). Economic losses associated with reported DVCs in these states are more than $400 million each year on average ($243 million in Ohio and $174 million in Wisconsin); accounting for under-reporting, economic losses exceed $1.4 billion each year ($810 million in Ohio and $577 in Wisconsin), or about one-third of annual spending on state highways in both states (Ohio Office of Budget and Management n.d.; Wisconsin Department of Transportation, n.d.).

As expected, deer abundance has a large and statistically significant effect on the frequency of DVCs. In the OLS specification using the full sample (Table 4), a 1 percent increase in deer population leads to a 0.43 percent increase in DVCs ($p < 0.01$). This effect is much larger in Ohio than in Wisconsin, with elasticities of 0.99 and 0.28 respectively ($p < 0.01$) (Table 5 and Table 6). Although most of the other covariates had little impact on the estimated coefficient for deer population, the specification that includes the full set of variables (Column 7) is preferred. Each of these variables theoretically has a causal impact on DVCs and is correlated with deer population in the data. As such, their exclusion would cause omitted-variable bias, however small.

VMT has the largest proportional impact on DVCs. A 1 percent increase in VMT leads to a 0.71 percent increase in DVCs ($p < 0.01$). The effect in the full sample is about twice the size of that in either state individually, with point estimates of 0.39 in each state. This effect is statistically significant in Wisconsin ($p < 0.10$) but not in Ohio.

Weather is also an important determinant of DVCs, but the effects are heterogeneous across states. In the full sample, cold weather has the largest effect among the weather variables. A 1 percent increase in below-freezing days decreases DVCs by 0.57 percent ($p < 0.01$); this effect is small and statistically indistinguishable from zero in each state individually. Precipitation has a small but statistically significant effect, with an elasticity of about 0.16 in both the full sample ($p < 0.01$) and in Ohio ($p < 0.05$) and no statistical effect in Wisconsin. The number of hot days has a statistically significant effect only in Ohio, with an elasticity on par with that for VMT (0.34, $p < 0.01$).

This study does not elucidate the effect of land cover on DVCs. The lack of within-county variation in forest and farmland suggests that the coefficient estimates for these variables are poorly identified. The within-county standard deviation is between one and four acres, or about one percent of the mean (Table 1, Table 2, and Table 3). The effects of land cover are statistically significant only in Wisconsin, where forest decreases and farmland increases DVCs. This finding is consistent with intuition; however, again, the reader should interpret these estimates with caution.

For the instrumental variables regressions, I tested all 15 possible combinations of the four candidate instruments—once-lagged below-zero days, winter precipitation, and deer population, and twice-lagged deer population—using the full sample and Ohio and Wisconsin alone. For most over-identified models, the Hansen's J statistic rejects the null hypothesis that the over-identifying restrictions are valid; I exclude all such models. I also exclude all remaining over-identified models because the first stage F statistics are lower than the just-identified models. I also exclude models that use below-zero days as an instrument because the F statistic is below one in every sub-sample. The three final instruments are once-lagged winter precipitation and deer population and twice-lagged deer population (Table 7, Table 8, and Table 9). Each of these instruments satisfy the common rule-of-thumb that a strong instrument should have a first stage F statistic of at least 10 (Staiger and Stock 1997).

Among the chosen instruments, lagged winter precipitation (Column 2) is preferred because it is the most likely to satisfy the exclusion restriction, as noted previously. This instrument is three or four times stronger in the full sample than in either state individually, likely due to greater cross-county variation in weather across a broader geography (i.e. the year effects are less likely to absorb the impacts of weather). Surprisingly, more winter precipitation leads to a larger prehunt deer population the following fall in all sub-samples (Table 10, Table 11, and Table 12). This may indicate that winters with higher precipitation (rain plus melted snow) are milder rather than more severe. This possibility is supported by basic thermodynamics. The amount of water vapor that the atmosphere can hold increases exponentially with temperature according to the Clausius-Clapeyron equation. If a constant fraction of available water vapor condenses and falls as precipitation, then precipitation will be positively correlated with temperature. Indeed, daily mean temperature and precipitation during winter are positively correlated in the source data. Although the positive relationship between winter precipitation and subsequent deer abundance could be spurious, the lagged deer population instruments provide a redundant confirmation of the results. Both lagged deer population instruments are very strong ($F > 1{,}100$ for once-lagged and 230 for twice-lagged in all sub-samples) and have the expected positive sign in the first stage.

Nearly all coefficient estimates are robust between the OLS and instrumental variables specifications, both in the full sample and for each state individually. The only exception is that the coefficient for deer population in Ohio doubles between the OLS and instrumental variables specifications (elasticities of 0.99 and 1.98, respectively, in the preferred models). Statistical significance also generally does not change across specifications, except the coefficient for deer population in Wisconsin is only significant when using lagged deer population as an instrument.

Overall, these results suggest that measurement error and reversed causality may not be very problematic in the data.

The economic impact scenarios that follow use the definition of elasticity $\varepsilon_{y,x} = \frac{\partial y}{\partial x}\frac{x}{y}$ and the point estimate and standard error of $\varepsilon_{y,x}$ in the preferred instrumental variables specification (Table 7, Column 2), evaluated at the county-year means of x and y for the full sample (Table 1). As such, the marginal changes presented should be interpreted as a change from the mean. Dollar values are the product of the predicted change in DVCs and the national average total economic loss from one DVC, \$9,234 (Huijser et al. 2008).

The marginal deer in the study area causes \$83 in economic losses from DVCs [90 percent confidence interval: \$31, \$134]. Equivalently, 112 additional deer [69, 294] cause one more DVC on average. A one-percent reduction in deer abundance across all counties in the study area would lead to 195 fewer DVCs [74, 316] and a \$1.8 million reduction in DVC losses each year [\$685 thousand, \$2.9 million]. In 2013 the deer population was roughly 26 above the population management goal in Ohio and 30 percent above the goal in Wisconsin (unpublished data).[9] A 30 percent reduction in the deer population across the study area, or roughly achieving the population target in both states, would lead to about 5,800 fewer DVCs each year and a \$54.1 million dollar reduction in DVC losses each year [\$20.5 million, \$87.6 million].

6. Discussion

The positive impact of deer population on DVCs may not be surprising, but the magnitude is interesting. In the study area, the annual estimated cost of “overabundant” deer is

[9] Ohio’s management goal is based on prehunt population while Wisconsin’s is based on posthunt population. ODNR and WDNR provided actual population and goal population by management unit for 2013.

$54 million or $83 per deer, when considering only the economic losses from DVCs.[10] Coincidentally, deer hunting licenses and permits generate about $34 million in revenue annually for the two states combined (Paul Neumann, personal communication), and the price for a resident deer harvest permit is $24 in both states (Ohio Department of Natural Resources 2017b; Wisconsin Department of Natural Resources 2016a). These results suggest that a transfer program from hunters to DVC victims could offset the DVC losses attributed to overabundant deer, although this is impractical in the real world.

However, DVCs are by no means the only cost of deer. There were an estimated 3,000 new cases of Lyme Disease in Wisconsin in 2015 (Wisconsin Department of Health Services 2016); deer are implicated as a major reservoir host for this disease. Deer populations also cause 90% of all wildlife damage to agriculture in the state (Wisconsin Department of Natural Resources 1998) (Wisconsin Department of Natural Resources 1998). While Ohio has a similar number of DVCs, these other sources of deer damage appear to be less problematic. Lyme disease is rare, and in a recent survey only 13 percent of farmers generally consider deer a nuisance (Ohio Department of Health 2017; Ohio Department of Natural Resources, n.d.). Regardless, deer may still be causing irreparable ecological effects in both states. Deer are keystone species in forest communities; at moderate densities, deer can suppress forest regeneration, alter the composition of tree species and understory herbaceous plants, and contribute to the spread of invasive species (Waller and Alverson 1997; Rooney 2001; Rooney and Waller 2003). These ecological impacts are difficult to monetize, but nonetheless represent major social losses associated with large deer populations.

[10] Overabundance is defined here as abundance exceeding the deer population management goal.

Reducing the deer population to mitigate the many costs of deer may reduce the economic benefits of deer hunting. It is not possible to determine the change in equilibrium hunting effort and expenditures with the available data, but aggregate measures may be illuminating. Deer hunters spent $276.9 million in Ohio (about one-third of reported and estimated unreported DVC losses) and $2.3 billion in Wisconsin (nearly four times estimated DVC losses) (Southwick Associates 2012a). The total economic impact of this spending (direct, indirect, and induced spending) was $443.7 million in Ohio and $3.6 billion in Wisconsin. Deer hunting supported nearly 40 thousand jobs in the two states, 90 percent of which were in Wisconsin. Despite the large and important economic impacts of deer hunting in these states (especially Wisconsin), it is conceivable that high deer populations actually could be hurting hunting value. In Ohio, stressors associated with large deer populations have led to a decline in overall herd condition and antler quality, and 90 percent of deer hunters state that herd quality is at least as important as deer numbers for setting population goals (Ohio Department of Natural Resources, n.d.). Overall, there is a pressing need for additional research that clarifies how the many costs and benefits of deer change with deer abundance.

There is also a need for future research on the impact of land cover on DVCs. As noted previously, the coefficient estimates on forest and farmland in this study are likely poorly identified due to low within-county variation in the sample data. Previous research does not clarify the issue. Most previous studies find that forests have a positive effect on DVCs (Bashore, Tzilkowski, and Bellis 1985; Farrell and Tappe 2007; Finder, Roseberry, and Woolf 1999; Found and Boyce 2011; Hubbard, Danielson, and Schmitz 2000; Mckee and Cochran 2012; Meyer and Ahmed 2004; Seiler 2004; Sudharsan, Riley, and Campa III 2009), but some find negative effects (Found and Boyce 2011; Grovenburg et al. 2008; Iverson and Iverson 1999;

Knapp, Khattak, and Oakasa 2005; Sudharsan et al. 2005). Similarly, the estimated effect of farmland is both positive (Gkritza, Baird, and Hans 2010; McCaffery 1973; Sudharsan, Riley, and Campa III 2009) and negative (Farrell and Tappe 2007; Hubbard, Danielson, and Schmitz 2000; Hussain et al. 2007; Iverson and Iverson 1999). It would be useful from a management perspective to know whether small-scale strategic changes in landcover close to roads could mitigate DVCs. If effective, these interventions could offer an alternative to more traditional and expensive DVC mitigation measures, such as fencing, or broad scale population reductions.

This is the first study of which I am aware that includes weather variables as predictors of DVCs, despite these variables being pervasive in the broader traffic safety literature. Previous research finds that extreme temperatures, either hot or cold, increase the frequency of vehicle collisions (Andreescu and Frost 1998; Leard and Roth 2015; Malyshkina and Mannering 2009). Although the effect of hot days on DVCs is not statistically significant on average in this study, the positive point estimate for the full sample and the statistically positive effect in Ohio are consistent with previous research that suggests driver irritability and slower reaction times on hot days increase vehicle collisions. In contrast, my finding that the number of below-freezing days reduces the frequency of DVCs is contrary to previous research. For all vehicle collisions, the positive effect of cold weather on DVCs is likely caused by slippery road conditions. In this study, it is possible that cold weather indeed does have an analogous effect on DVCs, holding deer abundance and movement fixed, but it is not possible to test this hypothesis with the available data. Recall that the observation period begins in summer (July), deer population is estimated in the fall (October), and DVCs continue to accumulate through the following winter. Any phenomenon that decreases deer population or movement during that winter would also tend to reduce DVCs during the same period.

The strong positive effect of precipitation on DVCs is consistent with previous research. There is a consensus that rain increases vehicle collisions (Andreescu and Frost 1998; Andrey and Yagar 1993; Bertness 1980; Eisenberg 2004; Fridstrøm et al. 1995; Levine, Kim, and Nitz 1995; Malyshkina and Mannering 2009; Shankar, Mannering, and Barfield 1995; Sherretz and Farhar 1978), while snow may increase (Andreescu and Frost 1998; Eisenberg 2004; Shankar, Mannering, and Barfield 1995), decrease (Fridstrøm et al. 1995), or have no effect on collisions (Aguero-Valverde and Jovanis 2006). Estimating the effects of rain and snow separately would be preferable, when the data is available. Given the overwhelming consensus in the broader traffic safety literature combined with the results of this study, future DVC research, especially the very common matched-pair hotspot studies, should control for extreme temperatures and precipitation to avoid confounding effects.

7. Conclusions

From the perspective of economic efficiency, wildlife management plans should maximize the total economic value of wildlife, with the optimal population equating the marginal benefit and marginal cost of deer. This paper quantifies the marginal DVC cost of deer and finds that relatively small reductions in deer abundance generate an economically significant reduction in DVCs. There is a need for research that quantifies the marginal impacts of deer on other major cost and benefit categories.

For DVC losses, the results from this study have several important methodological implications for future research. First, strategic aggregation of data across time can limit the impact of reversed causality on OLS estimates. Ideally, management decisions should occur in the period before the decision's impact on deer population is observed. Second, weather emerged as an important predictor of DVCs, presumably via impacts on road conditions and visibility as well as on deer populations. Matched-pair, cross-sectional DVC studies should directly control for precipitation and extreme temperature, as is common in the general vehicle collision literature. Parsing out the individual effects of rain and snow separately may reveal interesting insights about driver behavior and risk avoidance in inclement weather. Lastly, the coefficient estimates for the impact of landscape characteristics on the frequency of DVCs should be interpreted with caution. These coefficient estimates are not well-identified due to small within-county variation over time.

Looking to the future, the economic costs of DVCs likely will continue to grow as humans encroach further into deer habitat. There are few feasible policies that could reduce human population growth or the amount that people drive, so deer population management will become increasingly important.

8. Tables and Figures

Table 1. Descriptive statistics for Ohio and Wisconsin combined, 1998-2013*

Variable		Mean	Std. Dev.	Min	Max
Deer-vehicle collisions	overall ($\bar{\bar{x}}$)	290	189	2	1,322
	between ($\bar{x}_i$)		174	8	999
	within ($x_{it} - \bar{x}_i$)		64	-257	344
Deer population	overall ($\bar{\bar{x}}$)	14,441	11,955	505	65,537
	between ($\bar{x}_i$)		11,276	934	51,519
	within ($x_{it} - \bar{x}_i$)		3,161	-19,653	21,385
Total annual precipitation (in.)	overall ($\bar{\bar{x}}$)	38	8	21	61
	between ($\bar{x}_i$)		5	29	49
	within ($x_{it} - \bar{x}_i$)		6	-13	25
Total winter precipitation (in.)	overall ($\bar{\bar{x}}$)	13	5	4	28
	between ($\bar{x}_i$)		4	7	19
	within ($x_{it} - \bar{x}_i$)		3	-8	9
Days w/ min. temperature ≤ 32°F	overall ($\bar{\bar{x}}$)	137	26	78	206
	between ($\bar{x}_i$)		23	101	190
	within ($x_{it} - \bar{x}_i$)		11	-31	25
Days w/ max. temperature ≥ 80°F	overall ($\bar{\bar{x}}$)	69	21	15	124
	between ($\bar{x}_i$)		19	29	109
	within ($x_{it} - \bar{x}_i$)		10	-27	27
Annual vehicle miles traveled (mil.)	overall ($\bar{\bar{x}}$)	1,072	1,587	60	11,111
	between ($\bar{x}_i$)		1,624	75	10,771
	within ($x_{it} - \bar{x}_i$)		90	-1,264	855
Forest (acres)	overall ($\bar{\bar{x}}$)	221	219	13	1,205
	between ($\bar{x}_i$)		212	14	1,203
	within ($x_{it} - \bar{x}_i$)		2	-11	14
Farmland (acres)	overall ($\bar{\bar{x}}$)	303	167	13	932
	between ($\bar{x}_i$)		163	16	914
	within ($x_{it} - \bar{x}_i$)		3	-19	18

Notes: This table decomposes each variable (x_{it}) into "between" variation ($\bar{x}_i$) and "within" variation ($x_{it} - \bar{x}_i$), with $\bar{x}_i = \frac{1}{T}\sum_{t=1}^{T} x_{it}$ and $\bar{\bar{x}} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} x_{it}$ for county *i* at time *t*. The within statistics measure the deviation from the mean by county, and therefore can be positive or negative. *Overall statistics use 2,152 county-years of data for 88 Ohio counties between July 1, 2001 and June 30, 2013 and 63 Wisconsin counties between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. Between statistics use 151 counties. The average number of years a county was observed is 14.25.

Table 2. Descriptive statistics for Ohio, 2001-2013

Variable		Mean	Std. Dev.	Min	Max
Deer-vehicle collisions	overall ($\bar{\bar{x}}$)	295	149	11	779
	between ($\bar{x}_i$)		134	24	648
	within ($x_{it} - \bar{x}_i$)		67	-235	344
Deer population	overall ($\bar{\bar{x}}$)	7,863	5,952	905	27,575
	between ($\bar{x}_i$)		5,876	1,292	24,107
	within ($x_{it} - \bar{x}_i$)		1,119	-5,964	3,468
Total annual precipitation (in.)	overall ($\bar{\bar{x}}$)	43	6	27	59
	between ($\bar{x}_i$)		2	38	49
	within ($x_{it} - \bar{x}_i$)		5	-13	17
Total winter precipitation (in.)	overall ($\bar{\bar{x}}$)	16	4	7	28
	between ($\bar{x}_i$)		1	13	19
	within ($x_{it} - \bar{x}_i$)		3	-6	9
Days w/ min. temperature ≤ 32°F	overall ($\bar{\bar{x}}$)	118	13	78	147
	between ($\bar{x}_i$)		7	101	134
	within ($x_{it} - \bar{x}_i$)		11	-31	21
Days w/ max. temperature ≥ 80°F	overall ($\bar{\bar{x}}$)	83	15	41	124
	between ($\bar{x}_i$)		12	57	109
	within ($x_{it} - \bar{x}_i$)		10	-27	20
Annual vehicle miles traveled (mil.)	overall ($\bar{\bar{x}}$)	1,262	1,871	104	11,111
	between ($\bar{x}_i$)		1,880	122	10,771
	within ($x_{it} - \bar{x}_i$)		80	-998	855
Forest (acres)	overall ($\bar{\bar{x}}$)	145	118	14	454
	between ($\bar{x}_i$)		119	14	453
	within ($x_{it} - \bar{x}_i$)		1	-11	14
Farmland (acres)	overall ($\bar{\bar{x}}$)	274	121	13	551
	between ($\bar{x}_i$)		121	16	551
	within ($x_{it} - \bar{x}_i$)		2	-11	8

Notes: This table decomposes each variable (x_{it}) into "between" variation ($\bar{x}_i$) and "within" variation ($x_{it} - \bar{x}_i$), with $\bar{x}_i = \frac{1}{T}\sum_{t=1}^{T} x_{it}$ and $\bar{\bar{x}} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} x_{it}$ for county *i* at time *t*. The within statistics measure the deviation from the mean by county, and therefore can be positive or negative. Overall statistics use 1,144 county-years of data for 88 Ohio counties between July 1, 2001 and June 30, 2013, with period *t* representing July 1 to June 30. Between statistics use 88 counties. The number of years a county was observed is 13.

Table 3. Descriptive statistics for Wisconsin, 1998-2013

Variable		Mean	Std. Dev.	Min	Max
Deer-vehicle collisions	overall ($\bar{\bar{x}}$)	283	225	2	1,322
	between ($\bar{x}_i$)		218	8	999
	within ($x_{it} - \bar{x}_i$)		61	-257	333
Deer population	overall ($\bar{\bar{x}}$)	21,908	12,654	505	65,537
	between ($\bar{x}_i$)		11,930	934	51,519
	within ($x_{it} - \bar{x}_i$)		4,463	-19,653	21,385
Total annual precipitation (in.)	overall ($\bar{\bar{x}}$)	33	6	21	61
	between ($\bar{x}_i$)		2	29	37
	within ($x_{it} - \bar{x}_i$)		6	-12	25
Total winter precipitation (in.)	overall ($\bar{\bar{x}}$)	9	3	4	19
	between ($\bar{x}_i$)		1	7	12
	within ($x_{it} - \bar{x}_i$)		2	-8	8
Days w/ min. temperature ≤ 32°F	overall ($\bar{\bar{x}}$)	159	19	114	206
	between ($\bar{x}_i$)		16	130	190
	within ($x_{it} - \bar{x}_i$)		10	-24	25
Days w/ max. temperature ≥ 80°F	overall ($\bar{\bar{x}}$)	53	16	15	94
	between ($\bar{x}_i$)		13	29	75
	within ($x_{it} - \bar{x}_i$)		10	-26	27
Annual vehicle miles traveled (mil.)	overall ($\bar{\bar{x}}$)	858	1,149	60	7,969
	between ($\bar{x}_i$)		1,153	75	7,146
	within ($x_{it} - \bar{x}_i$)		100	-1,264	824
Forest (acres)	overall ($\bar{\bar{x}}$)	307	269	13	1,205
	between ($\bar{x}_i$)		271	16	1,203
	within ($x_{it} - \bar{x}_i$)		2	-6	9
Farmland (acres)	overall ($\bar{\bar{x}}$)	336	202	14	932
	between ($\bar{x}_i$)		203	17	914
	within ($x_{it} - \bar{x}_i$)		4	-19	18

Notes: This table decomposes each variable (x_{it}) into "between" variation ($\bar{x}_i$) and "within" variation ($x_{it} - \bar{x}_i$), with $\bar{x}_i = \frac{1}{T}\sum_{t=1}^{T} x_{it}$ and $\bar{\bar{x}} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} x_{it}$ for county *i* at time *t*. The within statistics measure the deviation from the mean by county, and therefore can be positive or negative. Overall statistics use 1,008 county-years of data for 63 Wisconsin counties between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. Between statistics use 63 counties. The number of years a county was observed is 16.

Table 4. Ordinary least squares (OLS) fixed effects estimates of deer-vehicle collisions for Ohio and Wisconsin combined

	(1) ln(DVC)	(2) ln(DVC)	(3) ln(DVC)	(4) ln(DVC)	(5) ln(DVC)	(6) ln(DVC)	(7) ln(DVC) (preferred)
ln(Deer pop.)	0.415***	0.408***	0.436***	0.428***	0.428***	0.426***	0.432***
	(0.0882)	(0.0881)	(0.0848)	(0.0872)	(0.0810)	(0.0816)	(0.0835)
ln(Precip. (inch))		0.224***	0.178***	0.199***	0.164***	0.164***	0.163***
		(0.0484)	(0.0491)	(0.0591)	(0.0561)	(0.0560)	(0.0563)
ln(Days w/ temp. < 32˚F)			-0.630***	-0.646***	-0.554***	-0.558***	-0.571***
			(0.182)	(0.180)	(0.165)	(0.166)	(0.167)
ln(Days w/ temp. > 80˚F)				0.0780	0.0104	0.0114	0.00756
				(0.0690)	(0.0660)	(0.0662)	(0.0660)
ln(AVMT)					0.693***	0.697***	0.714***
					(0.179)	(0.180)	(0.186)
ln(Forest)						-0.148	-0.654
						(0.402)	(1.181)
ln(Farm)							0.554
							(1.095)
County effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2152	2152	2152	2152	2152	2152	2152
Within R-squared	0.209	0.216	0.224	0.225	0.249	0.249	0.250

Notes: Statistics are based on county by year observations for Ohio between July 1, 2001 and June 30, 2013 and Wisconsin between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. Deer-vehicle collisions are police-reported. Deer population is the number of deer estimated as of October 1. County by day precipitation, minimum, and maximum temperature are spatially-weighted averages of daily 4km weather. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 5. Ordinary least squares (OLS) fixed effects estimates of deer-vehicle collisions for Ohio

	(1) ln(DVC)	(2) ln(DVC)	(3) ln(DVC)	(4) ln(DVC)	(5) ln(DVC)	(6) ln(DVC)	(7) ln(DVC) (preferred)
ln(Deer pop.)	0.959***	0.953***	0.952***	0.967***	0.964***	0.991***	0.992***
	(0.177)	(0.177)	(0.177)	(0.177)	(0.176)	(0.169)	(0.170)
ln(Precip. (inch))		0.108	0.0958	0.161**	0.162**	0.169**	0.171**
		(0.0750)	(0.0752)	(0.0790)	(0.0793)	(0.0790)	(0.0786)
ln(Days w/ temp. < 32˚F)			-0.209	-0.145	-0.157	-0.152	-0.149
			(0.171)	(0.176)	(0.178)	(0.178)	(0.175)
ln(Days w/ temp. > 80˚F)				0.347***	0.346***	0.337***	0.338***
				(0.105)	(0.103)	(0.104)	(0.103)
ln(AVMT)					0.343	0.383	0.397
					(0.369)	(0.375)	(0.375)
ln(Forest)						0.814	0.426
						(0.736)	(2.122)
ln(Farm)							0.348
							(1.440)
County effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1144	1144	1144	1144	1144	1144	1144
Within R-squared	0.431	0.432	0.433	0.436	0.438	0.439	0.440

Notes: Statistics are based on county by year observations for Ohio between July 1, 2001 and June 30, 2013, with period *t* representing July 1 to June 30. Deer-vehicle collisions are police-reported. Deer population is the number of deer estimated as of October 1. County by day precipitation, minimum, and maximum temperature are spatially-weighted averages of daily 4km weather. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 6. Ordinary least squares (OLS) fixed effects estimates of deer-vehicle collisions for Wisconsin

	(1) ln(DVC)	(2) ln(DVC)	(3) ln(DVC)	(4) ln(DVC)	(5) ln(DVC)	(6) ln(DVC)	(7) ln(DVC) (preferred)
ln(Deer pop.)	0.240^{**}	0.232^{**}	0.230^{**}	0.230^{**}	0.238^{**}	0.234^{**}	0.284^{***}
	(0.0977)	(0.0980)	(0.0937)	(0.0937)	(0.0903)	(0.0916)	(0.0925)
ln(Precip. (inch))		0.144^{**}	0.145^{**}	0.139^{*}	0.121	0.118	0.0968
		(0.0638)	(0.0638)	(0.0740)	(0.0743)	(0.0739)	(0.0765)
ln(Days w/ temp. < 32˚F)			0.0491	0.0555	0.108	0.0884	-0.00436
			(0.306)	(0.308)	(0.303)	(0.302)	(0.281)
ln(Days w/ temp. > 80˚F)				-0.0232	-0.0497	-0.0430	-0.0446
				(0.0858)	(0.0825)	(0.0820)	(0.0810)
ln(AVMT)					0.330^{*}	0.362^{*}	0.392^{*}
					(0.193)	(0.196)	(0.201)
ln(Forest)						-0.785	-3.906^{**}
						(0.484)	(1.950)
ln(Farm)							3.804^{*}
							(2.134)
County effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1008	1008	1008	1008	1008	1008	1008
Within R-squared	0.121	0.125	0.125	0.125	0.135	0.139	0.155

