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Eyal G. Frank
Anouch Missirian
Dominic P. Parker
Jennifer L. Raynor

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ABSTRACT

"Option value" provides theoretical justification for conserving wildlife species lacking known value, but empirical assessments of actual realizations are rare. We examine quasi-option value in the context of gray wolf eradication, which aimed to protect humans and their property historically, but also reduced the potential for wolves to improve human well-being today. We estimate the effects of long-run differences in the presence of wolves north, but not south, of Canada's Saint Lawrence River on animal-related (primarily deer) vehicle collisions. Wolves reduce the share of animal collisions by 38 percent, reducing risk to human life and property.

Eyal G. Frank
University of Chicago
Harris School of Public Policy
and NBER
eyalfrank@uchicago.edu

Anouch Missirian
Toulouse School of Economics
and INRAe
anouch.missirian@tse-fr.eu

Dominic P. Parker
University of Wisconsin - Madison
and Hoover Institution at
Stanford University
dominic.parker@wisc.edu

Jennifer L. Raynor
University of Wisconsin - Madison
jennifer.raynor@wisc.edu

An online appendix is available at http://www.nber.org/data-appendix/w34377

1 Introduction

"... for it so falls out
That what we have we prize not to the worth
Whiles we enjoy it, but being lacked and lost,
Why, then we rack the value, then we find
The virtue that possession would not show us
While it was ours."

—William Shakespeare, Much Ado about Nothing, VI.1 (ca. 1600)

The benefits that humans derive from many wildlife species are often unclear until those species and their associated ecosystem functions are lost (Daily et al. 2000). Conservation affords future generations the option to realize such benefits if future conditions make a species more valuable or scientific knowledge evolves to make unknown values transparent—illustrating the concept of quasi-option value. Seminal theoretical contributions highlight conditions that can justify the delay of irreversible environmental changes—such as allowing a species to go globally extinct—when present values are uncertain (Arrow and Fisher 1974; Dixit and Pindyck 1994; Simpson et al. 1996; Weitzman 1998; Vining 1998; Weitzman 2009; Taylor and Weder 2024). Similar logic can justify delaying local extinction, because even local losses can be difficult to reverse if changes to the local environment make recovery prohibitively costly. Despite the growing theoretical attention to the role quasi-option values play in conservation (Pascual et al. 2011; Leroux et al. 2009), and the emphasis in policy discussions on "Keeping Options Alive" (Reid and Miller 1989), empirical assessments of such values are limited.

Using a spatial discontinuity in the presence of wolves along the Saint Lawrence River in Quebec, Canada, this paper quantifies the quasi-option value of the gray wolf (*Canis lupus*) in improving road safety by controlling deer, moose, and other prey commonly involved in animal-vehicle collisions (AVCs). Wolves provide an excellent case study because of the stark contrast between their potential to benefit humans today versus their historical standing as pest and varmint. Wolves were hunted down to local extinction throughout the northern hemisphere by the turn of the 20th century for threatening humans, livestock, pets, and wild prey animals valued by human hunters. Yet major unanticipated changes since 1900 may be shifting wolves from economic liability to asset. Deer, elk, and moose populations have exploded from scarce due to overhunting under open access to overabundant in many regions. For example, deer populations in the United States rebounded from 500,000 in 1900 to 35 million today (Lueck and Parker 2025). Lacking control by an apex predator, today's deer, elk, and moose are a costly and sometimes deadly nuisance involved in AVCs, the spreading of disease, and the damage to crops and forests (Raynor et al. 2021; Levi et al. 2012; Kilpatrick et al. 2014; Reed et al. 2022; Miller et al. 2023). Importantly for the study of option value, personal vehicles are a relatively new technology, making any relationship between wolves, their prey, and AVCs an "unknown unknown" when wolf-killing campaigns peaked.