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. Deer-vehicle collisions are police-reported. Deer population is the number of deer estimated as of October 1. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 7. Instrumental variables (IV) fixed effects estimates of deer-vehicle collisions, second stage results for Ohio and Wisconsin combined

	(1) ln(DVC) OLS	(2) ln(DVC) IV (preferred)	(3) ln(DVC) IV	(4) ln(DVC) IV
ln(Deer pop.)	0.432***	0.446***	0.381***	0.322*
	(0.0835)	(0.168)	(0.110)	(0.168)
ln(Precip. (inch))	0.163***	0.161***	0.171***	0.180***
	(0.0563)	(0.0523)	(0.0566)	(0.0610)
ln(Days w/ temp. < 32˚F)	-0.571***	-0.578***	-0.545***	-0.515***
	(0.167)	(0.158)	(0.165)	(0.165)
ln(Days w/ temp. > 80˚F)	0.00756	0.00422	0.0202	0.0351
	(0.0660)	(0.0606)	(0.0660)	(0.0720)
ln(AVMT)	0.714***	0.714***	0.712***	0.710***
	(0.186)	(0.183)	(0.185)	(0.186)
ln(Forest)	-0.654	-0.664	-0.612	-0.564
	(1.181)	(1.155)	(1.176)	(1.183)
ln(Farm)	0.554	0.578	0.463	0.356
	(1.095)	(1.068)	(1.099)	(1.124)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	2152	2152	2152	2152
Instrument		Winter precip. $(\text{inch})_{t-1}$	ln(Deer pop.)$_{t-1}$	ln(Deer pop.)$_{t-2}$
First stage F		80.31	1104.1	236.2

Notes: Statistics are based on county by year observations for Ohio between July 1, 2001 and June 30, 2013 and Wisconsin between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. Deer-vehicle collisions are police-reported. Deer population is the number of deer estimated as of October 1. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 8. Instrumental variables (IV) fixed effects estimates of deer-vehicle collisions, second stage results for Ohio

	(1) ln(DVC) OLS	(2) ln(DVC) IV (preferred)	(3) ln(DVC) IV	(4) ln(DVC) IV
ln(Deer pop.)	0.992***	1.985***	1.156***	1.366***
	(0.170)	(0.587)	(0.206)	(0.255)
ln(Precip. (inch))	0.171**	0.138*	0.166**	0.159**
	(0.0786)	(0.0835)	(0.0784)	(0.0805)
ln(Days w/ temp. < 32˚F)	-0.149	-0.0928	-0.140	-0.128
	(0.175)	(0.205)	(0.172)	(0.174)
ln(Days w/ temp. > 80˚F)	0.338***	0.441***	0.355***	0.377***
	(0.103)	(0.149)	(0.103)	(0.108)
ln(AVMT)	0.397	0.417	0.400	0.404
	(0.375)	(0.366)	(0.364)	(0.359)
ln(Forest)	0.426	1.728	0.641	0.916
	(2.122)	(2.404)	(2.055)	(2.032)
ln(Farm)	0.348	0.504	0.374	0.407
	(1.440)	(1.454)	(1.420)	(1.426)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	1144	1144	1144	1144
Instrument		Winter precip. (inch)$_{t-1}$	ln(Deer pop.)$_{t-1}$	ln(Deer pop.)$_{t-2}$
First stage F		19.30	1860.7	391.1

Notes: Statistics are based on county by year observations for Ohio between July 1, 2001 and June 30, 2013, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. Deer-vehicle collisions are police-reported. Deer population is the number of deer estimated as of October 1. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 9. Instrumental variables (IV) fixed effects estimates of deer-vehicle collisions, second stage results for Wisconsin

	(1) ln(DVC) OLS	(2) ln(DVC) IV (preferred)	(3) ln(DVC) IV	(4) ln(DVC) IV
ln(Deer pop.)	0.284***	0.248	0.244**	0.274*
	(0.0925)	(0.207)	(0.116)	(0.155)
ln(Precip. (inch))	0.0968	0.103	0.104	0.0988
	(0.0765)	(0.0649)	(0.0769)	(0.0795)
ln(Days w/ temp. < 32˚F)	-0.00436	0.0471	0.0535	0.0109
	(0.281)	(0.359)	(0.288)	(0.294)
ln(Days w/ temp. > 80˚F)	-0.0446	-0.0428	-0.0426	-0.0441
	(0.0810)	(0.0780)	(0.0794)	(0.0798)
ln(AVMT)	0.392*	0.387*	0.386*	0.390*
	(0.201)	(0.203)	(0.200)	(0.199)
ln(Forest)	-3.906**	-3.782**	-3.766*	-3.869**
	(1.950)	(1.684)	(1.944)	(1.946)
ln(Farm)	3.804*	3.637**	3.616*	3.755*
	(2.134)	(1.812)	(2.150)	(2.166)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	1008	1008	1008	1008
Instrument		Winter precip. $(\text{inch})_{t-1}$	ln(Deer pop.)$_{t-1}$	ln(Deer pop.)$_{t-2}$
First stage F		27.13	1366.9	340.7

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. Deer-vehicle collisions are police-reported. Deer population is the number of deer estimated as of October 1. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 10. Instrumental variables (IV) fixed effects estimates of deer-vehicle collisions, first stage results for Ohio and Wisconsin combined

	(1) ln(Deer pop.) OLS	(2) ln(Deer pop.) IV (preferred)	(3) ln(Deer pop.) IV	(4) ln(Deer pop.) IV
Exogenous variables:				
ln(Precip. (inch))	0.150***	0.100***	0.0143	0.0670**
	(0.0362)	(0.0349)	(0.0256)	(0.0313)
ln(Days w/ temp. < 32˚F)	0.515***	0.369***	-0.0248	0.275***
	(0.126)	(0.110)	(0.0498)	(0.0815)
ln(Days w/ temp. > 80˚F)	0.249***	0.265***	0.188***	0.250***
	(0.0355)	(0.0351)	(0.0215)	(0.0319)
ln(AVMT)	-0.0289	-0.0379	0.0399	0.122
	(0.113)	(0.111)	(0.0444)	(0.0806)
ln(Forest)	0.807	0.749	0.607**	0.862*
	(0.684)	(0.649)	(0.276)	(0.474)
ln(Farm)	-1.792***	-1.745***	-1.107***	-1.669***
	(0.586)	(0.557)	(0.293)	(0.477)
Excluded instruments:				
Winter precip. (inch)$_{t-1}$		0.0148***		
		(0.00165)		
ln(Deer pop.)$_{t-1}$			0.708***	
			(0.0213)	
ln(Deer pop.)$_{t-2}$				0.452***
				(0.0294)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	2152	2152	2152	2152

Notes: Statistics are based on county by year observations for Ohio between July 1, 2001 and June 30, 2013 and Wisconsin between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. The dependent variable is the natural log of the number of deer estimated as of October 1. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 11. Instrumental variables (IV) fixed effects estimates of deer-vehicle collisions, first stage results for Ohio

	(1) ln(Deer pop.) OLS	(2) ln(Deer pop.) IV (preferred)	(3) ln(Deer pop.) IV	(4) ln(Deer pop.) IV
Exogenous variables:				
ln(Precip. (inch))	0.0332	0.0340	0.0516***	0.0338
	(0.0351)	(0.0354)	(0.0169)	(0.0252)
ln(Days w/ temp. < 32˚F)	-0.0564	-0.0523	0.0526	0.0449
	(0.0834)	(0.0826)	(0.0343)	(0.0559)
ln(Days w/ temp. > 80˚F)	-0.104**	-0.0639	-0.0559*	-0.0720
	(0.0485)	(0.0506)	(0.0320)	(0.0461)
ln(AVMT)	-0.0210	-0.0236	-0.0202	-0.0335
	(0.178)	(0.177)	(0.0507)	(0.0861)
ln(Forest)	-1.311	-1.259	-0.392**	-0.753**
	(0.828)	(0.822)	(0.196)	(0.372)
ln(Farm)	-0.157	-0.184	-0.259**	-0.398*
	(0.496)	(0.492)	(0.128)	(0.236)
Excluded instruments:				
Winter precip. (inch)$_{t-1}$		0.00655***		
		(0.00149)		
ln(Deer pop.)$_{t-1}$			0.810***	
			(0.0188)	
ln(Deer pop.)$_{t-2}$				0.619***
				(0.0313)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	1144	1144	1144	1144

Notes: Statistics are based on county by year observations for Ohio between July 1, 2001 and June 30, 2013, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. The dependent variable is the natural log of the number of deer estimated as of October 1. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 12. Instrumental variables (IV) fixed effects estimates of deer-vehicle collisions, first stage results for Wisconsin

	(1) ln(Deer pop.) OLS	(2) ln(Deer pop.) IV (preferred)	(3) ln(Deer pop.) IV	(4) ln(Deer pop.) IV
Exogenous variables:				
ln(Precip. (inch))	0.185***	0.0874**	-0.0303	0.136***
	(0.0541)	(0.0443)	(0.0355)	(0.0450)
ln(Days w/ temp. < 32˚F)	1.441***	1.060***	0.652***	1.175***
	(0.227)	(0.201)	(0.104)	(0.147)
ln(Days w/ temp. > 80˚F)	0.0494	0.0772*	0.0554**	0.143***
	(0.0489)	(0.0454)	(0.0282)	(0.0388)
ln(AVMT)	-0.134	-0.114	-0.0559	-0.0271
	(0.140)	(0.135)	(0.0497)	(0.0938)
ln(Forest)	3.482***	2.883***	0.539	1.051
	(1.068)	(1.036)	(0.414)	(0.681)
ln(Farm)	-4.678***	-4.064***	-0.911*	-1.791**
	(1.150)	(1.134)	(0.473)	(0.777)
Excluded instruments:				
Winter precip. (inch)$_{t-1}$		0.0264***		
		(0.00507)		
ln(Deer pop.)$_{t-1}$			0.799***	
			(0.0216)	
ln(Deer pop.)$_{t-2}$				0.605***
				(0.0328)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	1008	1008	1008	1008

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. The dependent variable is the natural log of the number of deer estimated as of October 1. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

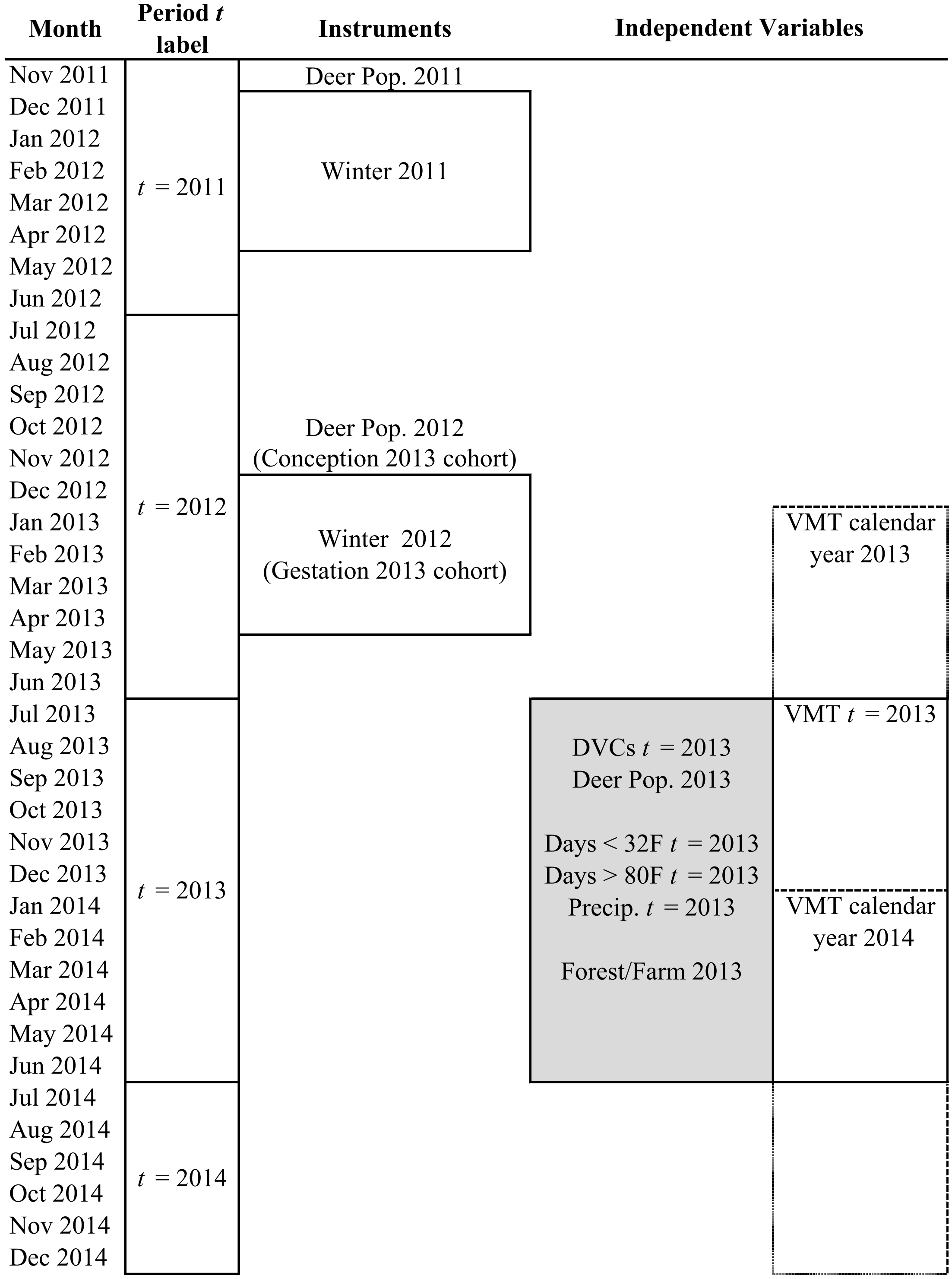
Table 13. Economic impact scenarios

Reduction in Deer Population	Reduction in DVCs per year	Economic Value per year
1 deer	0.01	$83
112 deer	1	$9,234
1 percent (in all 151 counties)	1.3 ×151	$1.8 million
10 percent (in all 151 counties)	12.9×151	$18.0 million
20 percent (in all 151 counties)	25.9×151	$36.1 million
30 percent (in all 151 counties)[a]	38.8×151	$54.1 million

Notes: Estimates are based on county by year observations for Ohio between July 1, 2001 and June 30, 2013 and Wisconsin between July 1, 1998 and June 30, 2013, with period *t* representing July 1 to June 30. The economic impact scenarios use the definition of elasticity $\varepsilon_{y,x} = \frac{\partial y}{\partial x}\frac{x}{y}$ and the point estimate of $\varepsilon_{y,x}$ in the preferred instrumental variables specification, evaluated at the county-year means of x and y, namely $\widehat{\varepsilon_{y,x}} = 0.446$, $\bar{\bar{x}} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} x_{it} = 14{,}441$, and $\bar{\bar{y}} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} y_{it} = 290$ for county *i* at time *t*. As such, the marginal changes presented should be interpreted as a decrease from the mean. Dollar values are the product of the predicted change in DVCs and the average total economic losses from one DVC in 2015 dollars, $9,234 (Huijser et al. 2008).

[a] This scenario roughly represents achieving population targets in both states. Statewide deer populations in 2013 were 26 percent above target in Ohio and 30 percent above target in Wisconsin (unpublished data).

Figure 1. Midyear data aggregation and period labeling



Notes: Data in this study are aggregated such that period *t* represents July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. Lagged winter severity and deer population are used as instruments for contemporaneous deer population in the instrumental variables regressions.

9. Appendix

Table 14. Annual Aggregate Economic Impacts of Deer in the United States (Billions of 2015 Dollars)

Category	Annual Impact Low	Annual Impact High	Source
Costs[a,b]	**14.6**	**26.6**	
Deer-vehicle collisions	9.2	18.5	(Huijser et al. 2008)
Deer-aircraft collisions[c]	0.004	0.004	(Biondi et al. 2011)
Lyme disease	3.5	6.3	
Medical costs	0.7	1.3	(Adrion et al. 2015)
Avoidance behavior	2.8	5.0	(Berry et al. 2017)
Agricultural damage	0.3	0.3	(Drake et al. 2005)
Timber productivity losses	1.2	1.2	(Conover 1997)
Damage to metropolitan households	0.4	0.4	(Conover 1997)
Benefits[a]	**60.6**	**60.6**	
Deer hunting	54.8	54.8	
Direct expenditures	19.1	19.1	(Southwick Associates 2012a)
Indirect and induced effects of expenditures[d]	22.9	22.9	(Southwick Associates 2012a)
Consumer surplus[e]	12.7	12.7	(Fuller 2016; Aiken 2016)
Wildlife viewing expenditures[f]	5.8	5.8	(U.S. Fish and Wildlife Service and U.S. Census Bureau 2014; Conover 1997)

Notes: All estimates converted from original values to 2015 dollars using the Bureau of Labor Statistics' Consumer Price Index. Estimates are directly from the reports cited unless otherwise noted below.

[a] Aggregate benefits minus costs does not represent net economic benefits. Most costs presented here include transfers (e.g. some portion of DVC losses to drivers are benefits to mechanics). Likewise, expenditures represent a transfer between consumers and producers.

[b] Cost estimates exclude impacts of overabundant deer on forest ecosystems, which are significant but difficult to monetize (Waller and Alverson 1997; Rooney and Waller 2003; Van Deelen, Pregitzer, and Haufler 1996; Côté et al. 2004; Frerker, Sabo, and Waller 2014).

[c] Estimate based on dividing $81,521,605 in damage between 1990 to 2009 by the number of years in this period; original estimate for full period in 2010 dollars.

[d] Estimate based on subtracting direct expenditures from total economic impact, the latter of which includes direct, indirect, and induced effects.

[e] Estimate based on multiplying daily mean consumer surplus by days of hunting; result is an under estimate and only accounts for in-state deer hunting by state resident hunters in 43 states. Aiken (2016) calculates a mean consumer surplus of $79 per day for in-state deer hunting by state resident hunters for 43 states. Fuller (2016) reports 153.127 million in-state deer hunting days by state resident hunters for the same 43 states.

[f] Estimate based on attributing 10 percent of wildlife viewing expenditures to deer as a conservative estimate per Conover (1997). U.S. Fish and Wildlife Service and U.S. Census Bureau (2014) report $57.8 billion in total wildlife viewing expenditures (all species). Indirect and induced effects from these expenditures ($91.9 billion) and consumer surplus ($10.1 billion) are available for wildlife watching (Aiken 2016; Caudill 2014); however, it is not possible to determine what fraction of these impacts are attributable to deer.

Chapter 2. Wolves as a Biological Control for Deer: Measuring the Indirect Economic Impacts of Predators

1. Introduction

The recent expansion of the gray wolf (*Canis lupus*) into rural areas of the United States, Canada, and Europe is creating conflicts and challenges. In the contiguous United States, the wolf population has increased from a few hundred in 1973 to about 5,600 wolves today (U.S. Fish and Wildlife Service 2011, 2017a). Managers are now grappling with balancing the costs and benefits of wolves in an uncertain and politically divisive environment. Wolf adversaries, such as some ranchers and hunters, believe that increases in the wolf population cause excessive livestock depredation, reduce valuable game species, and threaten children and pets in rural communities. Wolf proponents, who tend to concentrate in urban areas, believe that wolves play a crucial role in the ecosystem and managers should allow wolves to expand over their historical range. There is a time-sensitive need to identify the conditions under which it is socially optimal to allow wolves and other apex predators to expand, or when stricter control is economical.

Although wolves undoubtedly harm some livestock farmers, wolves also have the potential to control an even bigger source of wildlife damage—deer. Aggregate economic costs associated with deer likely exceed $15 billion to $27 billion each year (Table 14). Deer-vehicle collisions account for the majority of these damages, with annual losses estimated at $9 billion to $18 billion each year (Huijser et al. 2008). DVC losses in states that currently have established wolf populations—Idaho, Montana, and Wyoming in the west and Michigan, Minnesota, and Wisconsin in the mid-west—likely exceeded $2 billion in 2013, the most recent year available, with 93 percent of these costs accruing in the mid-western states (unpublished data).[11] By comparison, the value of verified wolf depredation on livestock and domestic animals totaled about $282,000 in the most recent year available for the mid-western states (Michigan Department of Natural Resources 2008; International Wolf Center 2017; Wisconsin Department of Natural Resources 2017) (Michigan Department of Natural Resources 2008; International Wolf Center 2017; Wisconsin Department of Natural Resources 2017).[12] Unverified losses, including potential impacts on livestock productivity, would need to be about 7,000 times larger than verified losses for depredation to exceed DVC losses in those states. Although many DVCs undoubtedly occur in areas with no suitable habitat for wolves, even a marginal reduction in DVCs could outweigh the direct depredation costs of wolves. The objective of this study is to identify whether wolves indirectly affect the frequency of DVCs through changes in deer abundance or behavior.

Wolves can shape entire ecosystems through impacts on ungulate prey such as deer, elk, and moose. Government-sponsored programs caused the extirpation of wolves everywhere in the United States except northeastern Minnesota and Isle Royal, Michigan by the 1960s (U.S. Fish and Wildlife Service 2011). At the same time, deer populations erupted, intensifying herbivory pressure on forest ecosystems (Leopold, Sowls, and Spencer 1947). Perhaps the most famous record of these impacts appears in Aldo Leopold's (1949, 130) Sand County almanac:

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[11] DVC loss estimates multiply reported and estimated unreported collisions by the national average loss per DVC of $9,234 (Huijser et al. 2008). There were 69,693 police-reported DVCs in Michigan, Minnesota, and Wisconsin combined and 4,991 deer- or wildlife-vehicle collisions in Idaho, Montana, and Wyoming (Idaho Transportation Department, Michigan State Police, Minnesota Department of Public Safety, Montana Department of Transportation, Wisconsin Department of Transportation, and Wyoming Department of Transportation, unpublished data).The estimated number of unreported collisions is based on the national reporting rate of 3 reported DVCs to 7 unreported DVCs.

[12] Depredation losses refer to 2007 for Michigan, fiscal year 2011 for Minnesota, and 2013 for Wisconsin.

> *I have lived to see state after state extirpate its wolves. I have watched the face of many a newly wolfless mountain, and seen the south-facing slopes wrinkle with a maze of new deer trails. I have seen every edible bush and seedling browsed, first to anaemic desuetude, and then to death. I have seen every edible tree defoliated to the height of a saddlehorn.*

The tides turned for wolves in 1974 when the federal government listed wolves as endangered under the Endangered Species Act (ESA) (U.S. Fish and Wildlife Service 2011). The protections afforded by the ESA and concerted rehabilitation efforts by federal wildlife managers helped wolf populations to rebound. The recolonization of wolves appeared to release some of the pressure ungulate browsing had on sensitive plant communities and preceded increases in aspen, willow, and cottonwood tree recruitment in Yellowstone National Park (Ripple and Larsen 2000; Ripple et al. 2001; Ripple and Beschta 2007; Beyer et al. 2007), forb and shrub species richness in Wisconsin (Callan et al. 2013), and balsam fir growth on Isle Royal (McLaren and Peterson 1994). Although debate remains about whether wolves caused these changes or were merely correlated with them (Marris 2014; Mech 2012), there is strong circumstantial evidence that the presence of wolves significantly alters ungulate abundance and/or behavior.

Reductions in deer abundance would tend to reduce DVCs, as shown in Chapter 1. It is intuitive that wolf predation would decrease deer abundance, but this relationship is complicated and difficult to test empirically. There is some evidence that wolves can suppress ungulate populations (Ripple and Beschta 2012; Leopold, Sowls, and Spencer 1947; Messier 1991, 1994), but this effect may be mediated by many factors, such as the relative levels of predator and prey, forage availability, and weather (Eberhardt et al. 2003; J. A. Vucetich and Peterson 2004; John A. Vucetich et al. 2011).

Even if wolves do not affect deer abundance, changes to the spatial distribution of deer may affect the frequency of DVCs. Previous literature hypothesizes that when wolves are present, ungulates avoid roads and other features that block or slow down escape from predation (Ripple and Beschta 2004, 2007; Fortin et al. 2005). However, statistical evidence for this relationship is sparse. Like many animals, both ungulates and wolves avoid roads in general because roads are a source of human disturbance (Rowland et al. 2000; Mladenoff, Sickley, and Wydeven 1999). For wolves to affect the frequency of DVCs, deer must avoid roads more when wolves are present than when they are absent. Two studies of which I am aware test this relationship statistically. In areas with wolves, Ripple and Beschta (2007) find that distance to roads has no statistical effect on aspen regeneration, suggesting elk do not avoid roads, whereas Fortin et al. (2005) find that elk tend to move away from nearby roads but not faraway roads. The latter results are suggestive, but may confound roads with other landscape features that dictate elk movement (e.g. topography).

This is the first study of which I am aware that estimates the causal impact of wolf-deer interactions on the frequency of DVCs. The analysis is based on data for Wisconsin, which has many DVCs each year ($577 million in DVC losses per year, see Chapter 1) and relatively low depredation losses ($1.9 million in cumulative verified depredation losses between 1985 and 2015) (Wisconsin Department of Natural Resources 2017). The benefits of a small reduction in DVCs conceivably could exceed the direct costs of wolf depredation, which would have interesting management implications not just for Wisconsin but also for other states that have both suitable wolf habitat and high DVCs. Such a finding also would bolster confidence that the trophic cascade literature indeed identified a causal relationship between wolves and the regeneration of plant communities, which operates through changes in deer abundance and/or behavior.