The fact that AVCs are a consequential and difficult modern problem motivates our study of this facet of the quasi-option value of wolves.[1] We employ the universe of vehicle crash records from 2000 to 2019 in Quebec to calculate the share of AVCs relative to all-cause collisions, and compare shares along both sides of the Saint Lawrence River. Wolves are found only north of the river because they were historically driven to extinction in some parts of southern Canada. The eradication of wolves was incomplete, with some wolf packs surviving in the far northern parts of the country, allowing them to recolonize the northern side of the river after the eradication efforts subsided. Recolonization of wolves further south is obstructed because the river acts as a physical barrier—creating a natural experiment. Habitat conditions on both sides of the river are similar, as reflected in a wolf recovery plan by the U.S. Fish and Wildlife Service that outlines areas south of the river as "areas with re-establishment possibilities" (1992, p. 58). The credibility of the causal interpretation relies

[1] In the U.S. alone, they account for 1-2 million accidents (relative to a total of 6 million accidents), 26,000 human injuries, and 200 deaths annually (Huijser et al. 2008). The problem could get worse if climate conditions throughout North America shift, as expected, toward shorter winters and wetter springs, which are conducive to higher deer population levels (Weiskopf et al. 2019). In addition, continued fragmentation of habitat through the expansion of road infrastructure may increase the number of collisions with wild animals (Rytwinski and Fahrig 2015).

on the fact that roadway conditions are similar across the river, yet wolves are absent on one side due to century-old events.

Our regression discontinuity design estimates a five percentage point drop in the share of AVCs, reflecting a 38 percent difference just north of the river relative to just south. Using available estimates on collision costs by severity, we value the averted losses attributed to the presence of wolves to be $29 million annually (2024 USD) along the river. This is equivalent to 5.4 percent of highway budget spending in Quebec. Our more speculative back-of-the-envelope calculations suggest wolves have the potential to avert $6.36 billion (2024 USD) annual losses from AVCs across North America.

Several robustness tests support the validity of our research design and our interpretation of results. For example, environmental and demographic covariates do not change sharply at the border and a discontinuity in AVCs is present even when we include those covariates as controls. The results are robust to using the animal-vehicle collision rate (number of animal-related collisions per 1,000 people), and to using human population weights. Furthermore, the estimated effect is not driven by river-edge effects, nor are the results sensitive to arbitrary or optimal bandwidth choices, or the removal of outliers.

We hypothesize two main channels through which wolves may be reducing AVCs north of the river: (i) by limiting population sizes of prey such as deer and moose, and (ii) by changing prey behavior in ways that reduce their exposure to vehicle collisions. Using hunting data, we document that wolves' primary prey species are found in similar densities on both sides of the river, and that hunting certificates per capita are not higher north relative to south of the river. This finding does not accord with the population channel and therefore provides indirect support for the behavioral channel. As other research has suggested, wolf presence can introduce a "landscape of fear" causing prey to avoid open corridors, such as roadways, to reduce their risk of predation (Ripple and Beschta 2004; Zanette and Clinchy 2020; Ganz et al. 2024). In the long-run, natural selection forces also differ in landscapes with and without wolves, implying more genetically fit prey will populate the north relative to the south. This is important if genetically fit prey are better able to avoid vehicle collisions (Réale and Festa-Bianchet 2003; Dingemanse et al. 2009; Tariel et al. 2020; MacLeod et al. 2022).

Related Literature.— This study provides empirical evidence that supports the recent growing hindsight recognition that apex predators provide indirect benefits to humans today that were historically unknown. These after-the-fact realizations have motivated "rewilding" efforts in which jurisdictions are reintroducing species such as bears, lynxes, snakes, jaguars, alligators, and wolves, despite concerns that predators continue to pose direct threats to humans and property (e.g., pets and livestock) (Hayward and Somers 2009; Ceballos et al. 2015; Malcom et al. 2019; Chapman et al. 2024; Seddon et al. 2007; Taylor et al. 2017; Perino et al. 2019).

The finding adds to a small set of recent empirical contributions that quantify positive economic value for species previously thought to have little or negative value. This includes studies of how insect-eating bats deliver health benefits through the provision of biological pest control (Frank 2024), how horseshoe crabs became valuable for their blood in vaccines (Krisfalusi-Gannon et al. 2018), how sea otters control urchin populations that deplete carbon sequestering sea kelp (Gregr et al. 2020), how vultures are instrumental in reducing human mortality by removing festering animals (Frank and Sudarshan 2024), and how the recent spread of wolves in parts of Wisconsin has reduced deer-vehicle collisions in affected counties (Raynor et al. 2021).

Our work complements Raynor et al. (2021) in an important way. Whereas Raynor et al. (2021) employed difference-in-differences methods to measure short-run responses of AVCs to wolf spread in Wisconsin from the 1990s through the 2010s, the present study measures long-run *equilibrium* responses to the presence and absence of wolves across a natural barrier for over 100 years. Some long-run responses could mitigate the effects of wolf absence (e.g., more aggressive human hunting of deer in the absence of wolves), whereas others could exacerbate them (e.g., deer populations becoming less cautious in the absence of wolves). In the long run, wolf presence could also influence driving habits (e.g., more careful driving in larger vehicles where wolves are absent and deer are abundant), natural selection (e.g., deer that avoid wolves produce different offspring than deer that do not have to), as well as changes in animal behavior (e.g., deer, adapted to wolves may learn to travel different routes and at different times). Differences in long- and short-run responses are thus theoretically ambiguous, thereby necessitating empirical analysis.

While both short- and long-run estimates inform potential benefits and costs of reintroductions, opportunities to study long-run effects are rare. Causal inference from observational data in complex ecosystems is difficult (Ferraro et al. 2019). In addition, reintroductions and recolonizations are quite recent and, thus far, have not been coupled with randomized controlled trials (RCT) to evaluate their socioeconomic effects. Both observational and experimental approaches may fail to capture long-term and general equilibrium effects, including changes in species abundance and behavior and associated human adaptation (Sarrazin and Barbault 1996; Hale and Koprowski 2018). That is, short-run gains or losses from the addition of a predator are partial equilibrium responses that may not reflect general equilibrium realizations of option value. The use of historical natural experiments can overcome the potential inadequacy of an RCT where it could take decades for people, prey, and the rest of the ecosystem to adjust to predators in the landscape.

2 River Discontinuity in Wolf Presence as a Natural Experiment

In this section, we first review the background that led to the discontinuity in the presence of wolves north and south of the Saint Lawrence River, and then review the estimation of the spatial discontinuity. In Figure 1, we plot the area of study around the river (we describe data sources in Section 3).

2.1 Presence of Wolves Around the Saint Lawrence River

Before the European colonization of the Americas, the habitat range of the gray wolf spanned most of North America, including around what is today the border between the United States and Canada (Morell 2016). As European settlers hunted deer, elk, and other ungulate species, they inadvertently depleted the natural prey of wolves, leading wolves to prey on livestock animals. As a result, wolves were seen as a growing threat to livestock and the livelihood of ranchers. While a living wolf was seen as a pest, a dead wolf was a resource because their pelts and furs were valuable in commercial markets and for payouts in government-sponsored bounty programs (Fischer 1995; Lueck 2002). This combination of circumstances contributed to the success of the wolf eradication campaigns in North America (Morell 2016).