The rest of this Chapter proceeds as follows. Sections 2 and 3 describes the conceptual model and estimation methods, respectively. Section 4 outlines data sources. Section 5 highlights the main results. Sections 6 and 7 include a discussion of findings and concluding remarks, respectively. Section 8 includes all tables and figures.

2. Conceptual Model

The hypothesized effect of wolves on DVCs operates through impacts on both deer abundance and deer behavior. Consider the following reduced form equation

$$DVC_{it} = \varphi_1 WolfPop_{it} + \varphi_2 WolfPop_{j\neq i,t} + \alpha_2 VMT_{it} + \beta_1 Precip_{it} + \beta_2 DaysBelow32F_{it} + \beta_3 DaysAbove80F_{it} + \beta_4 Forest_{it} + \beta_5 Farm_{it} + \theta_i + \delta_t + u_{it}$$

where $WolfPop_{it}$ is the mid-winter wolf population in county i and time t, $WolfPop_{j\neq i,t}$ is the wolf population in the counties that neighbor county i, and the other variables are defined as previously. φ_1 measures whether wolves have a net effect on DVCs. φ_2 measures the extent to which this effect spills over into neighboring counties. Assume that wolves reduce the deer population through predation, which I test formally later, and that reductions in deer population reduce DVCs, which I showed in Chapter 1. If wolves push deer away from roads, as hypothesized, then $\varphi_1 < 0$ unambiguously. However, if wolves push deer towards roads, then the sign of φ_1 or the net effect of wolves on DVCs is ambiguous: $\varphi_1 > 0$ if the effect on deer behavior is larger, $\varphi_1 < 0$ if the effect on deer population is larger, and $\varphi_1 = 0$ if the effects are exactly offsetting.

To disentangle potentially competing effects of wolves on deer behavior and deer population, consider the structural equation that includes both wolf and deer populations

$$DVC_{it} = \varphi_3 WolfPop_{it} + \varphi_4 WolfPop_{j\neq i,t} + \alpha_1 DeerPop_{it} + \alpha_2 VMT_{it} + \beta_1 Precip_{it} + \beta_2 DaysBelow32F_{it} + \beta_3 DaysAbove80F_{it} + \beta_4 Forest_{it} + \beta_5 Farm_{it} + \theta_i + \delta_t + u_{it}$$

φ_3 measures the effects of wolves on deer behavior only. If wolves push deer away from roads, then $\varphi_3 < 0$. If wolves push deer towards roads, then $\varphi_3 > 0$. If wolves have no effect on the spatial distribution of deer, then $\varphi_3 = 0$.

As a practical matter, the log transformation used in Chapter 1 may not be appropriate for this data set because a large number of observations (62 percent) have no wolves. I implement three alternatives to this transformation: 1) a dummy variable for wolf presence rather than wolf abundance in the log-transformed equation, 2) the inverse hyperbolic sine transformation for all variables, or 3) levels and quadratic terms for all variables.

The dummy varible specification is defined as follows

$$\ln(\mathrm{DVC_{it}}) = \varphi_3 DWolf_{it} + \varphi_4 DWolf_{j\neq i,t} + \alpha_1 \ln(DeerPop_{it}) + \alpha_2 \ln(VMT_{it}) + \beta_1 \ln(Precip_{it}) + \beta_2 \ln(DaysBelow32F_{it}) + \beta_3 \ln(DaysAbove80F_{it}) + \beta_4 \ln(Forest_{it}) + \beta_5 \ln(Farm_{it}) + \theta_i + \delta_t + u_{it}$$

where $DWolf_{it}$ equals one if the wolf population is at least one in county i at time t and $DWolf_{j\neq i,t}$ equals one if the wolf population in any neighbor of county i is at least one. Although the dummy variable mathematically indicates whether at least one individual wolf is present, practically it indicates whether at least one wolf pack is present. The only way a county could have one wolf in the data set is when a wolf pack has a small fraction of its total territory in that county (i.e. a wolf pack with population n has $\frac{1}{n} \times 100$ percent of its territory in county i). This model assumes that only the presence of wolves, not their relative abundance, matters. This assumption may not be restrictive in the data because the wolf population is relatively low in most counties and years. It is reasonable to believe that the effect for the observed levels of wolves is similar. Unfortunately, the coefficient on the dummy variable may be poorly identified. For most observations, the wolf dummy variable is fixed over time, and its effect is absorbed by the county fixed effect. The coefficient on the wolf dummy variable is idendified based on thirteen counties that switch between having wolves and no wolves a grand total of 23 times in the data set.

The inverse hyperbolic sine specification is defined as follows

$$\begin{aligned}\sinh^{-1}(DVC_{it}) = {}& \varphi_3 \sinh^{-1}(Wolf_{it}) + \varphi_4 \sinh^{-1}(Wolf_{j\neq i,t}) + \alpha_1 \sinh^{-1}(DeerPop_{it}) \\ &+ \alpha_2 \sinh^{-1}(VMT_{it}) + \beta_1 \sinh^{-1}(Precip_{it}) + \beta_2 \sinh^{-1}(DaysBelow32F_{it}) \\ &+ \beta_3 \sinh^{-1}(DaysAbove80F_{it}) + \beta_4 \sinh^{-1}(Forest_{it}) + \beta_5 \sinh^{-1}(Farm_{it}) + \theta_i + \delta_t \\ &+ u_{it}\end{aligned}$$

where $\sinh^{-1}(a) = \ln(a + \sqrt[2]{1 + a^2})$. As with the log-transformation, this model assumes that a percentage change in each independent variable causes a percentage change in DVCs. While this relationship is plausible for high levels of deer and wolf abundance, it is unclear whether the same relationship holds at very low wolf population levels, such as those observed in this data set.

Finally, the quadratic specification is defined as follows

$$\begin{aligned}\mathrm{DVC_{it}} = {}& \varphi_3 WolfPop_{it} + \varphi_4 WolfPop_{j\neq i,t} + \alpha_1 DeerPop_{it} + \alpha_2 VMT_{it} + \beta_1 Precip_{it} \\ &+ \beta_2 DaysBelow32F_{it} + \beta_3 DaysAbove80F_{it} + \beta_4 Forest_{it} + \beta_5 Farm_{it} \\ &+ \varphi_5 WolfPop_{it}^2 + \varphi_6 WolfPop_{j\neq i,t}^2 + \alpha_3 DeerPop_{it}^2 + \alpha_4 VMT_{it}^2 + \beta_6 Precip_{it}^2 \\ &+ \beta_7 DaysBelow32F_{it}^2 + \beta_8 DaysAbove80F_{it}^2 + \beta_9 Forest_{it}^2 + \beta_{10} Farm_{it}^2 + \theta_i \\ &+ \delta_t + u_{it}\end{aligned}$$

This specification allows for non-linear effects of the exogenous variables on DVCs while also accommodating low wolf levels. However, the possibility of a turning point in the marginal effect of some of these variables, particularly deer abundance, is somewhat dubious.

Each of these models has strengths and weaknesses, and one does not clearly dominate the other. As such, I estimate all three models to ensure the qualitative findings are robust to changes in specification.

If the coefficient on $WolfPop_{it}$ in the reduced form (that excludes $DeerPop_{it}$) is less than the coefficient in the structural equation (that includes $DeerPop_{it}$), then excluding deer abundance causes negative omitted variable bias. Since the coefficient on deer abundance is positive, it must be the case that $Cov(WolfPop_{it}, DeerPop_{it}) < 0$. This would suggest that wolves negatively affect the deer population, as hypothesized. However, in a discrete predator-prey model, wolves causally affect deer abundance in the next period not the current period; therefore, the effect of contemporaneous wolves on DVCs can *only* operate through changes in deer behavior by definition. As a result the coefficient on wolves should be statistically unchanged when deer abundance is included in or excluded from the model.

A formal predator-prey model is needed to identify the impact of wolves on DVCs through changes in deer abundance. Consider the following functional form from Dennis and Otten (2000)

$$N_{t+1} = N_t exp(r + \frac{r}{K} N_t + \zeta P_t + \boldsymbol{\gamma}' \boldsymbol{W_t} + \sigma Z_{t+1})$$

where N_t is the prey population at time t, r is the instantaneous rate of growth in N, K is the carrying capacity of the environment for N, P_t is predator abundance, W_t is a vector of weather variables, and Z_{t+1} represents stochastic environmental shocks other than observed weather with $Z_{t+1} \sim N(0, \sigma^2)$. When $\boldsymbol{\gamma}' = \boldsymbol{0}$ and $\sigma = 0$ (i.e. weather has no effect on subsequent abundance), this model reduces to the classic density-dependent Ricker logistic growth model with Type 1 (linear) predation. Reorganizing the equation yields the following relationship

$$\ln(\frac{N_{t+1}}{N_t}) = \beta_0 + \beta_1 N_t + \zeta P_t + \boldsymbol{\gamma}'\boldsymbol{W_t} + \sigma Z_{t+1}$$

In other words, deer abundance, predation, and weather impact the annual growth rate of deer. I estimate the following simple approximation to this relationship

$$\begin{aligned}\ln(DeerPop_{it}) = \beta_1 \ln\left(DeerPopPost_{i,t-1}\right) + \zeta WolfPop_{i,t-1} + \gamma_1 WinterPrecip_{i,t-1} \\ + \gamma_2 DaysBelowZero_{i,t-1} + \theta_i + \delta_t + v_{it}\end{aligned}$$

where $DeerPop_{i,t}$ is the prehunt deer population measured in October for county i at time t, $DeerPopPost_{i,t-1}$is the posthunt deer population measured in January at time $t-1$, $WolfPop_{i,t-1}$ is the mid-winter wolf population, $WinterPrecip_{i,t-1}$ is total winter precipitation in inches, with winter defined as December 1 through April 30, $DaysBelowZero_{i,t-1}$ is the number of days with a minimum temperature below 0˚F, and the other variables are defined as previously. It is preferable to use posthunt deer population as the independent variable rather than prehunt deer population because the posthunt population explicitly accounts for the substantial impacts of human harvest.

I hypothesize that $\beta_1 > 0$, $\zeta < 0$, $\gamma_1 > 0$, and $\gamma_2 < 0$. As a concrete example, consider period t = 2013, which covers July 1, 2013 to June 30, 2014 (Figure 1). I expect that: 1) a larger deer population in January 2013 leads to a larger deer population in October 2013, 2) more wolves in January/February 2013 leads to more predation and a lower deer population in October 2013, and 3) more severe weather during winter (December 2012 to April 2013) leads to a lower deer population the following fall (October 2013). The mechanisms that describe these effects are intuitive, but previous sections also provide support from existing literature. Recall that more precipitation in winter is associated with a milder winter rather than a more severe winter, because precipitation is positively correlated with temperature.

The wolf population is not randomly distributed in space. Wisconsin's most recent wolf management plan defines four wolf management zones (Figure 3) (Wisconsin Department of Natural Resources 1999). Zone 1 is core wolf territory and comprises forest-dominated counties in the northern part of the state. Zone 2 is secondary wolf territory and comprises forest-dominated counties in the central part of the state. Zone 3 is a buffer area that may contain low levels of wolves dispersing between Zones 1 and 2. Zone 4 is unsuitable for wolf recolonization and includes agriculture-dominated counties and all of the urban areas in the states. Although wolves have not colonized Zone 4, and likely never will, I include these counties in the regressions because they provide useful information about the impact of deer on DVCs.

Given the large differences in land cover, human use, and habitat suitability across zones, I test for heterogeneity in the the impact of wolves by interacting the wolf variables with dummy variables for each zone. The wolf population is zero in all counties and years in the southern farmland region. As such the effect of wolves is zero in this region and is technically (and irrelevantly) absorbed by the county effects. Thus, this region is the excluded group by necessity. It is not necessary to include main effects for the zone dummies because these are collinear with the county effects (zones are groups of counties).

3. Estimation Methods

As noted in Chapter 1, OLS estimates are biased and inconsistent because: 1) DVCs are underreported, and the level of underreporting is likely correlated with deer abundance and 2) deer population and DVCs to some extent are jointly determined. Instrumental variables methods can address both sources of bias. Although the difference between OLS and instrumental variables estimates is small in the previous section, it is conceivable that the inclusion of wolves could change this relationship. As such, I also employ instrumental variables in this section and use the same instruments as previously, namely lagged winter precipitation and deer population.

4. Data

The Wisconsin data from Chapter 1 provide the basis for this analysis. The only additional data included is wolf abundance. WDNR provided maps of wolf pack territories and mid-winter wolf population counts for each pack for 1979 to 2010. The data end in 2010 because the federal government delisted wolves from the Endangered Species Act thereafter, and WDNR stopped publicly releasing wolf pack locations. To calculate wolf population by county, I used a procedure analogous to the one used in Chapter 1 to convert deer population from a DMU basis to a county basis. The procedure is as follows: 1) join the wolf population data to the pack territory map, 2) calculate wolf pack population density by dividing the population for each pack by the area of that pack's territory, 3) intersect the pack territory map with the U.S. Census Bureau's 2015 county boundary map, 4) calculate the area in square miles of each wolf pack-county polygon, 5) multiply wolf density (wolves/square mile) by square miles for each intersected polygon to estimate the number of wolves in that area, 6) sum the estimated number of wolves by county, and 7) round the wolf population estimate to zero decimals. This procedure assumes that wolves are uniformly distributed within each pack's territory. This assumption is probably inconsequential. WDNR estimates pack territories based on recorded coordinates for radio-collared wolves throughout the year. While each pack may have spent more time during the year in one part of their territory than another, pack territories are extremely small relative to counties (Figure 2).[13]

Over the study period, wolves eventually spread to 35 of 72 Wisconsin counties (Figure 2). I exclude five wolf counties from the regressions due to breaks in the DVC time series and one wolf county that is a tribal area, noted in Chapter 1. In total, the dataset covers 63 counties between 1998 and 2010, or 819 county-year observations. Of these, 307 county-years (37 percent) have wolves and 512 county-years (63 percent) have no wolves.

Both wolf and deer populations increased substantially over the study period (Figure 4). The statewide deer population was highly variable year to year and increased from 1.48 million in 1998 to 1.54 million in 2010. In contrast, the statewide wolf population increased nearly monotically over the period from 205 wolves in 1998 to 782 wolves in 2010. Much of this growth occurred in Bayfield, Douglas, and Price counties (Figure 5). The average wolf population was 6 across all county-years (Table 15) and 16 among the county-years with at least one wolf. By the end of the study period, wolves had recolonized nearly all suitable habitat in the state (Figure 2 and Figure 3). On average, the counties in core and secondary wolf territory had fewer DVCs and more deer than counties in the dispersal and farmland zones (Table 16). It is important to note that the coefficient estimates in all regressions are indentified based on changes within counties over time, not these cross-sectional differences.

Some regressions also incorporate data on wolf populations in neighboring counties (see Conceptual Model section). Briefly, a neighbor of county i is any county $j \neq i$ that shares any part of county i's boundary. To calculate the number of wolves in counties $j \neq i$, I sum the wolf

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[13] The average pack territory in 2010 is 57 mi.^{2} The average county is 779 mi.^{2}

populations in all neighbor counties, including the six wolf counties that I exclude from the regressions due to breaks in the DVC time series. For example, consider Adams county and Juneau county, which are neighbors. I exclude Adams county from the regressions due to a break in the DVC series, but I include its wolves in the calculations for wolves in Juneau's neighboring counties.

5. Results

The results consistently show that wolves decrease the frequency of DVCs. On net, the presence of wolves decreases DVCs by 21 percent ($p < 0.01$) in the wolf dummy specification (Table 17, Column 2). A one percent increase in the wolf population leads to a 0.1 percent decrease in DVCs ($p < 0.05$) in the hyperbolic sine transformation (Table 18, Column 2). One additional wolf leads to 0.88 fewer DVCs ($p < 0.10$) in the quadratic specification (Table 19, Column 2).[14] The impact of wolves on deer behavior accounts for 66 percent to 90 percent of the net effect (Column 3). The point estimate is negative in all models, which suggests wolves cause deer to avoid roads. However, the effect is noisy and statistically significant only in the wolf dummy model.

The average effect of wolves on deer behavior masks heterogeneity across habitat types. In the dispersal area, wolves have a negative and highly statistically significant effect on DVCs through changes in deer behavior in all specifications. In contrast, wolves generally have no perceptible effect in core and secondary wolf habitat. In the dispersal area, the presence of wolves decreases DVCs by 17 percent ($p < 0.01$) in the wolf dummy specification (Table 17,

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[14] The preferred quadratic specification excludes all quadratic terms that are statistically insignificant or that cause the main effect to become statistically insignificant when included (Appendix, Table 27). The quadratic term for wolves also was insignificant in all models and is excluded from the tables.

Column 5). A one percent increase in the wolf population leads to a 0.1 percent decrease in DVCs ($p < 0.01$) in the hyperbolic sine transformation (Table 18, Column 5). One additional wolf leads to 17 fewer DVCs ($p < 0.05$) in the quadratic specification (Table 19, Column 5). These models, which include deer abundance and wolves interacted with zone dummies, are the preferred specifications. Wolves in neighboring counties do not have a perceptible effect on DVCs (Table 17-Table 19, Column 6) and so are excluded from further analysis.

Although the population effect of wolves on DVCs appears to be small based on the relatively small difference between the net effect (Column 2) and the behavioral effect (Column 3) in the OLS estimates, the predator-prey model confirms that an effect indeed exists. On average, each additional wolf in period $t-1$ leads to a 0.48 percent reduction in the prehunt deer population in period t ($p < 0.01$) (Table 26, Column 1) or 104 fewer deer in the average county. By comparison, each additional wolf in period t leads to a slightly smaller reduction, 0.38 percent ($p < 0.05$) (Column 2). Although, contemporaneous wolves theoretically have no effect on contemporaneous deer population; the strong estimated effect likely reflects serial correlation in the wolf population. Indeed, when including both lagged wolf population and contemporaneous population in the regression, the effect of the contemporaneous population is statistically insignificant, as expected (Column 3).

As with the behavioral effect of wolves, the average population effect masks heterogeneity across regions. In core and secondary wolf habitat, each additional wolf in period $t-1$ leads to a 0.45 percent and 0.76 percent reduction in the prehunt deer population in period t ($p < 0.01$), respectively (Column 4). Whereas wolves in the dispersal area had no statistical effect. The wolf populations in all three zones shows the same pattern of serial correlation as did the statewide wolf population (Columns 5-6).

As in Chapter 1, any endogeneity in the deer population is minor and the instrumental variables perform well. The OLS and instrumental variables estimates of the impact of deer abundance on DVCs are statistically equal for all transformations and all instruments (Table 20-Table 22, Columns 1-4). In the log and hyperbolic sine specifications, all instruments are strong ($F \in [16, 496]$). For the quadratic specification, only once-lagged deer population is strong (first stage $F = 39$). Including days below zero as an estimate did not improve the F statistics.

The first stage estimates are consistent with the predator-prey model, namely lagged deer population and winter precipitation increase and wolf populations decrease deer abundance in the following period. The coefficient estimates for deer abundance are highly statistically significant in all specifications, except those that use weather as an instrument (Column 2). Despite the lack of statistical significance, weather is the preferred instrument in the log and hyperbolic sine specifications because it is the most plausibly exogenous. Once-lagged deer abundance is preferred in the quadratic specification because it is still likely exogenous (see earlier discussion) and the only strong instrument available.

In the instrumental variables regressions, increases in deer abundance increase the frequency of DVCs, and wolves mitigate this effect by causing deer to avoid roads. In the preferred specifications, a one percent increase in the deer population leads to a 0.29 percent increase in DVCs in the log specification and a 0.14 percent increase in the hyperbolic sine specification. The marginal impact of deer in the quadratic specification depends on the level of the deer population; one thousand additional deer leads to $11 - 0.296 \times$ deer fewer DVCs. The behavioral impact of wolves is statistically unchanged relative to the OLS estimates discussed previously.

To facilitate meaningful comparisons across the various specifications, the following scenarios manipulate the coefficient estimates to measure the impact of one additional wolf above the county-year mean on the frequency of DVCs. For the log and sine transformations, I use the definition of elasticity $\varepsilon_{y,x} = \frac{\partial y}{\partial x}\frac{x}{y}$ and the point estimate of $\varepsilon_{y,x}$, evaluated at the county-year means of x and y in the full sample (Table 15) and for each zone individually (Table 16). For the quadratic specification, I evaluate the marginal effect at the county-year mean of deer abundance. For the dummy variable transformation, I assume wolf presence implies the average number of wolves among county-years with non-zero wolf populations, which is 16 wolves statewide, 22 wolves in core wolf habitat, 10 wolves in secondary wolf habitat, and 3 wolves in the dispersal area. As such, the reader should interpret all marginal changes as a change from the mean. Multiplying the resulting change in DVCs by the national average total economic loss per DVC, \$9,234 (Huijser et al. 2008), provides an estimate of the economic impact of changes in wildlife abundance.

The net marginal effect wolves on DVCs is economically significant and robust across specifications. Statewide, one additional wolf leads to 5 fewer DVCs each year in the hyperbolic sine specification, 3 fewer DVCs in the dummy variable specification, and 1 fewer DVC in the quadratic specification (Table 17-Table 19, Column 2); these reductions are valued at \$8,000 to \$42,000 per wolf per year. Increasing the wolf population by one standard deviation or 13 wolves leads to reductions in DVC losses of \$105,000 to \$545,000 each year.

The effect of wolves on DVCs through changes in deer behavior are only statistically significant in the dispersal area (Table 17-Table 19, Columns 2 and 5). In this area, each wolf leads to 41 fewer DVCS in the hyperbolic sine specification, and about 17 fewer DVCs in both the dummy variable and level specifications. These reductions are valued at \$156,000 to

$375,000 per wolf per year. In this region, a one standard deviation change in the wolf population is 2 wolves, which approximately doubles the estimated impact.

The effect of wolves on DVCs through changes in deer abundance are also economically significant, albeit smaller in magnitude than the impacts on deer behavior. Statewide, each additional wolf leads to 106 fewer deer in the next period in the average county (Table 26, Column 1). Plugging this change in deer abundance into the marginal impact equations for the preferred instrumental variables specification leads to 0.2 to 1.1 fewer DVCs each year depending on the transformation used (Table 20-Table 22, Column 2). This reduction is valued at $1,800 to $10,500 per wolf per year. In both core wolf habitat and secondary wolf habitat, each additional wolf reduces deer abundance by about 138 deer in the average county, which translates to an annual reduction in DVC losses valued at about $600 to $13,000 per wolf per year.

6. Discussion

The results provide strong evidence that wolves reduce DVCs both by reducing the deer population and causing deer to avoid roads; however, the magnitude of these impacts vary by region. Impacts on deer abundance dominate in the core and secondary wolf habitat zones, whereas impacts on deer behavior dominate in the dispersal area. This finding is consistent with intuition. The dispersal area is mainly agricultural and has high road density and low wolf abundance. In the absence of wolves, deer forage frequently near the edges of agricultural fields (Wywialowski 1996; Tzilkowski, Brittingham, and Lovallo 2002; Alverson, Waller, and Solheim 1988), which also tend to be bordered by roads. These areas are exposed and increase predation risk; therefore, deer may retreat to wooded areas with more cover (and less roads) when wolves are present (Mao et al. 2005; Fortin et al. 2005). The high ratio of deer to wolves in this zone implies that most predation is likely compensatory, resulting in little effect on deer abundance.[15] In contrast, the core and secondary wolf habitat zones are mainly forested and have low road density and high wolf abundance. The availability of food sources is more uniformly distributed in forests than in areas with agricultural fields. As such, in the absence of wolves deer likely do not aggregate near roads as frequently as they do in the dispersal areas, so there is less opportunity for a behavioral effect. The relatively lower ratio of deer to wolves in this region compared to the dispersal area implies more predation is likely additive, which leads to a larger population effect.

Changes to deer behavior have a much larger impact than do changes in deer abundance. One additional wolf leads to an estimated 0.1 to 0.4 fewer DVCs each year through reductions in deer abundance in the core and secondary wolf habitat zones and 17 to 41 fewer DVCs each year through changes in deer behavior in the dispersal area. It is sensible for the behavioral effect to be larger because wolves potentially could impact the behavior of every deer but will only kill a small proportion of deer. While the population effect is relatively small, the magnitude is reasonable. WDNR estimates that each wolf in Wisconsin consumes roughly 18 to 20 deer each year (Wisconsin Department of Natural Resources 2009). Some of this predation is probably compensatory, so the true reduction in deer population through consumption is smaller than 20 deer per wolf, as compared to the 140 deer per wolf reduction predicted by the predator-prey model for core and secondary wolf habitat zones. However, wolves may also cause non-consumptive effects on deer abundance. Specifically, predator avoidance behaviors could be

[15] Compensatory mortality refers to deaths that would have occurred in the absence of predation (e.g. starvation, disease, etc.). Compensatory mortality does not reduce the population. In contrast, additive mortality refers to deaths that would not have occurred in the absence of predation. Additive mortality reduces the population.

energetically costly (Creel and Christianson 2008; Preisser and Bolnick 2008; Laporte et al. 2010) and stress could reduce productivity (Bova et al. 2014); both effects would tend to reduce the deer population beyond the number of predated animals, especially in food-limited areas with severe winters such as the wolf habitat.

Overall, wolves appear to be a cost-effective control on the economic costs of deer. The estimated reduction in DVC losses per wolf per year is between \$600 and \$1800 in core and secondary wolf habitat and \$156,000 to \$375,000 in the dispersal area. These figures underestimate total economic impact when considering the other costs of deer. The results suggest that wolves cause deer to avoid edge habitats that tend to be near agricultural fields; as such, wolves likely also reduce agricultural damage caused by deer. In the core and secondary wolf habitat areas, the impact on DVCs was less pronounced, but previous research shows that wolves change deer foraging behavior in ways that support forest regeneration. This benefit is difficult to monetize but likely is highly valuable. In contrast, the main cost of wolves is livestock depredation. During the last five years in the study period, 2006-2010, verified wolf depredation in Wisconsin was about \$235 per wolf per year on average (Wisconsin Department of Natural Resources 2017; Wiedenhoeft et al. 2017). Unverified depredation losses would need to be at least 650 times larger than verified losses to outweigh the benefits of wolves in the dispersal/agricultural area. While managers should make every effort to reduce the impact of depredation on livestock farmers, non-lethal wolf deterrents or highly targeted wolf culling likely are more efficient strategies than blanket reductions in the wolf population.