Historical records date the disappearance of wolves from the southern shores of the Saint Lawrence River between 1850 and 1900 (Villemure and Jolicoeur 2004), well before our study period of 2000 to 2019. Because the river is substantial, rather than narrow and shallow, animals such as wolves, deer, and moose rarely cross the physical boundary the river provides.[2] Despite ongoing surveillance meant to detect wolf populations south of the river, such observations are rare. One well-documented instance of wolf detection south of the river is a single wolf observed in 2002 (Villemure and Jolicoeur 2004). Conservation groups have identified 12 other potential wolf sightings in this region since the 1990s (The Maine Wolf Coalition 2024). However, lone wolves that manage to cross the frozen river are often killed by hunters.[3]

Despite speculation about whether lone wolves are crossing the river, there is a consensus that there are no established wolf populations south of the river.[4] McAlpine et al. (2015)

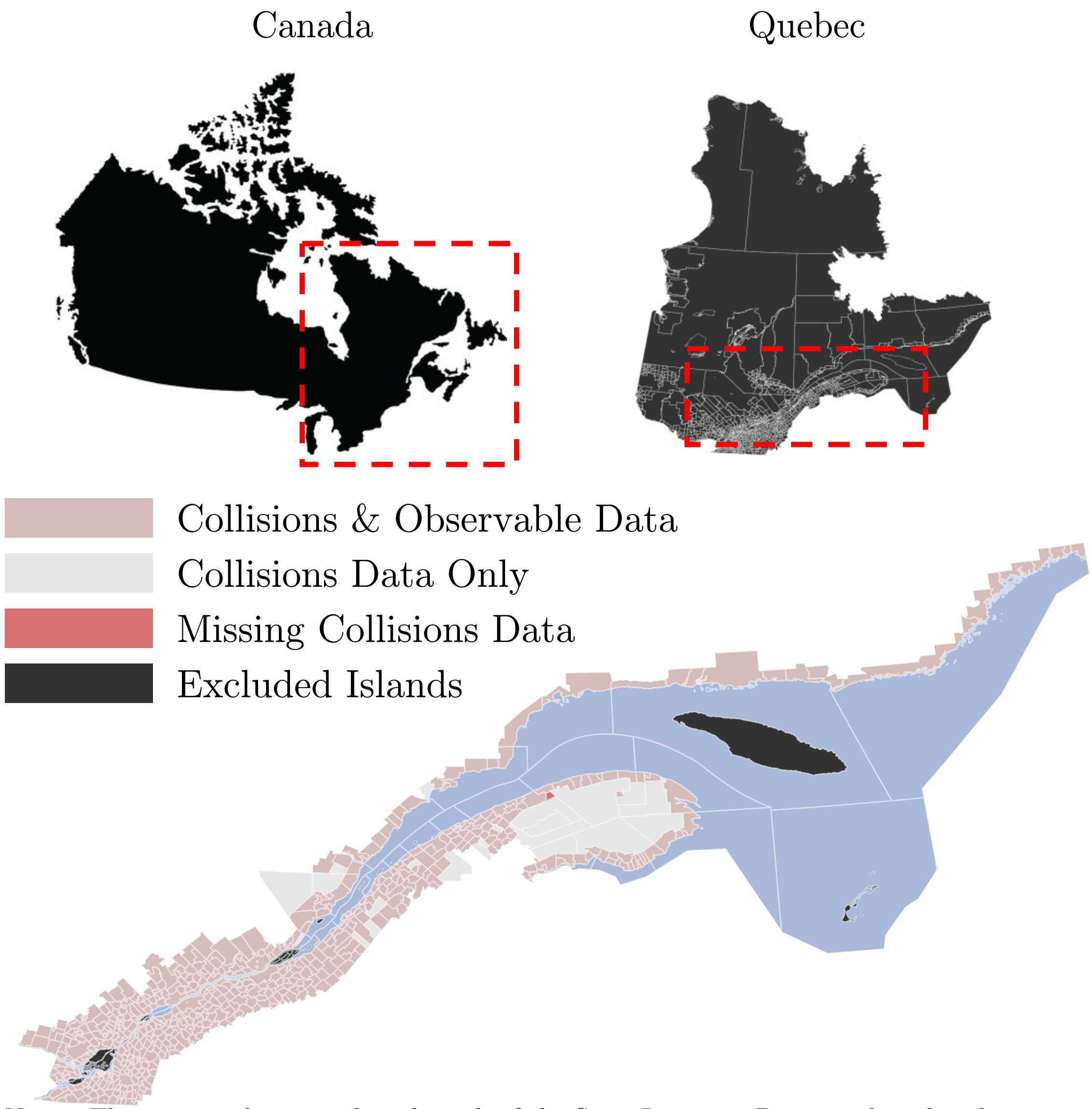
[2] Rare instances when animals do cross the river end up as local news stories. See: https://www.lesoleil.com/2017/06/18/un-orignal-fait-trempette-dans-le-fleuve-1a9e5a106b631546016cd0ca4dee4905/. Accessed: 9/25/2025.