There are three potentially important threats to identification to rule out. First, some of the strong behavioral effect in the dispersal area may be confounded with population impacts because wolf abundance in period *t-1* both increases wolf abundance and decreases deer abundance in period *t*. However, contemporaneous wolf population has a slightly statistically positive effect on same-period deer abundance in this zone. This positive covariance would suggest that the behavioral effect may be underestimated in this region, if anything. Second, the strong population impacts of wolves in core and secondary wolf habitat could be spurious if deer abundance had been on a downward trend before the recolonization of wolves. However, the deer population was increasing or stable prior to wolf entry in all counties that eventually got wolves (Figure 6). The inclusion of county and year effects further reduces the possibility of other sources of omitted variable bias. Lastly, if wolves and deer are endogenously determined, then all coefficient estimates will be biased and inconsistent. Specifically, the spatial spread of wolves over time could indicate that wolves choose habitats with high deer abundance; however, there is no evidence for this conclusion in the ecological literature. Two detailed studies of wolf pack locations in Wisconsin between 1979 and 1997 show that there is no significant difference in deer density between wolf pack areas and non wolf pack areas and deer density is not a significant predictor of wolf habitat suitability (Mladenoff et al. 1995; Mladenoff, Sickley, and Wydeven 1999).

Future research to identify whether the behavioral effect of wolves increases over time would be interesting. Ciuti et al. (2012) find that hunting mortality is lower for elk that avoid roads, likely because hunters use roads to access hunting grounds. If boldness or timidity is heritable, then harvest would cause the herd to become more timid over time. In addition, the elk that survived the harvest tended to avoid roads more over their life time, which suggests that the current generation is capable of learning to avoid human predation. It is reasonable to assume that wolf predation would have a similar effect on deer.

7. Conclusions

The expansion of wolves in the United States and abroad has the potential to mitigate the substantial economic costs of deer while at the same time restoring ecosystems. The results from this study show that these indirect benefits could be orders of magnitude larger than the direct costs of wolves, which suggests wolves are a cost-effective biological control on deer damage under certain conditions. Humans currently play this role, but recreational hunter participation has been declining for the past four decades and likely will continue to decline in the future (Holsman 2016; U.S. Fish and Wildlife Service 2017b). As such, deer and other prey species will only become more expensive and difficult to control over time in the absence of other predators. Wildlife managers and policy makers should take these factors into account when deciding whether to allow wolves and other apex predators to expand.

8. Tables and Figures

Table 15. Descriptive statistics for Wisconsin, 1998-2010

Variable		Mean	Std. Dev.	Min	Max
Deer-vehicle collisions	overall ($\bar{\bar{x}}$)	283	228	2	1,322
	between ($\bar{x}_i$)		222	8	1,042
	within ($x_{it} - \bar{x}_i$)		58	-263	317
Wolf population	overall ($\bar{\bar{x}}$)	6	13	0	98
	between ($\bar{x}_i$)		12	0	58
	within ($x_{it} - \bar{x}_i$)		5	-33	40
Deer population	overall ($\bar{\bar{x}}$)	22,005	12,938	505	65,537
	between ($\bar{x}_i$)		12,285	842	50,713
	within ($x_{it} - \bar{x}_i$)		4,321	-18,240	19,186
Total annual precipitation (in.)	overall ($\bar{\bar{x}}$)	33	6	21	61
	between ($\bar{x}_i$)		2	29	38
	within ($x_{it} - \bar{x}_i$)		6	-13	25
Total winter precipitation (in.)	overall ($\bar{\bar{x}}$)	9	3	4	19
	between ($\bar{x}_i$)		1	7	12
	within ($x_{it} - \bar{x}_i$)		2	-8	8
Days w/ min. temperature ≤ 32°F	overall ($\bar{\bar{x}}$)	158	18	115	206
	between ($\bar{x}_i$)		16	128	189
	within ($x_{it} - \bar{x}_i$)		9	-21	23
Days w/ max. temperature ≥ 80°F	overall ($\bar{\bar{x}}$)	51	15	15	88
	between ($\bar{x}_i$)		12	28	73
	within ($x_{it} - \bar{x}_i$)		9	-24	20
Annual vehicle miles traveled (mil.)	overall ($\bar{\bar{x}}$)	857	1,174	60	7,969
	between ($\bar{x}_i$)		1,181	71	7,411
	within ($x_{it} - \bar{x}_i$)		71	-1,009	559
Forest (acres)	overall ($\bar{\bar{x}}$)	307	269	14	1,204
	between ($\bar{x}_i$)		271	16	1,203
	within ($x_{it} - \bar{x}_i$)		2	-5	8
Farmland (acres)	overall ($\bar{\bar{x}}$)	337	202	15	932
	between ($\bar{x}_i$)		204	18	918
	within ($x_{it} - \bar{x}_i$)		3	-17	15

Notes: This table decomposes each variable (x_{it}) into "between" variation ($\bar{x}_i$) and "within" variation ($x_{it} - \bar{x}_i$), with $\bar{x}_i = \frac{1}{T}\sum_{t=1}^{T} x_{it}$ and $\bar{\bar{x}} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} x_{it}$ for county *i* at time *t*. The within statistics measure the deviation from the mean by county, and therefore can be positive or negative. Overall statistics use 819 county-years of data for 63 Wisconsin counties between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Between statistics use 63 counties. The number of years a county was observed is 13.

Table 16. Descriptive statistics for Wisconsin, by wolf management zone, 1998-2010

Variable		Mean	Std. Dev.	Min	Max
Core wolf habitat (Zone 1)					
Deer-vehicle collisions	overall ($\bar{\bar{x}}$)	99	85	2	374
	between ($\bar{x}_i$)		83	8	269
	within ($x_{it} - \bar{x}_i$)		27	-78	114
Wolf population	overall ($\bar{\bar{x}}$)	21	18	0	98
	between ($\bar{x}_i$)		16	4	58
	within ($x_{it} - \bar{x}_i$)		10	-33	40
Deer population	overall ($\bar{\bar{x}}$)	30,610	11,605	9,179	65,537
	between ($\bar{x}_i$)		9,795	13,067	48,596
	within ($x_{it} - \bar{x}_i$)		6,655	-18,240	19,186
Secondary wolf habitat (Zone 2)					
Deer-vehicle collisions	overall ($\bar{\bar{x}}$)	302	98	111	441
	between ($\bar{x}_i$)		92	214	391
	within ($x_{it} - \bar{x}_i$)		56	-119	148
Wolf population	overall ($\bar{\bar{x}}$)	10	8	0	39
	between ($\bar{x}_i$)		7	3	19
	within ($x_{it} - \bar{x}_i$)		6	-8	20
Deer population	overall ($\bar{\bar{x}}$)	30,861	9,550	14,939	50,818
	between ($\bar{x}_i$)		9,691	19,356	43,024
	within ($x_{it} - \bar{x}_i$)		4,402	-8,147	9,605
Dispersal area (Zone 3)					
Deer-vehicle collisions	overall ($\bar{\bar{x}}$)	328	254	23	971
	between ($\bar{x}_i$)		250	35	746
	within ($x_{it} - \bar{x}_i$)		74	-263	317
Wolf population	overall ($\bar{\bar{x}}$)	1	2	0	11
	between ($\bar{x}_i$)		1	0	3
	within ($x_{it} - \bar{x}_i$)		1	-3	9
Deer population	overall ($\bar{\bar{x}}$)	26,558	11,145	5,397	59,348
	between ($\bar{x}_i$)		10,870	7,377	50,713
	within ($x_{it} - \bar{x}_i$)		3,592	-12,647	8,635
Southern farmland (Zone 4)					
Deer-vehicle collisions	overall ($\bar{\bar{x}}$)	363	222	12	1,322
	between ($\bar{x}_i$)		217	41	1,042
	within ($x_{it} - \bar{x}_i$)		62	-204	280
Wolf population	overall ($\bar{\bar{x}}$)	0	0	0	0
Deer population	overall ($\bar{\bar{x}}$)	12,895	8,579	505	38,577
	between ($\bar{x}_i$)		8,306	842	30,994
	within ($x_{it} - \bar{x}_i$)		2,642	-6,834	10,781

Notes: This table decomposes each variable (x_{it}) into "between" variation ($\bar{x}_i$) and "within" variation ($x_{it} - \bar{x}_i$), with $\bar{x}_i = \frac{1}{T}\sum_{t=1}^{T} x_{it}$ and $\bar{\bar{x}} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} x_{it}$ for county i at time t. The within statistics measure the deviation from the mean by county, and therefore can be positive or negative. The data is a balanced panel that covers July 1, 1998 and June 30, 2010, with period t representing July 1 to June 30. Statistics are based on 16 counties for Zone 1, 4 counties for Zone 2, 16 counties for Zone 3, and 27 counties for Zone 4. Wolf territory classifications are based on the Wisconsin Department of Natural Resources wolf management zones.

Table 17. Ordinary least squares (OLS) fixed effects estimates of the impact of wolf presence on the natural log of deer-vehicle collisions for Wisconsin

Dependent variable: ln(DVC)	(1)	(2)	(3)	(4)	(5) (preferred)	(6)
Wolf presence dummy		-0.206***	-0.181***			
		(0.0576)	(0.0539)			
Wolf presence dummy ×						
Dispersal dummy				-0.191***	-0.171***	-0.175***
				(0.0541)	(0.0506)	(0.0499)
Central forest dummy				-0.0456	-0.0411	-0.0367
				(0.0274)	(0.0279)	(0.0289)
Northern forest dummy				-0.322	-0.273	-0.266
				(0.237)	(0.232)	(0.232)
Wolf presence dummy $_{j \neq i}$						0.0599
						(0.0607)
ln(Deer pop.)	0.302***		0.278***		0.275***	0.277***
	(0.0908)		(0.0870)		(0.0866)	(0.0875)
ln(Precip. (inch))	0.0323	0.0988	0.0304	0.103	0.0345	0.0274
	(0.0645)	(0.0616)	(0.0627)	(0.0642)	(0.0654)	(0.0652)
ln(Days w/ temp. < 32˚F)	-0.00458	0.243	-0.0263	0.226	-0.0356	-0.0454
	(0.290)	(0.328)	(0.297)	(0.319)	(0.290)	(0.289)
ln(Days w/ temp. > 80˚F)	-0.0279	0.0449	-0.0144	0.0583	-0.00278	-0.00689
	(0.0785)	(0.0865)	(0.0787)	(0.0898)	(0.0821)	(0.0817)
ln(AVMT)	0.581*	0.824**	0.665**	0.787**	0.639*	0.619*
	(0.334)	(0.366)	(0.331)	(0.391)	(0.356)	(0.355)
ln(Forest)	-2.880	-1.371	-3.028	-1.509	-3.118	-3.017
	(2.174)	(2.160)	(2.145)	(2.182)	(2.166)	(2.184)
ln(Farm)	2.860	1.017	3.076	1.174	3.176	3.059
	(2.369)	(2.335)	(2.339)	(2.363)	(2.365)	(2.386)
County effects	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	819	819	819	819	819	819
Within R-squared	0.197	0.187	0.216	0.189	0.218	0.220

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Deer-vehicle collisions are police-reported. The wolf presence dummy equals one for county-years with at least one wolf. The wolf presence dummy for counties $j \neq i$ equals one if any neighbor *j* of county *i* has a least one wolf. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 18. Ordinary least squares (OLS) fixed effects estimates of the impact of wolf abundance on the inverse hyperbolic sine of deer-vehicle collisions for Wisconsin

Dependent variable: $\sinh^{-1}$(DVC)	(1)	(2)	(3)	(4)	(5) (preferred)	(6)
$\sinh^{-1}$(Wolf pop.)		-0.0963**	-0.0668			
		(0.0456)	(0.0472)			
$\sinh^{-1}$(Wolf pop.) ×						
Dispersal dummy				-0.133***	-0.117***	-0.0761*
				(0.0368)	(0.0358)	(0.0388)
Central forest dummy				-0.0683	-0.0521	-0.0274
				(0.0661)	(0.0668)	(0.0586)
Northern forest dummy				-0.0716	-0.0203	0.00147
				(0.0826)	(0.0891)	(0.0817)
$\sinh^{-1}$(Avg. wolf pop. $_{j \neq i}$)						-0.0973
						(0.0624)
$\sinh^{-1}$(Deer pop.)	0.301***		0.249**		0.275***	0.224**
	(0.0905)		(0.0951)		(0.0966)	(0.105)
$\sinh^{-1}$(Precip. (inch))	0.0324	0.0803	0.0263	0.0831	0.0274	0.0347
	(0.0644)	(0.0613)	(0.0628)	(0.0602)	(0.0616)	(0.0603)
$\sinh^{-1}$(Days w/ temp. < 32˚F)	-0.00628	0.0663	-0.111	0.101	-0.0624	-0.0596
	(0.290)	(0.305)	(0.280)	(0.283)	(0.260)	(0.263)
$\sinh^{-1}$(Days w/ temp. > 80˚F)	-0.0283	0.0368	-0.0160	0.0377	-0.0218	-0.0159
	(0.0785)	(0.0849)	(0.0790)	(0.0856)	(0.0813)	(0.0831)
$\sinh^{-1}$(AVMT)	0.575*	0.764**	0.621*	0.823**	0.697**	0.704**
	(0.330)	(0.373)	(0.336)	(0.381)	(0.339)	(0.342)
$\sinh^{-1}$(Forest)	-2.896	-1.788	-3.086	-1.755	-3.076	-3.045
	(2.170)	(2.225)	(2.182)	(2.302)	(2.227)	(2.201)
$\sinh^{-1}$(Farm)	2.877	1.447	3.078	1.420	3.110	3.148
	(2.364)	(2.417)	(2.377)	(2.497)	(2.418)	(2.387)
County effects	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	819	819	819	819	819	819
Within R-squared	0.197	0.185	0.207	0.189	0.214	0.224

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period t representing July 1 to June 30. The dependent variable is the inverse hyperbolic sine of the number of police-reported deer vehicle collisions. The average wolf population in counties $j \neq i$ refers to neighbors of county i. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 19. Ordinary least squares (OLS) fixed effects estimates of the impact of wolf abundance on the level of deer-vehicle collisions for Wisconsin

Dependent variable: DVC	(1)	(2)	(3)	(4)	(5) (preferred)	(6)
Wolf pop.		-0.882*	-0.644			
		(0.510)	(0.547)			
Wolf pop. ×						
Dispersal dummy				-18.35**	-17.35**	-17.22**
				(8.081)	(7.482)	(7.224)
Central forest dummy				-3.038	-2.545	-2.456
				(2.313)	(2.472)	(2.446)
Northern forest dummy				-0.585	-0.328	-0.173
				(0.490)	(0.547)	(0.554)
Avg. wolf pop. $_{j \neq i}$						-0.406
						(1.121)
Deer pop. (thou.)	8.466***		8.499***		7.769***	7.560***
	(2.578)		(2.535)		(2.340)	(2.318)
Deer pop. (thou.)^2	-0.0895***		-0.0931***		-0.0812***	-0.0794***
	(0.0305)		(0.0300)		(0.0276)	(0.0269)
Precip. (inch)	-2.604*	-3.054**	-2.930**	-3.105**	-2.943**	-3.085**
	(1.419)	(1.399)	(1.411)	(1.377)	(1.383)	(1.469)
Precip. (inch)^2	0.0383*	0.0490**	0.0420**	0.0496**	0.0425**	0.0441**
	(0.0192)	(0.0191)	(0.0193)	(0.0189)	(0.0192)	(0.0205)
Days w/ temp. < 32˚F	2.807*	3.070**	2.357*	2.401	1.745	1.631
	(1.490)	(1.514)	(1.401)	(1.468)	(1.401)	(1.398)
Days w/ temp. < 32˚F^2	-0.0124***	-0.0120**	-0.0112**	-0.00992**	-0.00928**	-0.00899**
	(0.00458)	(0.00469)	(0.00444)	(0.00449)	(0.00432)	(0.00431)
Days w/ temp. > 80˚F	-0.904*	-0.862	-0.976*	-0.964*	-1.063**	-1.091**
	(0.540)	(0.540)	(0.530)	(0.531)	(0.525)	(0.532)
AVMT (bil.)	-37.52	-28.85	-36.61	-17.35	-24.80	-24.35
	(40.02)	(40.72)	(39.82)	(40.59)	(38.14)	(38.01)
Acres of forest (tens)	-25.79	-13.86	-29.55	-1.197	-17.77	-18.07
	(35.15)	(34.51)	(34.29)	(34.25)	(34.10)	(34.06)
Acres of farmland (tens)	84.19**	71.41*	86.16**	69.16*	83.07**	83.45**
	(36.45)	(38.52)	(36.47)	(38.87)	(36.77)	(37.24)
County effects	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	819	819	819	819	819	819
Within R-squared	0.275	0.244	0.277	0.280	0.310	0.310

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. The dependent variable is the number of police-reported deer vehicle collisions. The average wolf population in counties $j \neq i$ refers to neighbors of county *i*. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 20. Instrumental variables (IV) fixed effects estimates of the impact of wolf presence on the natural log of deer-vehicle collisions, second stage results for Wisconsin

Dependent variable: ln(DVC)	(1) OLS	(2) IV (preferred)	(3) IV	(4) IV
Wolf presence dummy ×				
Dispersal dummy	-0.171***	-0.171***	-0.173***	-0.165***
	(0.0506)	(0.0552)	(0.0499)	(0.0502)
Central forest dummy	-0.0411	-0.0409	-0.0414	-0.0396
	(0.0279)	(0.0292)	(0.0273)	(0.0280)
Northern forest dummy	-0.273	-0.271	-0.276	-0.256
	(0.232)	(0.217)	(0.226)	(0.221)
ln(Deer pop.)	0.275***	0.286	0.254**	0.366**
	(0.0866)	(0.247)	(0.117)	(0.172)
ln(Precip. (inch))	0.0345	0.0318	0.0397	0.0116
	(0.0654)	(0.0674)	(0.0689)	(0.0777)
ln(Days w/ temp. < 32˚F)	-0.0356	-0.0460	-0.0158	-0.123
	(0.290)	(0.262)	(0.282)	(0.260)
ln(Days w/ temp. > 80˚F)	-0.00278	-0.00521	0.00182	-0.0232
	(0.0821)	(0.0840)	(0.0814)	(0.0800)
ln(AVMT)	0.639*	0.633*	0.650*	0.589*
	(0.356)	(0.367)	(0.353)	(0.342)
ln(Forest)	-3.118	-3.182	-2.997	-3.656
	(2.166)	(2.185)	(2.256)	(2.450)
ln(Farm)	3.176	3.256	3.025	3.846
	(2.365)	(2.455)	(2.497)	(2.746)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	819	819	819	819
Instrument(s)		Winter precip. $(\text{inch})_{t-1}$	ln(Deer pop.)$_{t-1}$	ln(Deer pop.)$_{t-2}$
First stage F		16.88	444.4	118.1

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. Deer-vehicle collisions are police-reported. The wolf presence dummy equals one for county-years with at least one wolf. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 21. Instrumental variables (IV) fixed effects estimates of the impact of wolf abundance on the inverse hyperbolic sine of deer-vehicle collisions, second stage results for Wisconsin

Dependent variable: $\sinh^{-1}$(DVC)	(1) OLS	(2) IV (preferred)	(3) IV	(4) IV
$\sinh^{-1}$(Wolf pop.) ×				
Dispersal dummy	-0.117***	-0.124***	-0.119***	-0.113***
	(0.0358)	(0.0424)	(0.0356)	(0.0356)
Central forest dummy	-0.0521	-0.0598	-0.0546	-0.0480
	(0.0668)	(0.0697)	(0.0659)	(0.0665)
Northern forest dummy	-0.0203	-0.0447	-0.0283	-0.00749
	(0.0891)	(0.0985)	(0.0903)	(0.0908)
$\sinh^{-1}$(Deer pop.)	0.275***	0.144	0.232*	0.344*
	(0.0966)	(0.283)	(0.135)	(0.191)
$\sinh^{-1}$(Precip. (inch))	0.0274	0.0539	0.0361	0.0135
	(0.0616)	(0.0667)	(0.0657)	(0.0761)
$\sinh^{-1}$(Days w/ temp. < 32˚F)	-0.0624	0.0154	-0.0369	-0.103
	(0.260)	(0.231)	(0.257)	(0.239)
$\sinh^{-1}$(Days w/ temp. > 80˚F)	-0.0218	0.00647	-0.0125	-0.0366
	(0.0813)	(0.0902)	(0.0818)	(0.0832)
$\sinh^{-1}$(AVMT)	0.697**	0.757**	0.717**	0.665**
	(0.339)	(0.352)	(0.337)	(0.319)
$\sinh^{-1}$(Forest)	-3.076	-2.449	-2.871	-3.406
	(2.227)	(2.159)	(2.292)	(2.462)
$\sinh^{-1}$(Farm)	3.110	2.307	2.847	3.532
	(2.418)	(2.403)	(2.524)	(2.748)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	819	819	819	819
Instrument(s)		Winter precip. (inch)$_{t-1}$	$\sinh^{-1}$ (Deer pop.)$_{t-1}$	$\sinh^{-1}$ (Deer pop.)$_{t-2}$
First stage F		13.12	496.2	116.3

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. The dependent variable is the inverse hyperbolic sine of the number of police-reported deer vehicle collisions. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 22. Instrumental variables (IV) fixed effects estimates of the impact of wolf abundance on the level of deer-vehicle collisions, second stage results for Wisconsin

Dependent variable: DVC	(1) OLS Coefficient	Standard error	(2) IV (preferred) Coefficient	Standard error
Wolf pop. ×				
Dispersal dummy	-17.35**	(7.482)	-16.97**	(7.324)
Central forest dummy	-2.545	(2.472)	-2.411	(2.519)
Northern forest dummy	-0.328	(0.547)	-0.726	(0.605)
Deer pop. (thou.)	7.769***	(2.340)	11.37***	(4.310)
Deer pop. (thou.)^2	-0.0812***	(0.0276)	-0.148**	(0.0622)
Precip. (inch)	-2.943**	(1.383)	-3.239**	(1.426)
Precip. (inch)^2	0.0425**	(0.0192)	0.0440**	(0.0193)
Days w/ temp. < 32˚F	1.745	(1.401)	1.635	(1.377)
Days w/ temp. < 32˚F^2	-0.00928**	(0.00432)	-0.00928**	(0.00425)
Days w/ temp. > 80˚F	-1.063**	(0.525)	-1.123**	(0.532)
AVMT (bil.)	-24.80	(38.14)	-28.80	(37.40)
Acres of forest (tens)	-17.77	(34.10)	-15.70	(35.31)
Acres of farmland (tens)	83.07**	(36.77)	87.45**	(36.21)
County effects	Yes		Yes	
Year effects	Yes		Yes	
Observations	819		819	
Instrument(s)			Deer pop. (thou.)$_{t-1}$ Deer pop. (thou.)$_{t-1}^2$	
First stage F			38.79	

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population and its square are assumed to be endogenous. Regression 1 presents the preferred ordinary least squares coefficient estimates as a basis of comparison. Regression 2 presents instrumental variables coefficient estimates using lagged deer population and its square as instruments. The dependent variable is the number of police-reported deer vehicle collisions. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 23. Instrumental variables (IV) fixed effects estimates of the impact of wolf presence on the natural log of deer-vehicle collisions, first stage results for Wisconsin

Dependent variable: ln(Deer pop.)	(1) OLS	(2) IV (preferred)	(3) IV	(4) IV
Wolf presence dummy ×				
Dispersal dummy	-0.0724*	-0.0560	-0.0177	-0.0402
	(0.0415)	(0.0455)	(0.0168)	(0.0287)
Central forest dummy	-0.0164	0.0103	-0.0555***	0.00814
	(0.0229)	(0.0213)	(0.0120)	(0.0149)
Northern forest dummy	-0.180***	-0.208***	-0.125***	-0.184***
	(0.0500)	(0.0468)	(0.0369)	(0.0455)
ln(Precip. (inch))	0.250***	0.155***	0.0101	0.142***
	(0.0595)	(0.0443)	(0.0313)	(0.0409)
ln(Days w/ temp. < 32˚F)	0.953***	0.668***	0.407***	0.810***
	(0.196)	(0.176)	(0.0987)	(0.133)
ln(Days w/ temp. > 80˚F)	0.222***	0.238***	0.120***	0.210***
	(0.0571)	(0.0538)	(0.0310)	(0.0398)
ln(AVMT)	0.541***	0.491***	0.285***	0.438***
	(0.175)	(0.167)	(0.0767)	(0.126)
ln(Forest)	5.859***	5.361***	1.690***	3.408***
	(1.008)	(1.016)	(0.509)	(0.776)
ln(Farm)	-7.294***	-6.793***	-2.204***	-4.298***
	(1.000)	(1.031)	(0.546)	(0.809)
Winter precip. (in.)$_{t-1}$		0.0208***		
		(0.00508)		
ln(Deer pop.)$_{t-1}$			0.726***	
			(0.0344)	
ln(Deer pop.)$_{t-2}$				0.552***
				(0.0508)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	819	819	819	819

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. Deer-vehicle collisions are police-reported. The wolf presence dummy equals one for county-years with at least one wolf. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 24. Instrumental variables (IV) fixed effects estimates of the impact of wolf abundance on the inverse hyperbolic sine of deer-vehicle collisions, first stage results for Wisconsin

Dependent variable: $\sinh^{-1}$(Deer pop.)	(1) OLS	(2) IV (preferred)	(3) IV	(4) IV
$\sinh^{-1}$(Wolf pop.) ×				
Dispersal dummy	-0.0585**	-0.0462**	-0.0106	-0.0272*
	(0.0226)	(0.0233)	(0.00968)	(0.0146)
Central forest dummy	-0.0591***	-0.0460**	-0.0175	-0.0308**
	(0.0202)	(0.0203)	(0.0119)	(0.0131)
Northern forest dummy	-0.187***	-0.181***	-0.0716***	-0.125***
	(0.0456)	(0.0436)	(0.0185)	(0.0315)
$\sinh^{-1}$(Precip. (inch))	0.202***	0.122***	0.00407	0.121***
	(0.0538)	(0.0411)	(0.0311)	(0.0395)
$\sinh^{-1}$(Days w/ temp. < 32˚F)	0.595***	0.372**	0.316***	0.602***
	(0.184)	(0.175)	(0.102)	(0.134)
$\sinh^{-1}$(Days w/ temp. > 80˚F)	0.216***	0.227***	0.120***	0.202***
	(0.0541)	(0.0518)	(0.0319)	(0.0417)
$\sinh^{-1}$(AVMT)	0.460**	0.424**	0.274***	0.402***
	(0.180)	(0.172)	(0.0843)	(0.137)
$\sinh^{-1}$(Forest)	4.803***	4.449***	1.586***	3.060***
	(0.996)	(1.006)	(0.537)	(0.798)
$\sinh^{-1}$(Farm)	-6.141***	-5.797***	-2.129***	-3.964***
	(1.023)	(1.040)	(0.572)	(0.830)
Winter precip. (inch)$_{t-1}$		0.0177***		
		(0.00490)		
$\sinh^{-1}$(Deer pop.)$_{t-1}$			0.687***	
			(0.0308)	
$\sinh^{-1}$(Deer pop.)$_{t-2}$				0.490***
				(0.0455)
County effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Observations	819	819	819	819

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population is assumed to be endogenous. The dependent variable is the inverse hyperbolic sine of the number of police-reported deer vehicle collisions. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 25. Instrumental variables (IV) fixed effects estimates of the impact of wolf abundance on the level of deer-vehicle collisions, first stage results for Wisconsin

	(1)	(2)
Dependent variable:	Deer pop. (thou.)	Deer pop. (thou.)^2
Wolf pop. ×		
Dispersal dummy	0.165	12.23
	(0.134)	(10.41)
Central forest dummy	-0.0513	-2.595
	(0.0750)	(6.760)
Northern forest dummy	-0.136**	-12.59**
	(0.0598)	(5.252)
Precip. (inch)	-0.484***	-31.00***
	(0.118)	(8.143)
Precip. (inch)^2	0.00618***	0.371***
	(0.00169)	(0.115)
Days w/ temp. < 32˚F	0.470***	27.60**
	(0.129)	(10.62)
Days w/ temp. < 32˚F^2	-0.00131***	-0.0835**
	(0.000384)	(0.0316)
Days w/ temp. > 80˚F	-0.0107	-1.130
	(0.0245)	(2.107)
AVMT (bil.)	0.500	-2.336
	(1.238)	(65.03)
Acres of forest (tens)	1.337	75.07
	(1.010)	(82.57)
Acres of farmland (tens)	-0.768	1.450
	(0.571)	(39.14)
Deer pop. (thou)$_{t-1}$	0.901***	25.86***
	(0.0945)	(6.851)
Deer pop. (thou)$_{t-1}{}^2$	-0.00448***	0.181*
	(0.00140)	(0.107)
County effects	Yes	Yes
Year effects	Yes	Yes
Observations	819	819

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. Contemporaneous deer population and its square are assumed to be endogenous. Regression 1 presents the preferred ordinary least squares coefficient estimates as a basis of comparison. Regression 2 presents instrumental variables coefficient estimates using lagged deer population and its square as instruments. The dependent variable is the number of police-reported deer vehicle collisions. Wolf population is estimated mid-winter and deer population is estimated as of October 1. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Table 26. Fixed effects estimates of predator-prey population dynamics

Dependent variable: ln(Deer pop. prehunt)	(1)	(2)	(3)	(4) (preferred)	(5)	(6)
Wolf pop.$_{t-1}$	-0.0048***		-0.0041***			
	(0.00148)		(0.00149)			
Wolf pop.$_{t}$		-0.0038**	-0.0007			
		(0.0015)	(0.0017)			
Wolf pop.$_{t-1}$ ×						
Dispersal dummy				0.0129		0.0116
				(0.0082)		(0.0078)
Central forest dummy				-0.0076***		-0.0103***
				(0.0025)		(0.0037)
Northern forest dummy				-0.0045***		-0.0035**
				(0.00150)		(0.0015)
Wolf pop.$_{t}$ ×						
Dispersal dummy					0.0082*	0.0018
					(0.0047)	(0.0027)
Central forest dummy					-0.00155	0.00307
					(0.0023)	(0.0028)
Northern forest dummy					-0.0039**	-0.0012
					(0.0016)	(0.0019)
ln(Deer pop. posthunt)$_{t-1}$	0.625***	0.629***	0.624***	0.629***	0.630***	0.628***
	(0.0372)	(0.0369)	(0.0372)	(0.0369)	(0.0368)	(0.0370)
Total winter precip. (in.)$_{t-1}$	0.00475	0.00507	0.00470	0.00524	0.00546	0.00519
	(0.00323)	(0.00331)	(0.00326)	(0.00317)	(0.00328)	(0.00321)
Days w/ min. temp. <0˚F$_{t-1}$	-0.0023**	-0.0024**	-0.0023**	-0.0025**	-0.0025**	-0.0025**
	(0.00097)	(0.00099)	(0.00097)	(0.00098)	(0.00101)	(0.00099)
County effects	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	819	819	819	819	819	819
Within R-squared	0.716	0.713	0.716	0.718	0.715	0.719

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. Winter is defined as December 1 to April 30. The dependent variable is prehunt deer population measured as of October. Wolf population is estimated mid-winter. The independent deer population variable is posthunt population measured as of January. County by day precipitation is spatially-weighted averages of daily 4km weather grids. Northern forest, central forest, and dispersal dummy variables equal one for counties in Wisconsin Wolf Management Zones 1, 2, and 3, which represent core wolf habitat, secondary wolf habitat, and dispersal area, respectively. The excluded group is Zone 4, which is predominantly agricultural and contains all the urban areas in the state. This zone is unsuitable for wolf recolonization and has zero wolves in every period. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level.

Figure 2. Wolf pack distribution in Wisconsin, selected years 1998-2010

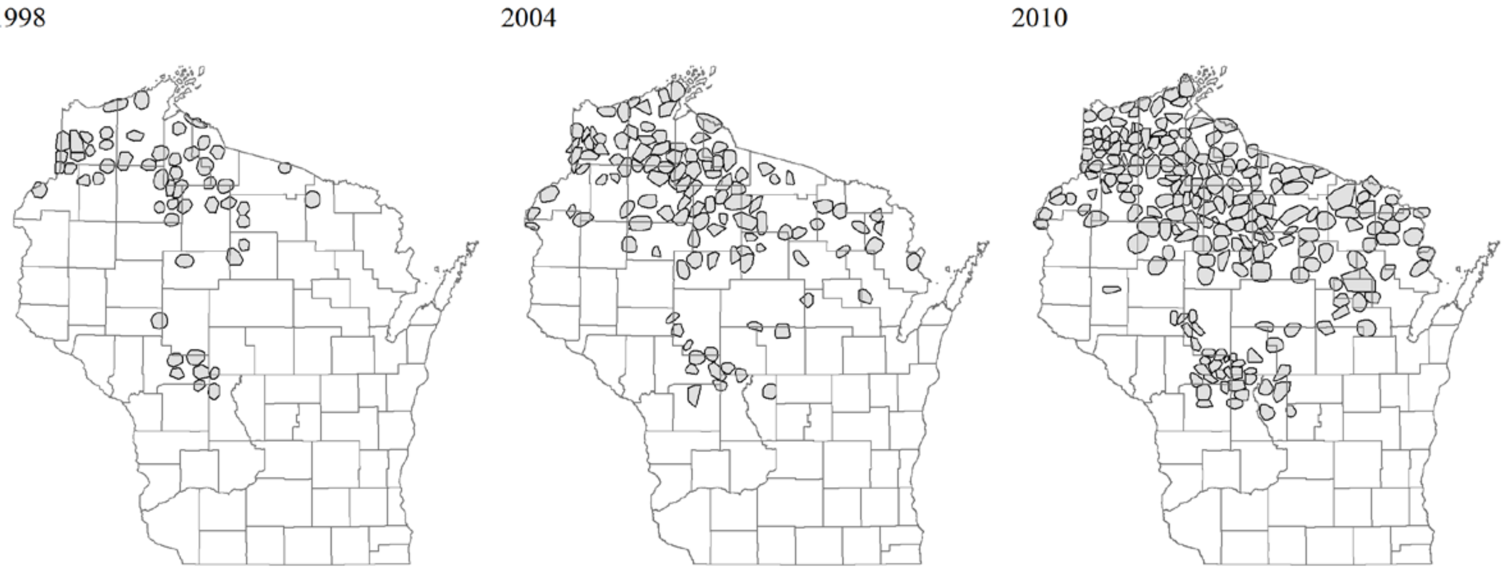
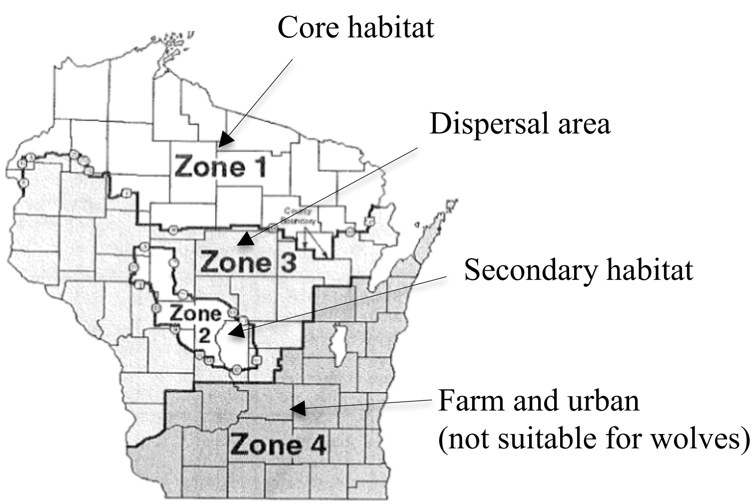
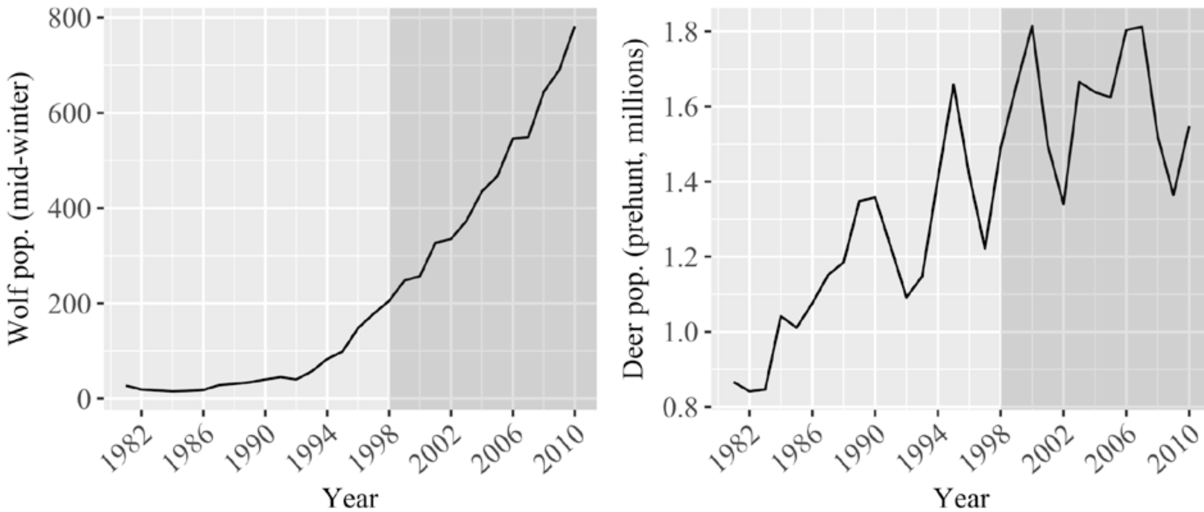


Figure 3. 1999 Wolf management zones in Wisconsin



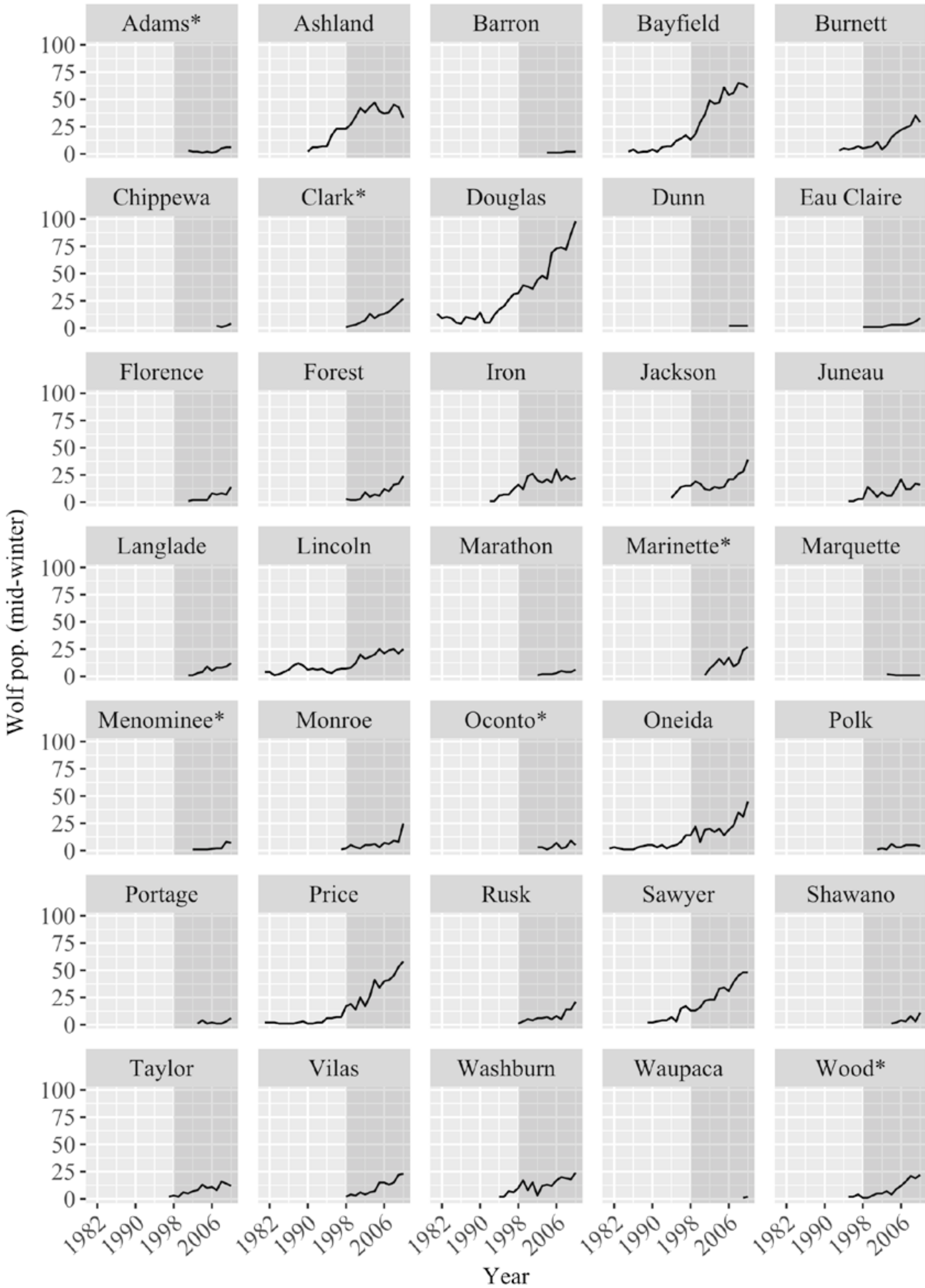
Source: WDNR 1999

Figure 4. Wolf and deer populations in Wisconsin, 1981-2010



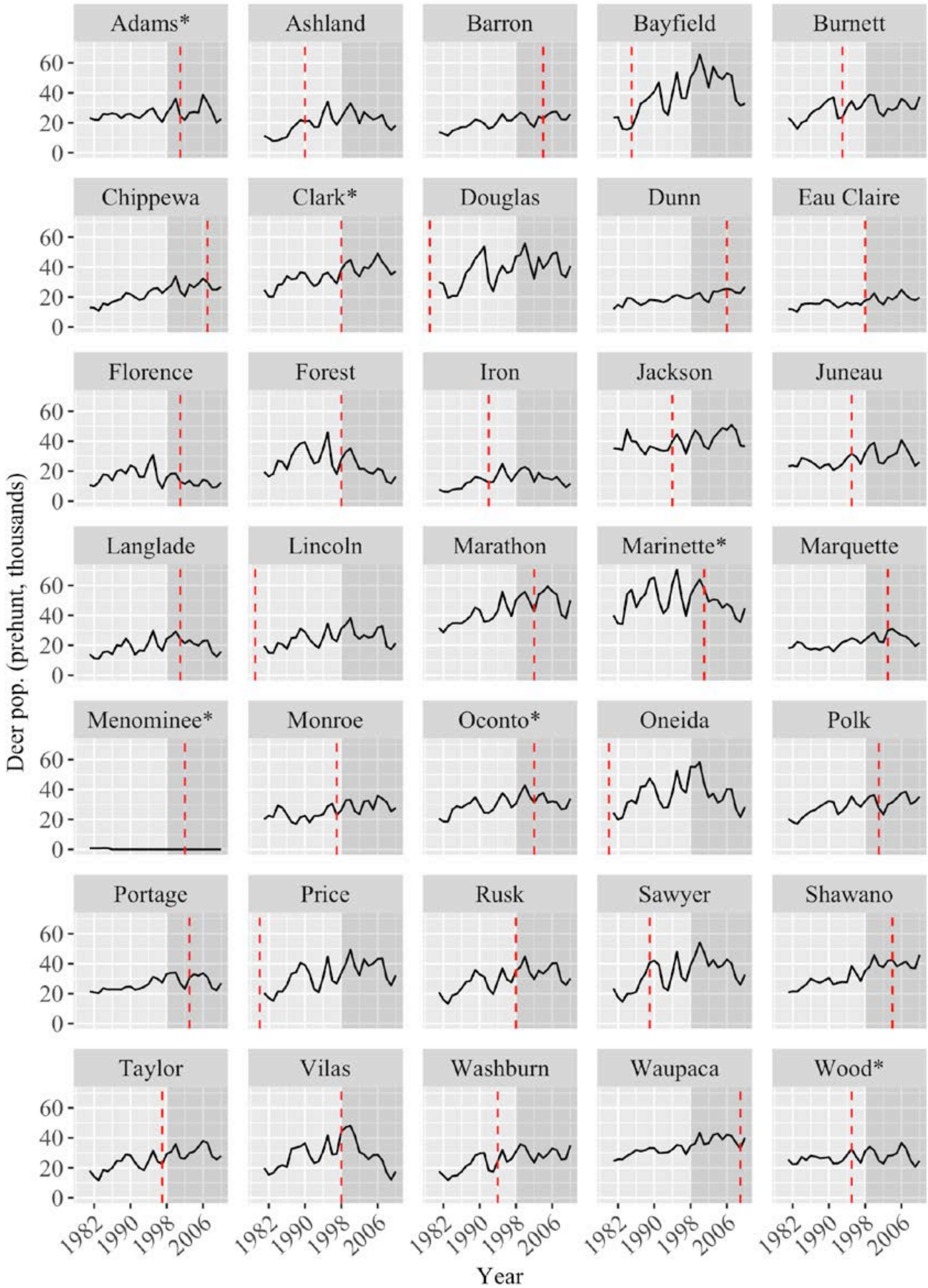
Notes: Regressions include data for 1998-2010, shaded in dark grey, and exclude earlier years due to data availability for other covariates.

Figure 5. Wolf population in Wisconsin counties with wolves, 1981-2010



Notes: The trend line excludes zeros at the beginning of the time series and includes them thereafter. Regressions include data for 1998-2010, shaded in dark grey, and exclude earlier years due to data availability for other covariates. *County excluded from regressions due to data quality issues in the deer-vehicle collision time series.

Figure 6. Deer population in Wisconsin counties with wolves, 1981-2010



Notes: Regressions include data for 1998-2010, shaded in dark grey, and exclude earlier years due to data availability for other covariates. Red dashed lines indicate the year wolves entered the county. Wolves entered four counties before the first year plotted, in 1979 for Douglas and Lincoln counties and 1980 for Oneida and Price counties. *County excluded from regressions due to data quality issues in the deer-vehicle collision time series. Menominee county is a tribal area for which deer abundance estimates are not available.

9. Appendix

Table 27. Ordinary least squares (OLS) fixed effects estimates of the impact of deer abundance on the level of deer-vehicle collisions for Wisconsin

Dependent variable: DVC	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8) (preferred)
Deer pop. (thou.)	2.477***	8.578***	8.501***	8.466***	8.453***	8.356***	7.379**	8.466***
	(0.870)	(2.611)	(2.595)	(2.578)	(2.593)	(2.654)	(2.778)	(2.578)
Precip. (inch)	0.425	0.147	-3.591**	-2.604*	-2.578*	-2.762*	-2.593*	-2.604*
	(0.455)	(0.439)	(1.469)	(1.419)	(1.446)	(1.465)	(1.429)	(1.419)
Days w/ temp. < 32˚F	-0.962***	-1.187***	-1.080***	2.807*	2.838*	2.837**	2.297	2.807*
	(0.358)	(0.380)	(0.368)	(1.490)	(1.438)	(1.414)	(1.398)	(1.490)
Days w/ temp. > 80˚F	-0.746	-0.823	-0.949*	-0.904*	-0.756	-0.732	-0.919	-0.904*
	(0.535)	(0.527)	(0.535)	(0.540)	(0.806)	(0.811)	(0.874)	(0.540)
AVMT (bil.)	-33.60	-39.85	-38.91	-37.52	-37.41	47.63	79.75	-37.52
	(40.35)	(39.92)	(40.03)	(40.02)	(40.01)	(157.4)	(154.0)	(40.02)
Acres of forest (tens)	-25.64	-26.79	-28.59	-25.79	-25.81	-21.71	35.45	-25.79
	(36.20)	(35.34)	(35.14)	(35.15)	(35.17)	(36.63)	(59.45)	(35.15)
Acres of farmland (tens)	75.31**	83.39**	83.08**	84.19**	84.25**	88.96**	-44.33	84.19**
	(37.10)	(36.44)	(36.33)	(36.45)	(36.44)	(35.98)	(36.52)	(36.45)
Deer pop. (thou.)^2		-0.0899***	-0.0893***	-0.0895***	-0.0893***	-0.0888***	-0.0769**	-0.0895***
		(0.0308)	(0.0307)	(0.0305)	(0.0307)	(0.0308)	(0.0321)	(0.0305)
Precip. (inch)^2			0.0506**	0.0383*	0.0379*	0.0401**	0.0376*	0.0383*
			(0.0201)	(0.0192)	(0.0197)	(0.0197)	(0.0189)	(0.0192)
Days w/ temp. < 32˚F^2				-0.0124***	-0.0125***	-0.0125***	-0.0106**	-0.0124***
				(0.00458)	(0.00441)	(0.00433)	(0.00421)	(0.00458)

Table 27. Ordinary least squares (OLS) fixed effects estimates of the impact of deer abundance on the level of deer-vehicle collisions for Wisconsin (continued)

Dependent variable: DVC	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8) (preferred)
Days w/ temp. > 80˚F^2					-0.00137	-0.00173	0.00174	
					(0.00629)	(0.00650)	(0.00679)	
AVMT (bil.)^2						-7.403	-8.183	
						(11.90)	(11.41)	
Acres of forest (tens)^2							-0.370	
							(0.545)	
Acres of farmland (tens)^2							1.208***	
							(0.272)	
County effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	819	819	819	819	819	819	819	819
Within R-squared	0.252	0.269	0.272	0.275	0.275	0.277	0.347	0.275

Notes: Statistics are based on county by year observations for Wisconsin between July 1, 1998 and June 30, 2010, with period *t* representing July 1 to June 30. The dependent variable is the number of police-reported deer vehicle collisions. Deer population is estimated as of October 1. Precipitation includes rain plus melted snow. Cold (hot) days are based on the minimum (maximum) daily temperature. Vehicle miles traveled is the number of miles driven on all roads in a year. Forest includes acres of deciduous forest, evergreen forest, mixed forest, disturbed national forest, disturbed other public lands forest, and disturbed private forests. Farmland includes acres of cropland and hay and pastureland. All models include a full set of county effects and year effects. Standard errors are clustered at the county level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level

Chapter 3. Valuing Ecological Changes in the Lake Michigan Recreational Fishery

1. Introduction

For more than 200 years, over-exploitation, land use change, and the introduction of non-native species have shaped the Great Lakes fish community (Wells and McLain 1973). At one time there were 163 native and probably native fishes in the lakes, but half of these species are currently endangered, extirpated, or globally extinct (Roth et al. 2012; Mandrak and Cudmore 2012). Lake Whitefish (*Coregonus clupeaformis*), Lake Herring (*Coregonus artedi*), and Lake Trout (*Salvelinus namaycush*) dominated the fishery prior to 1940, while introduced salmonid species (mainly *Oncorhynchus spp.*) were most prevalent in subsequent decades. Another shift appears to be under way. Salmonid and other demersal fish populations have collapsed in Lake Huron due to alterations in the food web, and the Chinook salmon (*O. tshawytscha*) population is decreasing rapidly in Lake Michigan (Chippewa-Ottawa Resource Authority et al. 2017; Claramunt, Madenjian, and Clapp 2012; Clark et al. 2016; Riley et al. 2008). In addition, the potential future impacts of new invaders such as Asian carp (*Hypophthalmichthys spp.*) and climate change are as of yet unknown, but could be devastating (Jerde et al. 2013; Myers et al. 2017; Sass et al. 2014). Maintaining the economic value of this highly dynamic resource requires active management that anticipates how recreational anglers react to changes in fishery attributes.