[3] See the following summary by the Center for Biological Diversity: https://biologicaldiversity.org/w/news/press-releases/dna-test-confirms-another-wolf-killed-in-new-york-2022-07-26/. Accessed 9/25/2025.

[4] See the following for coverage on the contentious claim regarding wolf presence in the northeastern parts of the United States: https://www.boston.com/news/local-news/2022/08/26/are-there-wolves-in-the-northeast-its-complicated/. Accessed 9/25/2025.

write that “natural dispersal alone will likely not be sufficient to re-establish wolves in northeastern North America.”

Figure 1: Spatial RDD Around the Saint Lawrence River



Notes: The municipalities north and south of the Saint Lawrence River, with and without gray wolves, respectively. We plot the municipalities whose centroids are within 50 km of the river.

2.2 Spatial Regression Discontinuity Design

To estimate the effect of wolf presence on AVCs, we exploit the sharp change in the presence of wolves north versus south of the Saint Lawrence River in a spatial regression discontinuity design (RDD). The history that led to the river discontinuity over a century ago means that there has been ample time for ecosystem and human adaptation to the absence of wolves in the south, and to their presence in the north. These conditions make it an ideal empirical setting for identifying the long-run effect of wolf presence.

The fact that wolves rarely cross the river, and even when they do, are unable to form wolf packs, prevents spillovers across wolf and non-wolf areas that could violate the stable unit treatment value assumption (SUTVA) required for valid empirical comparisons. Moreover, because prey animals cannot readily cross the river, we can also assume that deer and moose management has adjusted to wolf presence or absence within the north and within the south without being confounded by spillover dynamics across the north and south.

The physical boundary of the river affects humans as well, and constrains their potential behavioral responses. If human drivers notice fewer deer and moose near roadways in areas with wolves, they are unlikely to simply reroute their travel to the north because drivers do not have readily accessible opportunities to shift their daily driving routes across the river due to the fixed and limited locations of bridges and ferries. Because the sharp change in wolf presence along the river has been in place for over a century, we can, however, assume that driver behavior within the north and within the south has adjusted to either the presence or absence of wolves.

We estimate how the share of AVCs changes at the boundary of the river using the following RDD specification:

$$y_m = \beta_1 \text{North}_m + \beta_2 f(\text{Distance}_m) + \beta_3 f(\text{Distance}_m) \times \text{North}_m + \varepsilon_m \tag{1}$$

.

Here y_m is the share of animal-related collisions relative to all collisions in municipality m, collapsed to a cross-section of municipalities. In addition, we use data on covariates to provide support for the continuity assumption across the border. The indicator variable

North_m is equal to one for any municipality that is north of the river, and zero otherwise. We flexibly control for the distance to the river, Distance_m, using local linear regressions and allowing the effects of distance to be different on each side. We assign distance as negative or positive, south or north of the river. And while our RDD is geographic in nature, we do not consider the issues pertaining to the special case of multi-score RDD described in Cattaneo et al. (2024) to apply in this setting. This is because the boundary is not an arbitrary administrative one, but rather a natural feature that does not exhibit extreme irregularities. The specification assumes that any remaining unobservable heterogeneity is captured by the error term, which we cluster at the municipality level. In the Online Appendix, we report results for other levels of clustering.