Recreational fishing is a major economic sector in the Great Lakes region. In 2011, 1.7 million anglers spent 19.7 million days fishing the Great Lakes (U.S. Fish and Wildlife Service and U.S. Census Bureau 2014). These activities generated about $7.7 billion in economic activity and supported nearly 50,000 jobs (Southwick Associates 2012b).[16] While these figures are substantial, participation in the fishery has declined precipitously since 1985. The number of anglers and days spent fishing basin-wide have decreased by 56 percent and 58 percent, respectively, (U.S. Fish and Wildlife Service 1988). Lake Michigan was hit the hardest with reductions of around 70 percent. It is not known whether the recent reductions in salmonid populations have contributed to this trend or what impact continued changes in species composition may have on the value of the fishery in the future.

Lake Michigan is the only Great Lake that continues to support an economically viable salmonid population (Claramunt, Madenjian, and Clapp 2012; Clark et al. 2016), but a collapse may be on the horizon. Biomass of Chinook Salmon—historically one of the most important salmonid sportfish—decreased by more than 70 percent from 2013 to 2015 (Chippewa-Ottawa Resource Authority et al. 2017). Furthermore, abundance of Chinook Salmon's primary food source, Alewife (*Alosa pseudoharengus*), is at an all-time low. At current population levels of both species, the predatory pressure on Alewives may be too great to sustain (Tsehaye et al. 2014; Chippewa-Ottawa Resource Authority et al. 2017). There is a concern that the Alewife population could collapse entirely, with Chinook Salmon following soon after due to a lack of alternative food sources. Against this backdrop, managers must decide whether to dedicate their resources toward forestalling additional declines in the popular and economically important Chinook Salmon fishery or to favor other species that may be more resilient to the current and

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[16] Dollar values in this Chapter are converted to 2016 dollars using the Bureau of Labor Statistics' Consumer Price Index. These estimates use 2016 rather than 2015 as the base year to facilitate comparisons with the estimates from the 2016 angler survey.

future ecological conditions in the lake (Tsehaye et al. 2014; Claramunt, Madenjian, and Clapp 2012; Dettmers, Goddard, and Smith 2012).

The Lake Michigan fishery is an important resource for surrounding states. It is the second-most-popular Great Lakes fishing destination and hosted 25 percent of all Great Lakes anglers in 2011 (U.S. Fish and Wildlife Service and U.S. Census Bureau 2014; Southwick Associates 2012b). Great Lakes angling supported more than 22,000 jobs and generated more than $2.7 billion in economic activity in the states bordering Lake Michigan, namely Illinois, Indiana, Michigan, and Wisconsin. Among these states, Michigan and Wisconsin have the most at stake in preserving the fishery. These states hosted more than half of all Great Lakes anglers in 2011. In addition, about 20 percent of the population aged 16 years and older in both states participated in some form of fishing. Overall, both states ranked in the top 10 nationwide for angler expenditures in the state and in the top 3 for non-resident fishing destinations.

There is a large body of literature that values Great Lakes recreational fishing, particularly for Wisconsin (Provencher, Baerenklau, and Bishop 2002; Provencher and Bishop 2004; Phaneuf, Kling, and Herriges 2000) and Michigan anglers (Jones and Lupi 2000; Lupi, Hoehn, and Christie 2003). More recently, Melstrom and Lupi (2013) find that Chinook Salmon, Coho Salmon (*Oncorhynchus kisutch*), and Rainbow Trout (*O. mykiss*) are the most valuable fish to Michigan Great Lakes anglers. In addition, per-fish values increased substantially since Johnston et al. (2006). Melstrom and Lupi attribute this increase to shifts in the angler population over time. Between 1985 and 2011, per capita fishing participation rates among residents age 16 and older fell from 28 percent to 19 percent in Michigan (U.S. Fish and Wildlife Service 1988; U.S. Fish and Wildlife Service and U.S. Census Bureau 2014). In addition, the composition of individuals who participate in any given year can vary greatly. Nationwide, close to half of all anglers do not renew their licenses in a given year (American Sportfishing Association 2015)

The Michigan valuation estimates provide a useful baseline to identify angler preferences in Lake Michigan, but they may not provide the whole picture. First, declines in Chinook Salmon populations are not uniform (Clark et al. 2016); as such fishing site quality and values may vary over time and space. There also may be other observed or unobserved sources of heterogeneity in preferences. Unfortunately, prior estimates for Wisconsin may no longer represent current preferences, as was the case in Michigan. Fishing effort in the Wisconsin waters of Lake Michigan decreased by 45 percent between 1985 and 2015, after two decades of exponential increases prior to this period (Hansen, Schultz, and Lasee 1990; Eggold 2016); through 2011, fishing participation per capita for Wisconsin residents declined from 34 percent to 21 percent (U.S. Fish and Wildlife Service 1988; U.S. Fish and Wildlife Service and U.S. Census Bureau 2014). It is possible that shifts in the characteristics and preferences of anglers also occurred during this time.

The purpose of this study is to (a) predict how anglers in the Wisconsin waters of Lake Michigan respond to changes in species-specific catch rates and (b) estimate the economic losses associated with recent declines in salmonid populations, particularly Chinook Salmon. I build a behavioral model that describes anglers' choices of what species to target, conditional on environmental and fishery management variables. The model is parameterized using responses to a stated preference choice experiment administered in a survey of Wisconsin anglers in 2016. The experiment focuses on measuring the impacts of three primary target species, Chinook Salmon, Lake Trout, and Walleye, which are among the most popular sportfish in the fishery (Melstrom and Lupi 2013; Eggold 2016). I find that there is a clear preference ordering for primary target species, with Lake Trout the least preferred by far and Chinook Salmon and Walleye the most preferred. Overall, primary target species has a large impact on trip value, and the collapse of Chinook Salmon populations would lead to large economic losses if current salmon anglers instead targeted Lake Trout and economic gains if they targeted Walleye.

The rest of this paper is organized as follows. Section 2 provides background on the ecology of the Great Lakes fisheries. Section 3 describes the survey design and sample. Section 4 specifies the behavioral model. Section 5 includes results from the conditional logit estimation. Section 6 presents welfare effects associated with changes in angling trip configurations. Section 7 concludes.

2. Study Area/Ecology

Historically, Lake Trout was the top predator in the Great Lakes and among the most valuable species in the commercial fishery from 1890 until the mid-1940s (Wells and McLain 1973). Commercial fishermen heavily exploited Lake Trout over this period, and populations gradually decreased. But parasitism by invasive sea lamprey delivered the fatal blow and ultimately caused the extirpation of Lake Trout in Lake Michigan by 1956. While sea lamprey affected Lake Trout the most heavily, Lake Whitefish, Walleye, Yellow Perch (*Perca flavescens*), suckers, deepwater ciscoes, and Burbot (*Lota lota*) populations also suffered.

The depletion of native species created ideal conditions for the swift and devastating invasion of Alewife, a herring native to the Atlantic coast. The Alewife first appeared in Lake Michigan in 1949 and experienced explosive growth over the 1950s and 1960s (Wells and McLain 1973). Alewives depleted food sources and consumed fish eggs and larvae of native species, causing further declines in Lake Trout, Emerald Shiner (*Notropis atherinoides*), and deepwater ciscoes. Alewife were also a nuisance to human populations because they often died *en masse* during the 1960s, choking the Lake Michigan shoreline, clogging water intake pipes, and stifling recreation and tourism.

In 1960, fisheries managers began an aggressive campaign to rehabilitate the Lake Michigan fishery. Their first tactic was to control sea lampreys using chemical lampricide, traps, barriers, and other methods. These efforts were enormously successful and reduced the sea lamprey population by more than 95 percent in only a few years (Great Lakes Fishery Commission 2017). With the sea lamprey largely under control by the mid-1960s, managers began large-scale stocking of salmonid species, including Lake Trout as well as Coho Salmon, Chinook Salmon, and Rainbow Trout, native to the Pacific coast, and Brown Trout (*Salmo trutta*), native to Europe and western Asia (Wells and McLain 1973). The primary goals of the stocking program were to re-establish a naturally reproducing population of Lake Trout, while simultaneously capitalizing on massive Alewife biomass to create a popular sport fishery for the introduced salmonid species.

Stocking efforts have been considerable. Stocking ramped up from less than 3 million fish per year in 1966 to 16 million in 1980 (U.S. Fish and Wildlife Service 2016). Since then, stocking has ranged between about 11 and 23 million fish per year. Salmonids constituted more than 90 percent of all stocked fish through 2012 (the latest year for which data are available), with Chinook salmon claiming the largest individual share at 31 percent of total stocking. Nine entities have stocked fish in Lake Michigan at some point since 1966, but the Michigan Department of Natural Resources, Wisconsin Department of Natural Resources, and U.S. Fish and Wildlife Service jointly were responsible for nearly 90 percent of stocking.

Successful control of sea lampreys, aggressive stocking, and the eventual establishment of naturalized Pacific salmon populations contributed to large increases in salmonid biomass that supported an immensely successful recreational fishery (Wisconsin Department of Natural Resources 2016b; Madenjian et al. 2002). Between 1969 and 1985, fishing effort in Wisconsin's water of Lake Michigan increased by an order of magnitude, the catch rate for salmonids doubled, and harvest of salmonids increased 20-fold (Hansen, Schultz, and Lasee 1990). While catch increased for all the stocked species during this period, much of this trend can be attributed to Chinook Salmon and Coho Salmon, which respectively constituted 35 percent and 24 percent of total salmonid catch.

The bonanza would not last, however. Heavy predation by salmonids, particularly Chinook Salmon, caused large decreases in the Alewife population in both Lake Michigan and Lake Huron during the 1970s and 1980s (Madenjian et al. 2002; Dobiesz et al. 2005). In Lake Huron, Alewife almost completely collapsed by 2004, and Pacific salmon populations soon followed due to starvation (Clark et al. 2016). Catch of Chinook Salmon in the U.S. waters of Lake Huron decreased more than 95 percent from around 154,000 fish in 2002 to 6,000 in 2011. Catch rates fell from 9 fish/100 hours of fishing in 2002 to 1.3 fish/100 hours by 2009 (Michigan Department of Natural Resources n.d.). Due to a variety of stressors, including the establishment of several new invasive species, many other native fishes also collapsed between 1994 and 2006—abundance of Burbot, Spottail Shiner (*Notropis hudsonius*), Slimy Sculpin (*Cottus cognatus*), Deepwater Sculpin (*Myoxocephalus thompsonii*), Lake Whitefish, and Lake Trout decreased by 85 to 98 percent (Riley et al. 2008). However, one silver lining is that native species, such as Lake Trout and Emerald Shiner, began to show signs of recovery at the end of this period (Riley et al. 2007; Schaeffer, Warner, and O'Brien 2008).

Although Chinook Salmon and Alewives have fared somewhat better in Lake Michigan, populations are still at risk (Tsehaye et al. 2014). The predator/prey ratio (lake-wide biomass of

Chinook Salmon age ≥ 1 year divided by biomass of Alewives age ≥ 1 year) has been above the target of 0.05 in all but one year since 2010, reaching more than 0.09 in 2013 (Wisconsin Department of Natural Resources 2016b). Management agencies have set a safe upper limit of 0.10, above which predatory pressure potentially could cause Alewife to collapse—the ratio averaged 0.11 in the five years preceding the Alewife collapse in Lake Huron. To reduce the top-down pressure on Alewives, fisheries managers reduced lake-wide stocking of Chinook Salmon by 50 percent between 2012 and 2014 and proposed an additional 50 percent cut for 2018 (Michigan Department of Natural Resources 2017). It remains to be seen whether these actions will be sufficient to maintain a delicate balance between predator and prey. If Lake Michigan's Chinook Salmon population ultimately collapses, can native species offer a means to maintain the economic value of the fishery?

3. Survey Design and Sample

To better understand Wisconsin anglers' attitudes toward and uses of Lake Michigan, I administered a mail survey from September through December, 2016 following a modified Dillman et al. (2009) protocol. Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp (henceforth "Stamp") in addition to a fishing license. The Wisconsin Department of Natural Resources provided the sample universe of 2015 Stamp holders (n = 23,783) and resident fishing license holders (n = 168,189). To increase the likelihood that respondents fished in Lake Michigan, I limited the sample of license holders to those whose home counties are on the coastline, namely: Brown, Door, Kenosha, Kewaunee, Manitowoc, Marinette, Milwaukee, Oconto, Ozaukee, Racine, and Sheboygan counties (n = 42,677). I drew a random sample of 700 Stamp holders (representative of the state) and 300 resident license holders (representative of coastal counties). In cases where a selected license holder was already in the Stamp holder sample, I randomly selected another license holder. I received 478 responses, of which 360 were Stamp holders and 118 were license holders.

The survey collected information on revealed preferences, stated preferences, and standard demographic data. The revealed preference data include the number of fishing trips respondents made to Lake Michigan in the 2016 open water fishing season, by location, fishing mode, and targeted species, as well as characteristics of their most recent fishing trip. Demographic data include age, gender, education, household composition, and household and respondent income, as well as information related to boat access.

This study focuses on responses to a stated preference choice experiment. Each respondent faced six questions that offered two alternative fishing trips and the option not to fish. Figure 7 presents the choice experiment instructions and a sample choice card. There were four versions of these questions, with each version sent to one-quarter of the sample. I used a computer algorithm to identify the combinations of attribute levels for these questions that achieve a D-efficient experimental design.[17] Differences in efficiency scores were negligible among the most efficient designs, so I chose the design that had the fewest choice occasions with a potentially dominant choice based on hypothesized relationships among attributes.

Trip attributes included primary and secondary target species, number and size of fish caught, likelihood of catching the secondary target species, and trip cost. I included four possible combinations of primary and secondary target species and low, medium, and high values for the number and size of fish caught, by target species (Table 28). Combinations of primary/secondary

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[17] For more information on efficiency and experimental design in discrete choice experiments, see Kuhfeld, Tobias, and Garratt (1994).

target species included: Chinook Salmon/Coho Salmon, Lake Trout/Chinook Salmon, Lake Trout/Rainbow Trout, and Walleye/Yellow Perch. These species represent the four most popular cold water species and two most popular warm water species in Lake Michigan (Eggold 2016).[18] The probability of catching the secondary target species was low or high, and trip cost ranged from $50 to $200. I worked closely with the Wisconsin Department of Natural Resources, Wisconsin Sea Grant, other Great Lakes researchers, and Great Lakes anglers to ensure that the attributes represent the most important aspects of trip quality and attribute levels reflect realistic outcomes.

The distribution of demographic data was similar for Stamp holders and non-Stamp holders, except for the species targeted during their last fishing trip to Lake Michigan (Table 29). The clear majority of respondents were male (85.6 percent). Most respondents owned a boat (58.6 percent), were between 26 and 59 years old (60.7 percent), had completed some college or trade/vocational school (41.3 percent), and were working outside the home for pay (51.9 percent). More than 60 percent of respondents had annual household income of $60,000 or higher. A larger percentage of Stamp holders than non-stamp holders targeted salmon species (72.7 percent and 41.2 percent, respectively) and trout species (68.2 percent and 41.3 percent, respectively), whereas non-Stamp holders more frequently targeted warm water species (56.5 percent and 35.9 percent, respectively).[19] More than half of respondents indicated that they

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[18] I categorize fish species in my survey and in this study according to preferences for water temperature. Following Melstrom and Lupi (2013), cold water species include trout and salmon species; warm water species include Walleye, Yellow Perch, and other species such as Smallmouth Bass, Northern Pike, and Muskellunge.

[19] Respondents could target multiple species during their most recent fishing trip. Salmon species include Chinook Salmon and Coho Salmon. Trout species include Lake Trout, Brown Trout, and Rainbow Trout. Warm water species include Smallmouth Bass, Walleye, and Yellow Perch.

would not continue fishing in Lake Michigan if Pacific salmon populations continued to decline and populations of native fishes increased.

No single attribute or attribute level dominates the option selected (Table 30). Respondents chose to “do something other than fish” or “opt out” 30 percent of the time. Respondents selected Walleye as their preferred target species in 43 percent of the times it was offered compared to 35 percent for Chinook Salmon and about 30 percent for Lake Trout. Respondents selected each of the levels for the catch, size, and cost attributes in about equal proportions, ranging between 32 and 37 percent of the times offered.

4. Behavioral Model

I analyze the choice experiment results using a random utility maximization (RUM) model (Train 2009). In this framework, angler *i* chooses alternative *j* in choice situation *t* and gets utility

$$U_{ijt} = V_{ijt}(p_{jt}, q_{jt}, s_i) + \varepsilon_{ijt}, \quad i = 1, 2, \ldots, \mathrm{N}, \; j = 0, 1, 2, \quad t = 1, 2, \ldots, 6$$

where q_{jt} is a vector of attribute levels for the alternative, s_i is a vector of observed angler characteristics, $V_{ijt}(\cdot)$ is the component of utility that can be predicted based on observable variables, ε_{ijt} is a random variable that represents components of the angler's utility that are known to the angler but not to the analyst, and j=0 is the choice of not taking a fishing trip. p_{jt} is the trip cost of the alternative and may include round trip road transportation to the launch site, launch fees, boat fuel, bait costs, food and drinks, and other trip-related expenses

Utility maximization implies that angler *i* will choose alternative *j* in choice situation *t* if and only if that choice delivers the highest utility. In other words

$$U_{ijt} \geq U_{ikt}, \;\; \forall \;\, k \neq j$$

However, it is not possible to state with certainty the outcome of a person's choice *ex ante*, because $U_{ijt}(\cdot)$ contains the random variable ε_{ijt}. Rather, it is possible to state the probability of a person's choice, denoted by

$$Pr_{ijt} = Pr[\ U_{ijt} \geq U_{ikt}\ \forall\ \ k \neq j\ ]$$

To estimate the equations implied by (1) empirically, I must assume a functional form for $V_{ijt}(\cdot)$ and a probability distribution for ε_{ijt}. For the former, let

$$V_{ijt} = \alpha p_{jt} + \boldsymbol{\beta}' q_{jt} + \boldsymbol{\gamma}' q_{jt} \times s_i$$

where $(\alpha, \boldsymbol{\beta}, \boldsymbol{\gamma})$ are parameters to be estimated. The survey instructed respondents to assume that all characteristics of each alternative are identical except for the attribute levels represented by q_{jt}. As such, the functional form for $V_{ijt}(\cdot)$ assumes that there are no characteristics of the site that matter for an individual angler's choice but that cannot be measured by the analyst. Furthermore, I assume ε_{ijt} is distributed Type I Extreme Value. This distribution leads to a convenient functional form for Pr_{ijt} that implies a conditional logit model. Given these assumptions, along with angler choices from the choice experiment, attribute levels for the alternatives, and observed characteristics of the angler, I can estimate $(\alpha, \boldsymbol{\beta}, \boldsymbol{\gamma})$ using maximum likelihood.

Estimates of $(\alpha, \boldsymbol{\beta}, \boldsymbol{\gamma})$ characterize $V_{ijt}(\cdot)$ and, therefore, allow calculation of the nonmarket benefits to an angler of access to the fishery or of changes in ecological conditions. $\beta_k + \gamma_k \times s_i$ represents the marginal utility (MU) of the k^{th} quality attribute for an angler with observed characteristics s_i, and $-\alpha$ measures the MU of income. Therefore $-\alpha^{-1}(\beta_k + \gamma_k \times s_i)$ is the angler's marginal willingness to pay (WTP) for attribute k. I exploit this relationship in my welfare estimates.

5. Estimation

Specification

The final utility function is specified as follows:

$$U_{ijt} = \sum_{f=1}^{4} \beta_f F_{ijt}^f + \sum_{f=1}^{3} \gamma_c^f C_{ijt} F_{ijt}^f + \sum_{f=1}^{3} \gamma_w^f W_{ijt} F_{ijt}^f + \sum_{f=1}^{3} \gamma_h^f H_{ijt} F_{ijt}^f + \alpha_p P_{ijt} + \varepsilon_{ijt}$$

where F_{ijt}^f is a dummy variable indicating the combination of primary and secondary target species listed in the first row of Table 1, for angler i and choice alternative j in choice situation t, C_{ijt} is the expected catch of the target species, W_{ijt} is the expected size (weight) of the target species, H_{ijt} is a dummy variable equal to one if the probability of catching the secondary target species is high, and P_{ijt} is the trip cost.

The model includes a full set of main effects and interactions with primary target species. As such, the marginal utility of the primary target species depends on the expected catch and size for that species as well as the likelihood of catching the secondary target species. For example, the deterministic utility of a fishing trip that primarily targets Lake Trout, has an expected catch of two 5 lb. fish, has a high probability of catching Rainbow Trout as a secondary target species, and costs $50 is

$$V = \beta_{LR} \cdot 1 + \beta_h \cdot 1 + \gamma_c^{LR} \cdot 2 \cdot 1 + \gamma_w^{LR} \cdot 5 \cdot 1 + \gamma_h^{LR} \cdot 1 \cdot 1 + \alpha_p \cdot 50$$

where LR represents coefficients on variables for which the Lake Trout-Rainbow Trout target species dummy variable equals 1. I exclude the alternative specific constant for “do something other than fish” or “opt-out,” which normalizes the utility of not taking a fishing trip to zero.

I estimate the model using multinomial logistic regression. I report regression estimates for the full sample of respondents and test for observable heterogeneity by estimating the model separately for all respondents and Stamp-holders, disaggregating Stamp-holders by the species group targeted during their last fishing trip. Anglers could target more than one species during their last trip and so may be included in more than one regression. Species groups included salmon (Chinook Salmon and Coho Salmon), trout (Lake Trout, Brown Trout, and Rainbow Trout), and warm water species (Smallmouth Bass, Walleye, and Yellow Perch). Note that coefficient levels are not comparable across regressions because utility is ordinal. However, ratios of coefficients, such as estimates of WTP, are comparable.

Model estimates

The parameter estimates show that cost negatively affects the probability of choosing a trip for all angler groups, as expected (Table 31). This effect is highly statistically significant in all models ($p < 0.01$).

Consistent with intuition, catching more and larger fish increases the probability of choosing a trip, but these effects vary by species. Catch has a positive and statistically significant effect for Lake Trout and Chinook Salmon trips ($p < 0.10$) but generally does not for Walleye trips. The converse holds true for weight, which has a statistically significant positive effect for Walleye trips ($p < 0.10$) but not for Lake Trout or Chinook Salmon trips, with two exceptions. Weight does not affect the probability of choosing a Walleye trip for self-identified warm water anglers and has a positive effect on selecting a Chinook Salmon trip for the average angler and Stamp holder ($p < 0.05$). Overall, anglers generally prefer to catch more Lake Trout and Chinook Salmon and larger Walleye.

Increasing the probability of catching a secondary target species increases the probability of choosing a trip, but this effect also varies by target species. Increasing the probability of catching Yellow Perch during a Walleye trip has a statistically positive effect on the probability of choosing that trip for all angler groups except self-identified warm water anglers, for whom the effect was insignificant. For trips that primarily target Lake Trout, increasing the probability of catching Rainbow Trout has a statistically positive effect for the average angler and Stamp holder whereas the effect for catching Chinook Salmon as a secondary target species is statistically positive only for the average Stamp holder and self-identified trout and salmon anglers. Increasing the probability of catching a secondary target species on a Chinook Salmon trip had no statistical effect for all angler groups. Overall, catch of secondary target species is an important determinant of utility for the native species fishery but not for the Pacific salmon fishery.

It is difficult to infer the sign and statistical significance of primary target species directly from the table of parameter estimates due to the inclusion of multiple interaction terms. One way to interpret the results is to evaluate the minimum conditions required to generate positive trip utility, or in other words the conditions under which it is optimal to fish rather than not fish because the utility of opting out is normalized to zero (Table 32). For these scenarios, small, medium, and large fish refer to the small, medium, and large attribute levels for weight (Table 28).

Relatively poor trip conditions—one small fish with a low probability of catching a secondary species—are always sufficient to entice anglers to fish for Chinook Salmon or Walleye rather than opt out, while conditions must be slightly better for some angler groups to take a Lake Trout trip. For Lake Trout trips, self-identified trout and salmon anglers will always choose to fish. Warm water anglers require two or three medium fish depending on the secondary species; increasing the probability of catching either secondary species decreases the requirement by one fish. On average, Stamp holders require one or two small fish when the probability of catching a secondary species is high or low, respectively. Overall, these results suggest that substitution to native species, on average, could be sufficient to prevent anglers from dropping out of the fishery entirely. It is not clear based on this analysis alone, however, how the value of these trips would change.

6. Welfare Estimates

Choice experiments only evaluate preferences over a restricted choice set; therefore, it is not possible to calculate unconditional welfare effects using SP data (except in the special case where the choice set covers all possible uses of the resource); however, it is possible estimate conditional changes in utility caused by moving from one alternative in the choice set to another. Let V_0 be the deterministic component of utility under the baseline trip configuration and V_1 be utility under an alternative trip configuration. $V_1 - V_0$ measures the change in utility caused by moving from the baseline trip to the alternative trip. This change in utility as a proportion of the MU of income, $-\alpha^{-1}(V_1 - V_0)$, measures the willingness to pay (WTP) for the change in trip configuration. When $V_1 - V_0$ is negative (i.e. when a change in trip configuration reduces well-being) this equation represents willingness to accept (WTA). Because only differences in utility affect WTP, this formula reduces to $-\alpha^{-1}\beta_k$ or the marginal WTP for attribute k when only one attribute changes between two trips.

Marginal WTP for changes in individual trip attributes

The value of increasing catch by one fish per trip is similar for Chinook Salmon and Lake Trout trips and ranges between \$20 and \$35 for most angler groups ($p < 0.10$) (Table 34). The exception is warm water anglers, whose per-fish values for Chinook Salmon are nearly double those for Lake Trout (\$67 versus \$34, respectively). Per-fish values for Walleye are statistically indistinguishable from zero for all angler groups except self-identified salmon anglers who value

Walleye at $14 per fish ($p < 0.10$). Anglers were, however, willing to pay between $16 and $22 to increase the weight of each Walleye caught on a trip by one pound.

My estimates of per-fish values are notably different than those implied by Melstrom and Lupi (2013). Although their emphasis is on measuring WTP to increase hourly catch rates by one fish at all sites (*ex ante* prediction for a system-wide change), it is possible to calculate a measure analogous to my results (*ex post* marginal WTP for a change in trip conditions) using their regression estimates.[20] Based on these calculations, Melstrom and Lupi find high per-fish values for Chinook Salmon ($77 to $89 in 2016 dollars), moderate values for Walleye ($23 to $25), and low values for Lake Trout ($2 to $13), while I find moderate values for Chinook Salmon and Lake Trout and negligible values for Walleye. There are several potential drivers of these differences. First, preferences may be changing over time due to the high annual turnover in the angling population noted previously; Melstrom and Lupi's estimates are based on a survey conducted in 2008 and 2009, whereas mine was conducted in 2016. Second, preferences may be heterogeneous across angler populations; their survey sampled Michigan resident anglers while mine sampled Wisconsin resident anglers. Lastly, instrument choice may matter. I use stated preference methods in part because there is no real-world analog for many interesting and policy-relevant attribute levels. Extrapolating the results of revealed preference methods such as Melstrom and Lupi's outside of the range of the sample may not be representative of preferences if current conditions were to degrade or improve drastically. It would be useful to estimate a

[20] I divide Melstrom and Lupi's coefficient on catch rate (fish caught per hour) by four to calculate the coefficient for catch per (four hour) trip. Dividing this estimate by the coefficient for travel cost yields the marginal WTP for increasing catch by one fish per trip.

travel cost model using my survey data to determine the relative influence of survey instrument versus heterogeneity in preferences, which is outside the scope of this study.

Surprisingly, for trips targeting native species, the marginal WTP for secondary target species is sometimes higher than WTP for the primary target species. For Lake Trout trips, selected Stamp holder groups are willing to pay \$54 to 66 ($p < 0.05$) to increase the probability of catching Rainbow Trout as a secondary species and \$50 to \$63 ($p < 0.10$) to increase the probability of catching Chinook Salmon, compared to WTP values between \$25 and \$35 to catch one additional Lake Trout. Yellow Perch is also valuable as a secondary species. All angler groups except self-identified warm water anglers (for whom the effect is statistically insignificant) are willing to pay roughly \$40 to \$50 ($p < 0.05$) to increase the probability of catching Yellow Perch as a secondary species on a Walleye trip. In contrast, WTP to increase the likelihood of catching Coho Salmon on a Chinook Salmon trip is statistically indistinguishable from zero. While secondary target species may not have been an important source of economic value in the Pacific Salmon-dominated fishery in recent years, maintaining a diverse fish community will be increasingly important if the fishery transitions towards native fishes.

Marginal WTP for changes in multiple trip attributes

Because the utility function includes multiple interaction terms between target species and other attributes, marginal WTP for individual trip attributes alone cannot capture the economic impacts of switching target species or opting out of the fishery entirely. To look at these outcomes, it is necessary to identify baseline and alternate trip values for all attribute levels. To this end, I designed nine policy-relevant trip configurations that reflect current and historical fishery conditions as well as plausible future conditions (Table 33). The configurations include current, good, and best case conditions for each of the three primary target species.

Current conditions are based on median values between 2010 and 2015 from Wisconsin's creel survey (Eggold 2016).[21] These scenarios include the lowest attribute levels for catch (1 fish for Chinook Salmon and Lake Trout and 2 fish for Walleye), values between the lowest and second-highest attribute levels for size (10 lbs. for Chinook Salmon, 5.5 lbs. for Lake Trout, and 2.5 lbs. for Walleye), and a low probability of catching all secondary target species except for Yellow Perch. Good scenarios include the second-highest attribute levels for catch (2 fish for Chinook Salmon and Lake Trout and 4 fish for Walleye) and size (10 lbs. for Chinook Salmon and Lake Trout and 3 lbs. for Walleye). Best scenarios include the highest attribute levels for catch (3 fish for Chinook Salmon and Lake Trout and 6 fish for Walleye) and size (15 lbs. for Chinook Salmon and Lake Trout and 4.5 lbs. for Walleye). All best and good scenarios have a high probability of catching the secondary target species.[22]

Across the selected trip configurations, target species has a large impact on trip value, with Lake Trout by far the least preferred (Table 35, Figure 8, and Figure 9). The average angler values the best Chinook Salmon trip and all Walleye trips statistically equally, with point estimates of $244 for Chinook Salmon and $231 to $275 for Walleye, respectively.[23] These trips

[21] For current scenarios, median weight refers to harvested fish and is rounded to the nearest half pound. Median catch is calculated as catch per four hours of targeted effort for each species by boat ramp anglers and is rounded to the nearest fish. For Chinook Salmon and Lake Trout, median catch was less than 0.5, but these values are rounded to one fish. The probability of catching Coho Salmon and Rainbow Trout is designated as low; each species had a median catch per trip that was less than one. The probability of catching Yellow Perch is designated as high; median catch per trip was 7.

[22] Note that these scenarios are different than those presented in the Model Estimates section (Table 32). While the previous section highlights the minimum conditions for which each angler group would be willing to fish, this section focuses on how trip value increases over the full space of attribute levels; therefore, this section includes higher quality trips.

[23] The tables only present statistical comparisons of WTP using the current Chinook Salmon trip as the baseline, but all other comparisons are still tested statistically.

are statistically more valuable than the current Chinook Salmon trip, valued at $142, and the good and best Lake Trout trips, valued between $89 and $118 ($p < 0.01$). The average angler was statistically indifferent between the current Lake Trout trip and not fishing.

The average Stamp-holder surprisingly shows a similar same trend—with good and best Walleye trips valued on par with the best Chinook Salmon trip—albeit with higher point estimates than the average angler. Among Stamp-holders, point estimates were highest for trip configurations that targeted the same species group that anglers targeted during their last fishing trip.

Non-Stamp holders are statistically indifferent between not fishing and taking any of the Lake Trout or Chinook Salmon trips, which is consistent with the decision not to buy a Stamp. Their WTP increases to around $130 to $180 for the Walleye trips. All Walleye trips are statistically valued the same.

If the Chinook Salmon population continues to decline, Lake Trout provides the most biologically-similar substitute; both species are large apex predators, live in similar areas of the lake, and require similar gear and tactics to catch. However, self-identified salmon anglers prefer a trip that targets Chinook Salmon under current conditions to any Lake Trout trip, even under the best-case Lake Trout scenario (Figure 10). Self-identified trout and warm water anglers are statistically indifferent when Lake Trout reaches the best-case conditions and good conditions, respectively.

Walleye surprisingly could be a higher value substitute. Stamp holders on average are willing to pay $67 to move from the current Chinook Salmon trip to the current Walleye trip ($p < 0.05$). Under best-case Walleye conditions, this figure increases to $135 on average and $192 for Stamp holders that targeted warm water species during their last fishing trip ($p < 0.01$) (Table

35). Self-identified warm water anglers always prefer Walleye trips to the current Chinook Salmon trip. Self-identified trout and salmon anglers require at least good or best-case Walleye conditions, respectively, to strictly prefer Walleye trips to the current Chinook Salmon trip.

These per-trip values translate to large aggregate economic values. Among non-chartered anglers, Chinook Salmon generates $34 million in non-market value per year [90 percent confidence interval: $26 million, $42 million].[24] If all current Chinook Salmon trips instead targeted Lake Trout and Rainbow Trout, economic value would decrease by $27 million [-$39 million, -$15 million] under current conditions and remain statistically unchanged under good [$-16 million, $1 million] and best-case conditions [$-10 million, $9 million]. Substituting towards Walleye would increase economic value by $13 million [$4 million, $22 million] under current conditions, $17 million [$10 million, $25 million] under moderate conditions, and $26 million [$15 million, $37 million] under best-case conditions.

However, Lake Trout losses are likely to be larger than estimated and Walleye gains are likely to be smaller. Fifty-eight percent of Stamp-holders indicated that they would not fish if Pacific salmon populations collapsed and native fishes increased; this extensive margin is not accounted for in the estimates above. In addition, 97 to 99 percent of Walleye catch between 2005 and 2015 occurred in Green Bay, which may not be accessible to all current salmon anglers. Accessibility may cause some salmon anglers who would like to fish for Walleye to opt out instead. Future research to predict how changes in species-specific catch rates affect targeted effort by species would be a useful extension to refine these estimates.

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[24] According to Wisconsin's creel survey, non-chartered anglers spent 766,787 hours targeting Chinook Salmon, 623,639 hours targeting Walleye, and 314,664 hours targeting Lake Trout in 2015. Assuming an average trip length of 4 hours, following Melstrom and Lupi (2016) and Johnston et al.(2006), these effort figures translate to 191,697 Chinook Salmon trips, 155,910 Walleye trips, and 78,666 Lake Trout trips.

7. Conclusions

Chinook Salmon continues to be a valuable resource in Lake Michigan, despite recent reductions in success rates. Even under current conditions, Chinook Salmon trips have among the highest per-trip values. In addition, these trips still represent the largest share of effort in the fishery. Further declines in the Chinook Salmon population likely will result in large economic losses due to a lack of comparable and accessible substitutes, at least in the short term.

Although Lake Trout is a weak substitute for Chinook Salmon among the current mix of anglers, value can still be generated from the species. If the Chinook Salmon population were to collapse, even poor Lake Trout conditions would be sufficient to prevent the average salmon and trout angler from opting out of the fishery. In addition, the resurgence of Lake Trout may provide an opportunity to recruit new anglers.

Surprisingly, the value of the current Walleye fishery rivals that of the historical best-case Chinook salmon conditions. It is possible that substitution toward Walleye could maintain or possibly increase the non-market value of the fishery, but the high geographic concentration of Walleye populations may limit access for some anglers. It will be important to rehabilitate populations of Walleye outside of Green Bay if this species comes to constitute the bulk of the economic value of the fishery.

Although maintaining exotic salmonid species may be at odds with the rehabilitation of native species from an ecological perspective (Crawford 2001), Pacific salmon are an economically important component of the Lake Michigan recreational fishery. Maintaining a diverse salmonid population, as recommended in the latest Fish Community Objectives for Lake Michigan (Eshenroder et al. 1995), will be an important strategy to maintain the value of the fishery. However, future work to reassess angler preferences as ecological conditions continue to change will be critical. Perceptions of native species may improve as success rates increase and new anglers enter the fishery.

8. Tables and Figures

Table 28. Attributes and attribute levels used in choice experiment

Attribute	Levels
Target species (secondary target species)	Chinook Salmon (Coho Salmon), Lake Trout (Chinook Salmon), Lake Trout (Rainbow Trout), Walleye (Yellow Perch)
Number of target species caught	Chinook Salmon and Lake Trout: 1, 2, 3; Walleye: 2, 4, 6
Average size of target species	Chinook Salmon and Lake Trout: 5 lbs./25 in., 10 lbs./30 in., 15 lbs./35 in.; Walleye: 2 lbs./17 in., 3 lbs./20 in., 4.5 lbs./23 in.
Likelihood of catching secondary target species	Low, high
Trip cost per person	$50, $100, $150, $200

Table 29. Summary statistics of demographic characteristics

Variable	Count (Total responses)			Percent		
	Total	Non-stamp holders[a]	Stamp holders[a]	Total	Non-stamp holders[a]	Stamp holders[a]
Age:						
18-25 years	24 (466)	3 (112)	21 (354)	5.2	2.7	5.9
26-59 years	283 (466)	66 (112)	217 (354)	60.7	58.9	61.3
60-75 years	140 (466)	39 (112)	101 (354)	30.0	34.8	28.5
76+ years	19 (466)	4 (112)	15 (354)	4.1	3.6	4.2
Education:						
High school graduate or less	132 (465)	30 (113)	102 (352)	28.4	26.5	29.0
Some college or trade/vocational school	192 (465)	50 (113)	142 (352)	41.3	44.2	40.3
Four-year college degree or higher	141 (465)	33 (113)	108 (352)	30.3	29.2	30.7
Household income:						
Less than $40,000	85 (427)	21 (103)	64 (324)	19.9	20.4	19.8
$40,000 to $59,999	81 (427)	23 (103)	58 (324)	19.0	22.3	17.9
$60,000 to $99,999	136 (427)	31 (103)	105 (324)	31.9	30.1	32.4
$100,00 and over	125 (427)	28 (103)	97 (324)	29.3	27.2	29.9
Currently working outside the home for pay	238 (459)	61 (115)	177 (344)	51.9	53.0	51.5
Male	398 (465)	82 (111)	316 (354)	85.6	73.9	89.3
Boat access:						
Do not own or have access to a boat	91 (466)	21 (113)	70 (353)	19.5	18.6	19.8
Have access to a boat	102 (466)	21 (113)	81 (353)	21.9	18.6	22.9
Own a boat	273 (466)	71 (113)	202 (353)	58.6	62.8	57.2
Would fish if salmon species were extirpated[b]	248 (448)	51 (108)	197 (340)	55.4	47.2	57.9
Targeted salmon species last fishing trip[b]	179 (266)	19 (46)	160 (220)	67.3	41.3	72.7
Targeted trout species last fishing trip[b]	169 (266)	19 (46)	150 (220)	63.5	41.3	68.2
Targeted warm water species last fishing trip[b]	105 (266)	26 (46)	79 (220)	39.5	56.5	35.9

[a]Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp in addition to a fishing license. [b]Salmon species include Chinook Salmon and Coho Salmon. Trout species include Lake Trout, Brown Trout, and Rainbow Trout. Warm water species include Smallmouth Bass, Walleye, and Yellow Perch. Respondents could target multiple species during their most recent trip to Lake Michigan during the 2016 open water season.

Table 30. Summary of choice experiment responses

Attribute levels	Number of choice occasions that included the attribute level	Percent of choice occasions that included the attribute level	Number of times the attribute level was chosen	Percent of times the attribute level was chosen, when offered
Total answered choice occasions	2,741			
Opt out	2,741	100%	822	30%
Primary target species (secondary target species):				
Chinook Salmon	1,827	67%	646	35%
Lake Trout (Chinook Salmon)	1,042	38%	317	30%
Lake Trout (Rainbow Trout)	1,030	38%	277	27%
Walleye	1,583	58%	679	43%
Catch[a]				
Low	1,873	68%	622	33%
Medium	1,787	65%	639	36%
High	1,822	66%	658	36%
Size[b]				
Small	1,829	67%	605	33%
Medium	1,832	67%	660	36%
Large	1,821	66%	654	36%
Cost:				
$50	1,483	54%	544	37%
$100	1,291	47%	414	32%
$150	1,483	54%	514	35%
$200	1,225	45%	447	36%

[a]Attribute levels presented to respondents for low, medium, and high catch, respectively, were 1, 2, and 3 fish for Chinook Salmon and Lake Trout and 2, 4, and 6 fish for Walleye. [b]Attribute levels presented to respondents for small, medium, and large size, respectively, were 5 lbs./25 in., 10 lbs./30 in., and 15 lbs./35 in for Chinook Salmon and Lake Trout and 2 lbs./17 in., 3 lbs./20 in., and 4.5 lbs./23 in. for Walleye.

Table 31. Conditional logit estimates of the marginal utility of Lake Michigan fishing trips, by angler type

	All respondents	Stamp holders[a]			
		All stamp holders[a]	Target salmon last trip[b]	Target trout last trip[b]	Target warm last trip[b]
Variable	(1)	(2)	(3)	(4)	(5)
Walleye	0.832***	0.806**	0.794*	0.893*	2.434***
	(0.278)	(0.319)	(0.477)	(0.495)	(0.745)
Lake Trout (Rainbow Trout)	-0.138	-0.00151	0.628	0.645	-0.0751
	(0.223)	(0.256)	(0.394)	(0.398)	(0.567)
Lake Trout (Chinook Salmon)	-0.00259	0.0413	0.475	0.401	-0.372
	(0.201)	(0.229)	(0.359)	(0.353)	(0.549)
Chinook Salmon	0.367	0.544*	1.449***	1.468***	0.379
	(0.255)	(0.290)	(0.427)	(0.433)	(0.704)
Walleye × Number Caught	0.0166	0.0407	0.120*	0.0934	-0.0123
	(0.0349)	(0.0410)	(0.0630)	(0.0640)	(0.0853)
Lake Trout × Number Caught	0.156***	0.207***	0.212**	0.177*	0.310**
	(0.0502)	(0.0585)	(0.0944)	(0.0958)	(0.132)
Chinook Salmon × Number Caught	0.150**	0.209***	0.262**	0.262**	0.595***
	(0.0665)	(0.0752)	(0.118)	(0.119)	(0.179)
Walleye × Weight (lbs.)	0.0932*	0.123*	0.167*	0.194*	0.160
	(0.0525)	(0.0637)	(0.0989)	(0.105)	(0.164)
Lake Trout × Weight (lbs.)	0.00222	0.00273	-0.00785	0.00561	0.0183
	(0.0100)	(0.0111)	(0.0168)	(0.0174)	(0.0277)
Chinook Salmon × Weight (lbs.)	0.0297**	0.0323**	0.0304	0.0219	0.0466
	(0.0124)	(0.0138)	(0.0202)	(0.0212)	(0.0328)
Walleye × High prob. Yellow Perch	0.222**	0.279**	0.433**	0.457**	0.0934
	(0.103)	(0.121)	(0.190)	(0.193)	(0.298)
Lake Trout × High prob. Rainbow Trout	0.311**	0.402***	0.388	0.346	0.436
	(0.134)	(0.155)	(0.242)	(0.249)	(0.399)
Lake Trout × High prob. Chinook Salmon	0.146	0.302*	0.492**	0.564**	0.302
	(0.138)	(0.161)	(0.235)	(0.242)	(0.460)
Chinook Salmon × High prob. Coho Salmon	0.133	0.179	0.0640	0.189	-0.0832
	(0.0942)	(0.110)	(0.156)	(0.165)	(0.256)
Trip Cost	-0.00572***	-0.00599***	-0.00860***	-0.00900***	-0.00902***
	(0.000813)	(0.000990)	(0.00159)	(0.00160)	(0.00289)
Observations	8223	6207	2838	2658	1371

Notes: The alternative specific constant for opting-out is excluded, which normalizes the utility of not taking a fishing trip to zero. Column 1 includes the full sample of responses and measures average effects. Columns 2-5 test for observable heterogeneity by estimating the utility equation separately for various groups of respondents. Note that coefficient levels are not comparable across regressions because utility is ordinal. However, ratios of coefficients, such as estimates of WTP, are comparable. Standard errors are clustered at the respondent level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level. [a]Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp in addition to a fishing license. [b]Columns 3-5 refer to the species the respondent tried to catch during his/her most recent trip to Lake Michigan during the 2016 open water season. Salmon species include Chinook Salmon and Coho Salmon. Trout species include Lake Trout, Brown Trout, and Rainbow Trout. Warm water species include Smallmouth Bass, Walleye, and Yellow Perch. Respondents could target multiple species during their last trip.

Table 32. Differences in utility for fishing trips relative to not fishing

	All respondents	Stamp holders[a]			
Primary target species *(Secondary target species)* Number and size of catch		All stamp holders[a]	Target salmon last trip[b]	Target trout last trip[b]	Target warm last trip[b]
	(1)	(2)	(3)	(4)	(5)
Low probability of catching secondary target species					
Chinook Salmon (Coho Salmon):					
One small fish	0.67***	0.91***	1.86***	1.84***	1.21**
	(0.19)	(0.23)	(0.33)	(0.33)	(0.58)
Walleye (Yellow Perch):					
One small fish	1.03***	1.09***	1.25***	1.37***	2.74***
	(0.20)	(0.23)	(0.36)	(0.37)	(0.55)
Lake Trout (Rainbow Trout):					
One small fish	0.03	0.22	0.80***	0.85***	0.33
	(0.17)	(0.20)	(0.30)	(0.31)	(0.44)
One medium fish	0.04	0.23	0.76***	0.88***	0.42
	(0.16)	(0.19)	(0.29)	(0.30)	(0.40)
One large fish	0.05	0.25	0.72**	0.91***	0.51
	(0.16)	(0.19)	(0.30)	(0.31)	(0.41)
Two small fish	0.19	0.43**	1.01***	1.03***	0.64
	(0.16)	(0.19)	(0.27)	(0.28)	(0.42)
Two medium fish	0.20	0.44**	0.97***	1.06***	0.73*
	(0.15)	(0.18)	(0.26)	(0.27)	(0.38)
Two large fish	0.21	0.45**	0.93***	1.08***	0.82**
	(0.15)	(0.18)	(0.28)	(0.28)	(0.39)
Three small fish	0.34**	0.63***	1.22***	1.21***	0.95**
	(0.16)	(0.19)	(0.27)	(0.28)	(0.44)
High probability of catching secondary target species					
Lake Trout (Rainbow Trout):					
One small fish	0.34**	0.62***	1.19***	1.20***	0.76
	(0.17)	(0.19)	(0.29)	(0.29)	(0.49)
One medium fish	0.35**	0.63***	1.15***	1.22***	0.85*
	(0.15)	(0.18)	(0.27)	(0.28)	(0.45)
Two small fish	0.50***	0.83***	1.40***	1.37***	1.07**
	(0.16)	(0.18)	(0.27)	(0.29)	(0.48)
Observations	8223	6207	2838	2658	1371

Notes: The alternative specific constant for opting-out is excluded from the regression estimates underlying these utility calculations, which normalizes the utility of not taking a fishing trip to zero. Positive values indicate that taking a fishing trip is preferred over opting out; negative values indicate that opting out is preferred. Column 1 includes the full sample of responses and measures average effects. Columns 2-5 test for observable heterogeneity by estimating the utility equation separately for various groups of respondents. Note that estimates are not comparable across regressions because utility is ordinal. Standard errors are clustered at the respondent level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level. [a]Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp in addition to a fishing license. [b]Columns 3-5 refer to the species the respondent tried to catch during his/her most recent trip to Lake Michigan during the 2016 open water season. Salmon species include Chinook Salmon and Coho Salmon. Trout species include Lake Trout, Brown Trout, and Rainbow Trout. Warm water species include Smallmouth Bass, Walleye, and Yellow Perch. Respondents could target multiple species during their last trip.

Table 33. Fishing trip configurations

Configuration name	Primary target species	Secondary target species	Primary target catch (fish)	Primary target size (lbs.)	Prob. of catching 2nd target
Current Lake Trout	Lake Trout	Rainbow Trout	1	5.5	Low
Good Lake Trout	Lake Trout	Rainbow Trout	2	10	High
Best Lake Trout	Lake Trout	Rainbow Trout	3	15	High
Current Chinook Salmon	Chinook Salmon	Coho Salmon	1	10	Low
Good Chinook Salmon	Chinook Salmon	Coho Salmon	2	10	High
Best Chinook Salmon	Chinook Salmon	Coho Salmon	3	15	High
Current Walleye	Walleye	Yellow Perch	2	2.5	High
Good Walleye	Walleye	Yellow Perch	4	3	High
Best Walleye	Walleye	Yellow Perch	6	4.5	High

Notes: Current conditions are based on median values between 2010 and 2015 from Wisconsin's creel survey. Median weight refers to harvested fish and is rounded to the nearest half pound. Median catch is calculated as catch per four hours of targeted effort for each species by boat ramp anglers and is rounded to the nearest fish. For Chinook Salmon and Lake Trout, median catch was less than 0.5, but these values are rounded to one fish. The probability of catching Coho Salmon and Rainbow Trout is designated as low; each species had a median catch less than one. The probability of catching Yellow Perch is designated as high; median catch was 7. Good and best scenarios are based on historical or potential future conditions.

Table 34. Marginal willingness to pay for catch, weight, and probability of catching a secondary target species, by target species (Dollars)

Target Species	All respondents	Stamp holders[a]			
		All stamp holders[a]	Target salmon last trip[b]	Target trout last trip[b]	Target warm water last trip[b]
	(1)	(2)	(3)	(4)	(5)
Increase Catch by One Fish Per Trip					
Lake Trout	27.34***	34.51***	24.64**	19.72*	34.32**
	(9.17)	(10.65)	(11.39)	(10.94)	(15.80)
Chinook Salmon	26.19**	34.98**	30.52**	29.09**	65.95***
	(12.51)	(13.86)	(14.11)	(13.41)	(25.33)
Walleye	2.91	6.80	13.98*	10.37	-1.36
	(6.05)	(6.76)	(7.41)	(7.20)	(9.53)
Increase Weight of Fish Caught During a Trip by One Pound					
Lake Trout	0.39	0.46	-0.91	0.62	2.03
	(1.75)	(1.86)	(1.97)	(1.92)	(3.19)
Chinook Salmon	5.19**	5.39**	3.54	2.44	5.16
	(2.22)	(2.38)	(2.41)	(2.37)	(3.95)
Walleye	16.29*	20.58*	19.46	21.52*	17.70
	(9.72)	(11.21)	(11.95)	(12.21)	(18.22)
Increase Prob. of Catching Secondary Target Species from Low to High					
Lake Trout (Rainbow Trout)	54.30**	67.14**	45.08	38.41	48.26
	(24.28)	(27.83)	(28.24)	(27.61)	(44.56)
Lake Trout (Chinook Salmon)	25.48	50.46*	57.26**	62.68**	33.50
	(24.20)	(27.96)	(28.99)	(29.39)	(50.56)
Chinook Salmon (Coho Salmon)	23.27	29.83	7.45	20.95	-9.22
	(16.92)	(19.33)	(18.14)	(18.70)	(27.91)
Walleye (Yellow Perch)	38.90**	46.59**	50.38**	50.75**	10.35
	(16.71)	(18.53)	(20.73)	(20.47)	(32.07)
Observations	8223	6207	2838	2658	1371

Notes: Positive values reflect willingness to pay; negative values reflect willingness to accept. Column 1 includes the full sample of responses and measures average effects. Columns 2-5 test for observable heterogeneity by estimating the utility equation separately for various groups of respondents. Standard errors are clustered at the respondent level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level. [a]Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp in addition to a fishing license. [b]Columns 3-5 refer to the species the respondent tried to catch during his/her most recent trip to Lake Michigan during the 2016 open water season. Salmon species include Chinook Salmon and Coho Salmon. Trout species include Lake Trout, Brown Trout, and Rainbow Trout. Warm water species include Smallmouth Bass, Walleye, and Yellow Perch. Respondents could target multiple species during their last trip.