3 Vehicle Collisions & Municipality Data

We obtained vehicle collision records spanning 2000 to 2019, at the crash record level, from the Road Safety Research Department in the Quebec Automobile Insurance Company—Société de l'assurance automobile du Québec (SAAQ) (SAAQ 2017). Each collision record contains the date of the collision, the longitude and latitude of the collision, and a classification code regarding the cause of the collision. We use the coordinates of the collision to match it to a municipality code (comparable to townships in the United States). For each collision, we classify it as animal-related or not, following the guidance provided by the SAAQ.

The crash records do not include information about the exact animal involved in each collision. However, from other sources, we know that AVCs in Québec are primarily deer, followed by moose. For example, in 2000, out of the total 2,810 AVCs, 87.3 percent were with deer, and 10.6 percent were with moose.[5] The abundance of deer and their share in animal collisions is rising. A report by the Canadian Traffic Injury Research Foundation

[5] See Exhibit 5.8 in https://tc.canada.ca/en/road-transportation/publications/statistical-review. Accessed: September 25, 2025.

states that Québec is experiencing the fastest growing trend in vehicle collisions with deer (Vanlaar et al. 2012).

Locations for which driving intensity is highest (e.g., due to having higher populations, more roads, or a higher reliance on personal vehicles) tend to experience more vehicle collisions. To account for this, we normalize the number of AVCs in two ways. Our main focus is on the share of AVCs relative to all vehicle collisions. In the Online Appendix, we also report summary statistics for the AVC rate per 1,000 people. The share of AVCs is our preferred measure because total collisions embeds all factors causing variation in driving intensity across and within municipalities, including differences in population levels, road characteristics, as well as fragmentation of the habitat by roads.

Figures A2-A3 report summary statistics over time for both versions of normalized AVCs, separately for municipalities that are either north or south of the river. The figures highlight two key patterns. First, there is a persistently higher share of AVCs relative to all collisions south relative to north of the river. However, examining other categories in the all-cause collisions data, we see no meaningful difference between north and south—namely those that are classified as resulting in property damages only (PDO) or those resulting in at least one reported human injury. Second, the all-cause vehicle collision rate per 1,000 people is similar between the south and the north, however, when we decompose the all-cause collision rate to animal-related and non-animal-related vehicle collision rates per 1,000 people, we observe a gap in the former, but not the latter. In other words, the south and the north have similar non-animal-related collisions, but animal-related collisions are higher in the south relative to the north.