Table 35. Welfare estimates for changes in fishing trip configurations, by angler type (Dollars)

Trip configuration[a]	All respondents	Stamp holders[b]			
		All stamp holders[b]	Target salmon last trip[c]	Target trout last trip[c]	Target warm water last trip[c]
	(1)	(2)	(3)	(4)	(5)
Baseline: Do Something Other Than Fish					
Current Lake Trout (Rainbow Trout)	5.30	36.76	92.65***	94.76***	37.16
	(29.82)	(31.42)	(34.20)	(32.99)	(44.69)
Good Lake Trout (Rainbow Trout)	88.69***	140.46***	158.26***	155.69***	128.87***
	(22.27)	(25.29)	(28.40)	(28.04)	(41.67)
Best Lake Trout (Rainbow Trout)	117.96***	177.25***	178.33***	178.52***	173.33***
	(25.80)	(30.98)	(33.10)	(32.81)	(49.71)
Current Chinook Salmon	142.23***	179.71***	234.47***	216.56***	159.54***
	(22.96)	(25.28)	(32.29)	(29.83)	(36.46)
Good Chinook Salmon	191.69***	244.51***	272.43***	266.60***	216.27***
	(20.19)	(26.71)	(32.85)	(31.79)	(34.98)
Best Chinook Salmon	243.82***	306.44***	320.64***	307.87***	308.04***
	(28.86)	(37.00)	(41.99)	(39.51)	(61.78)
Current Walleye	230.87***	246.26***	219.40***	224.49***	321.57***
	(22.16)	(26.03)	(26.42)	(25.94)	(58.88)
Good Walleye	244.83***	270.15***	257.09***	256.00***	327.70***
	(20.87)	(25.16)	(25.94)	(25.08)	(56.55)
Best Walleye	275.08***	314.61***	314.24***	309.03***	351.52***
	(32.76)	(38.22)	(40.00)	(38.46)	(69.45)
Baseline Trip: Current Chinook Salmon					
Current Lake Trout (Rainbow Trout)	-136.93***	-142.94***	-141.82***	-121.80***	-122.38**
	(34.07)	(37.81)	(40.21)	(37.92)	(57.80)
Good Lake Trout (Rainbow Trout)	-53.54**	-39.24	-76.21***	-60.87**	-30.67
	(25.30)	(26.80)	(28.38)	(27.29)	(49.15)
Best Lake Trout (Rainbow Trout)	-24.26	-2.45	-56.13*	-38.04	13.79
	(26.98)	(29.38)	(29.82)	(29.26)	(50.96)
Good Chinook Salmon	49.46**	64.81***	37.96*	50.04**	56.73
	(21.97)	(24.59)	(22.88)	(22.51)	(38.65)
Best Chinook Salmon	101.59***	126.73***	86.17**	91.31**	148.50**
	(35.28)	(39.29)	(37.29)	(36.02)	(69.17)
Current Walleye	88.64***	66.56**	-15.07	7.94	162.03***
	(26.36)	(27.96)	(29.61)	(27.50)	(62.13)
Good Walleye	102.60***	90.44***	22.62	39.45*	168.16***
	(23.45)	(24.65)	(23.67)	(22.51)	(56.51)
Best Walleye	132.86***	134.90***	79.78**	92.48***	191.98***
	(32.82)	(35.36)	(31.75)	(31.14)	(64.92)
Observations	8223	6207	2838	2658	1371

Notes: Positive values reflect willingness to pay; negative values reflect willingness to accept. Column 1 includes the full sample of responses and measures average effects. Columns 2-5 test for observable heterogeneity by estimating the utility equation separately for various groups of respondents. Standard errors are clustered at the respondent level and are presented in parentheses. Stars indicate significance at the 1 percent (***), 5 percent (**), and 10 percent (*) level. [a]Current scenarios represent median values for catch (per four hours of targeted effort by boat ramp anglers) and size (of harvested fish) between 2010 and 2015 from Wisconsin's creel survey, rounded to the nearest fish and pound. The current scenarios include one 10 lb. Chinook Salmon caught, one 5.5 lb. Lake Trout caught, and two 2.5 lb. Walleye caught. The current Walleye scenario includes a high probability of catching a secondary target species; the other current scenarios include a low probability. Good scenarios include the second-highest attribute levels for catch (2 fish for Lake Trout and Chinook Salmon and 4 fish for Walleye) and size (10 lbs. for Lake Trout and Chinook Salmon and 3 lbs. for Walleye). Best scenarios include the highest attribute levels for catch (3 fish for Lake Trout and Chinook Salmon and 6 fish for Walleye) and size (15 lbs. for Lake Trout and Chinook Salmon and 4.5 lbs. for Walleye). Both best and good scenarios include a high probability of catching a secondary target species. [b]Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp in addition to a fishing license. [c]Columns 3-5 refer to the species the respondent tried to catch during his/her most recent trip to Lake Michigan during the 2016 open water season. Salmon species include Chinook Salmon and Coho Salmon. Trout species include Lake Trout, Brown Trout, and Rainbow Trout. Warm water species include Smallmouth Bass, Walleye, and Yellow Perch. Respondents could target multiple species during their last trip.

Figure 7. Choice experiment instructions and sample choice card

Important Information

For the following 6 questions, we will ask you to consider different types of fishing trips to Lake Michigan or Green Bay. You will choose from among three options in a table: two **fishing trips** (options A and B) that may be different from what you experienced (or would have experienced) during the 2016 open water fishing season, and a '**do something else**' option (option C), which could include fishing an inland lake or not fishing.

For options A and B, please imagine ***a full day of fishing from a boat somewhere on Lake Michigan or Green Bay***. The trips are described by:

- The *main type of fish* you will try to catch on the trip (target species)
- The number of targeted *fish you personally will catch* on the trip
- The typical *size* of the targeted fish you will catch
- A *secondary type of fish* that you may try to catch (secondary target species)
- The *likelihood you will catch* the secondary type of fish
- Your share of the *monetary costs* of the trip.

Monetary costs might include round trip road transportation to the launch site, launch fees, boat fuel, bait costs, food and drinks, and other trip-related expenses. *Please assume that options A and B are the same except for the differences you see in the table.*

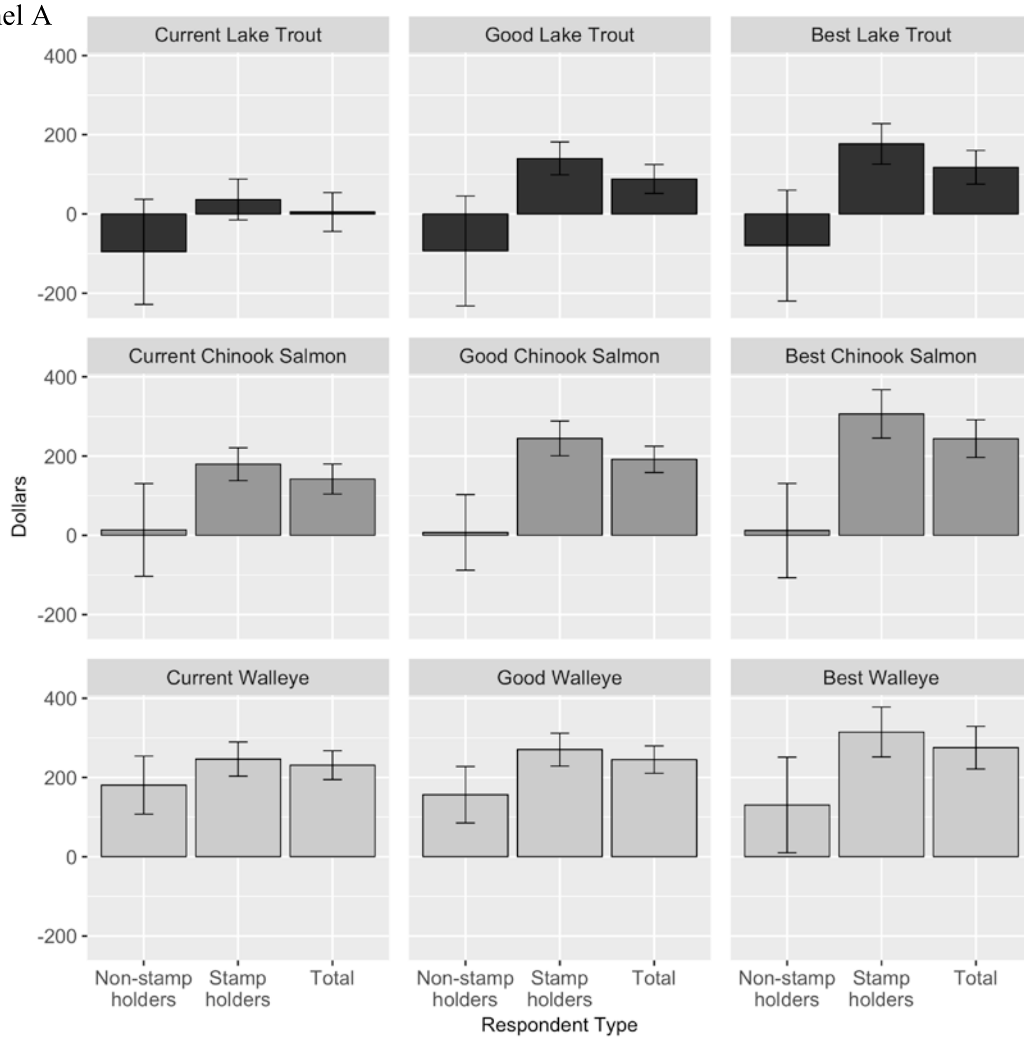
Although these questions do not represent real choices, you should answer ***as you would if you were actually paying*** the trip cost. This will help us understand how important different fishing experiences are to Wisconsin anglers.

11. Which of the following options would you prefer? Please choose only one.

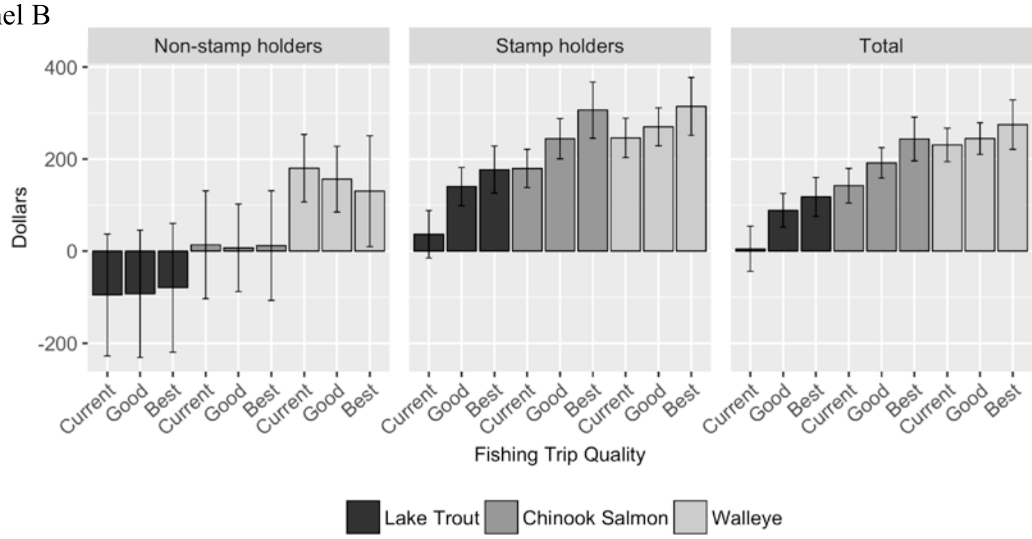
	Option A	**Option B**	**Option C**
• Target species	Chinook Salmon	Lake Trout	Do something other than fish Lake Michigan or Green Bay
• Number of target species caught	2	1	
• Average size of target species	10 pounds / 30 inches	15 pounds / 35 inches	
• Secondary target species	Coho Salmon	Rainbow Trout	
• Likelihood of catching secondary species	High	Low	
• Trip cost per person	$150	$50	
Preferred option	☐	☐	☐

Figure 8. Wisconsin angler's marginal willingness to pay/accept for fishing trips

Panel A



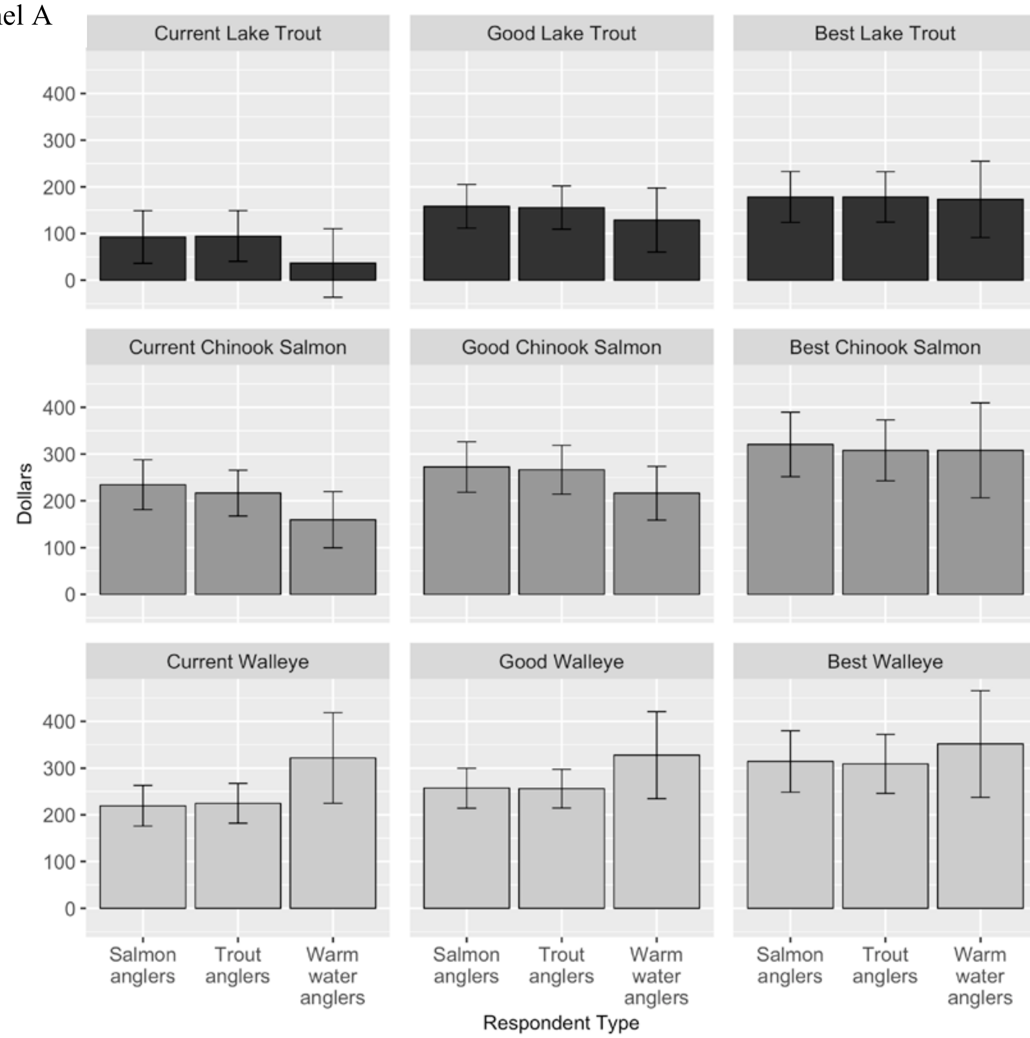
Panel B



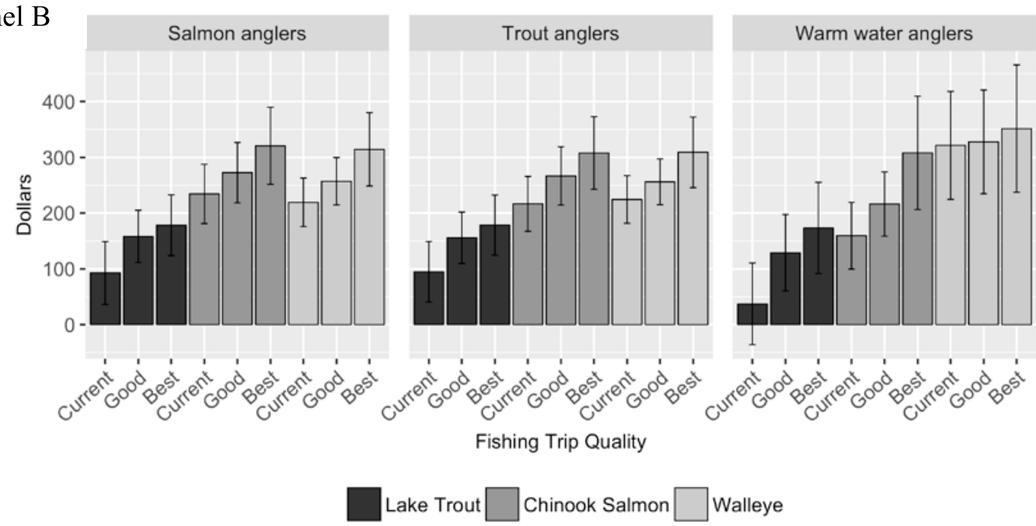
Notes: Positive values reflect willingness to pay; negative values reflect willingness to accept. Boxes represent point estimates. Whiskers represent 90 percent confidence intervals. Standard errors are clustered at the respondent level. Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp (or "Stamp") in addition to a fishing license. Stamp holders versus non-stamp holder status refers to the 2015 season. Lake Trout, Chinook Salmon, and Walleye refer to primary target species. Current scenarios represent median values for catch (per four hours of targeted effort by boat ramp anglers) and size (of harvested fish) between 2010 and 2015 from Wisconsin's creel survey, rounded to the nearest fish and pound. The current scenarios include one 10 lb. Chinook Salmon caught, one 5.5 lb. Lake Trout caught, and two 2.5 lb. Walleye caught. The current Walleye scenario includes a high probability of catching a secondary target species; the other current scenarios include a low probability. Good scenarios include the second-highest attribute levels for catch (2 fish for Lake Trout and Chinook Salmon and 4 fish for Walleye) and size (10 lbs. for Lake Trout and Chinook Salmon and 3 lbs. for Walleye). Best scenarios include the highest attribute levels for catch (3 fish for Lake Trout and Chinook Salmon and 6 fish for Walleye) and size (15 lbs. for Lake Trout and Chinook Salmon and 4.5 lbs. for Walleye). Both best and good scenarios include a high probability of catching a secondary target species.

Figure 9. Wisconsin Trout and Salmon Stamp holders' marginal willingness to pay for fishing trips

Panel A



Panel B

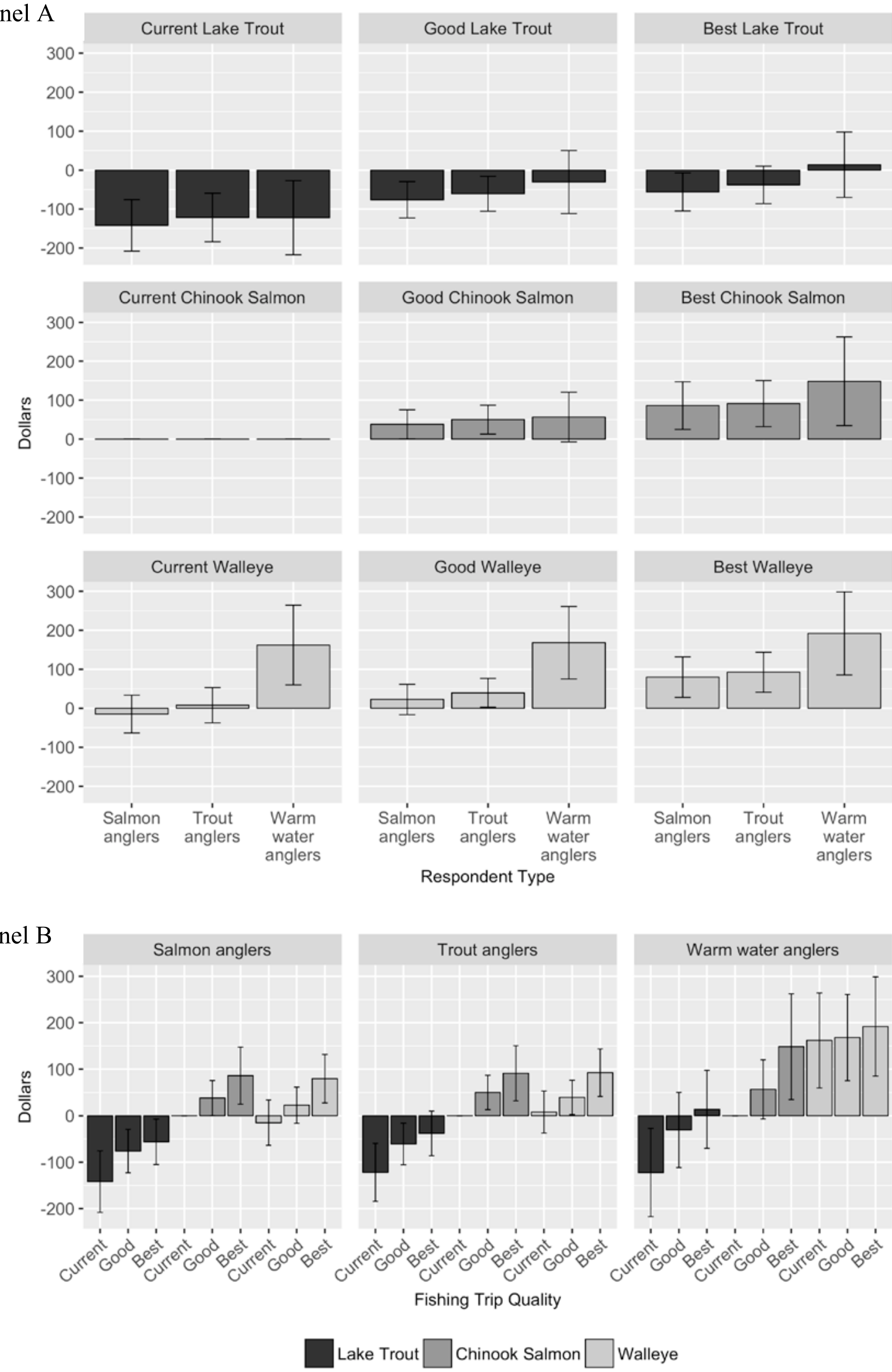


Notes: Positive values reflect willingness to pay; negative values reflect willingness to accept. Boxes represent point estimates. Whiskers represent 90 percent confidence intervals. Standard errors are clustered at the respondent level. Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp (or "Stamp") in addition to a fishing license. This figure includes only those respondents who were Stamp holders in the 2015 season. Salmon, trout, and warm water anglers on the x-axis of Panel A and the facet titles for Panel B refer to the species the respondent tried to catch during his/her most recent trip to Lake Michigan during the 2016 open water season. Salmon species include Chinook Salmon and Coho Salmon. Trout species include Lake Trout, Brown Trout, and Rainbow Trout. Warm water species include Smallmouth Bass, Walleye, and Yellow Perch. Respondents could target multiple species during their last trip. Lake Trout, Chinook Salmon, and Walleye on the facet titles of Panel A and the x-axis for Panel B refer to primary target species in the constructed scenarios. Current scenarios represent median values for catch (per four hours of targeted effort by boat ramp anglers) and size (of harvested fish) between 2010 and 2015 from Wisconsin's creel survey, rounded to the nearest fish and pound. The current scenarios include one 10 lb. Chinook Salmon caught, one 5.5 lb. Lake Trout caught, and two 2.5 lb. Walleye caught. The current Walleye scenario includes a high probability of catching a secondary target species; the other current scenarios include a low probability. Good scenarios include the second-highest attribute levels for catch (2 fish for Lake Trout and Chinook Salmon and 4 fish for Walleye) and size (10 lbs. for Lake Trout and Chinook Salmon and 3 lbs. for Walleye). Best scenarios include the highest attribute levels for catch (3 fish for Lake Trout and Chinook Salmon and 6 fish for Walleye) and size (15 lbs. for Lake Trout and Chinook Salmon and 4.5 lbs. for Walleye). Both best and good scenarios include a high probability of catching a secondary target species.

Figure 10. Wisconsin Trout and Salmon Stamp holders' marginal willingness to pay/accept for changes in fishing trips, with the current Chinook Salmon trip as the baseline

Panel A

Panel B



Notes: Positive values reflect willingness to pay; negative values reflect willingness to accept. Boxes represent point estimates. Whiskers represent 90 percent confidence intervals. Standard errors are clustered at the respondent level. Every angler who fishes for salmon or trout species in the Wisconsin waters of Lake Michigan is required to purchase a Great Lakes Trout and Salmon Stamp (or "Stamp") in addition to a fishing license. This figure includes only those respondents who were Stamp holders in the 2015 season. Salmon, trout, and warm water anglers on the x-axis of Panel A and the facet titles for Panel B refer to the species the respondent tried to catch during his/her most recent trip to Lake Michigan during the 2016 open water season. Salmon species include Chinook Salmon and Coho Salmon. Trout species include Lake Trout, Brown Trout, and Rainbow Trout. Warm water species include Smallmouth Bass, Walleye, and Yellow Perch. Respondents could target multiple species during their last trip. Lake Trout, Chinook Salmon, and Walleye on the facet titles of Panel A and the x-axis for Panel B refer to primary target species in the constructed scenarios. Current scenarios represent median values for catch (per four hours of targeted effort by boat ramp anglers) and size (of harvested fish) between 2010 and 2015 from Wisconsin's creel survey, rounded to the nearest fish and pound. The current scenarios include one 10 lb. Chinook Salmon caught, one 5.5 lb. Lake Trout caught, and two 2.5 lb. Walleye caught. The current Walleye scenario includes a high probability of catching a secondary target species; the other current scenarios include a low probability. Good scenarios include the second-highest attribute levels for catch (2 fish for Lake Trout and Chinook Salmon and 4 fish for Walleye) and size (10 lbs. for Lake Trout and Chinook Salmon and 3 lbs. for Walleye). Best scenarios include the highest attribute levels for catch (3 fish for Lake Trout and Chinook Salmon and 6 fish for Walleye) and size (15 lbs. for Lake Trout and Chinook Salmon and 4.5 lbs. for Walleye). Both best and good scenarios include a high probability of catching a secondary target species.

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