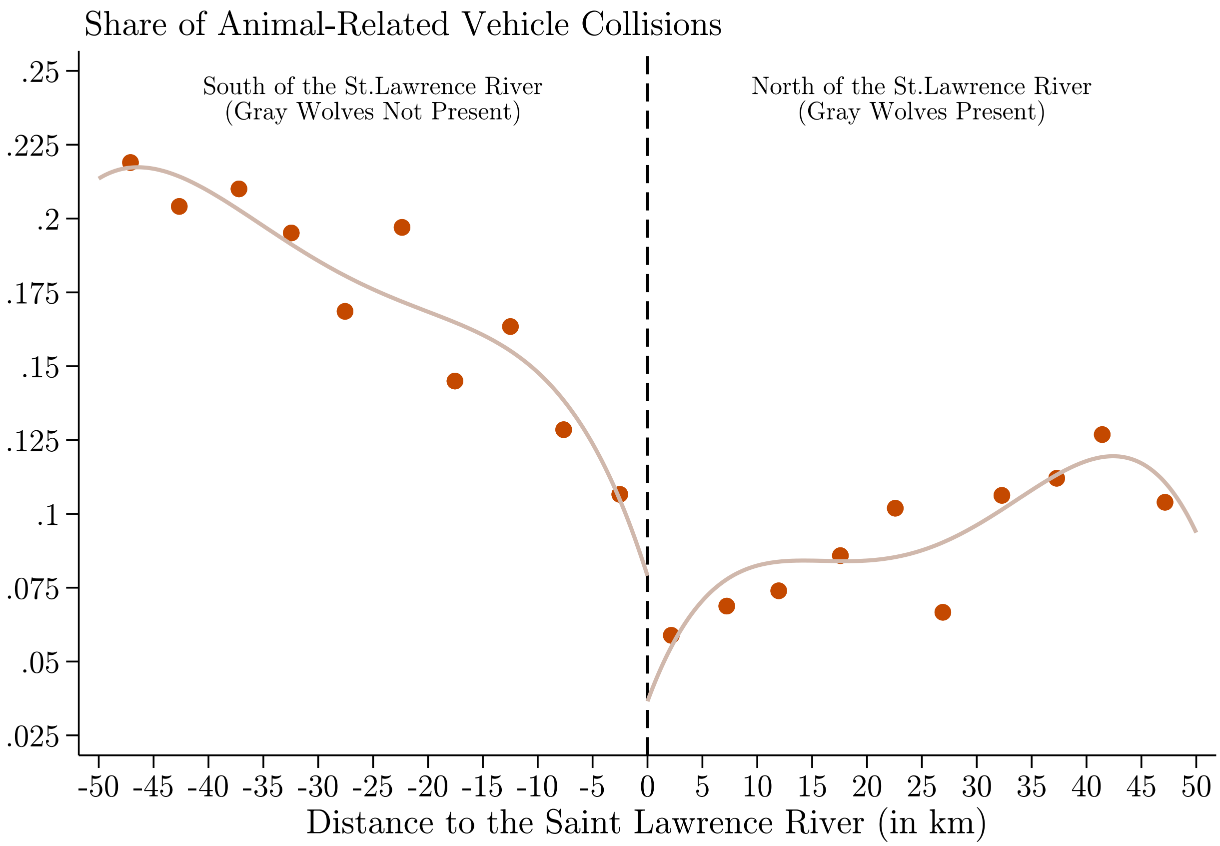
For each municipality, we collect additional socioeconomic and environmental data. We obtain demographic variables from the Canadian Census (e.g., population size, share married, share with a university degree; von Bergmann et al. (2021)), fiscal revenue (Ministère des Affaires Municipales et de l'Habitation 2017)), road and traffic densities (Ministère des Transports et de la Mobilité Durable 2017), as well as environmental characteristics such as elevation (Farr et al. 2007; NASA 2015), slope (calculated from elevation), forest cover (Commission for Environmental Cooperation 2024), mean temperature, and mean annual precipitation 2000-2019 (Muñoz Sabater 2019). This data collection effort yields 15 variables that we observe for nearly all municipalities.

4 The Effects of Wolf Presence on Animal-Related Vehicle Collisions

Visual and econometric evidence both suggest the presence of wolves meaningfully reduces AVCs. Figure 2 illustrates the river discontinuity by plotting binned values for the share of AVCs south (left of the cutoff) and north (right of the cutoff) of the river for the municipalities that have their centroid distance within 50 km of the river. The share of AVCs relative to total collisions changes sharply at the border, from 0.11 to 0.06 (a 5 percentage point reduction), reflecting a change of 45 percent relative to the level south of the river. Turning to areas up to 10 km further from the border in Figure 2, we observe a drop from 0.13 to 0.07, reflecting a similar drop in relative and in absolute terms.

While the presence of wolves changes abruptly at the river, environmental conditions change continuously along the south-to-north gradient. This continuous change means that the habitat suitability for animals such as deer and moose is also changing, and this helps to explain the decline in the share of AVCs approaching the river from the south (e.g., increasing precipitation further south of the river). We also observe an increasing gradient in the share of AVCs moving further north of the river, albeit weaker than the one we observe south of the river. In subsequent analysis, we document that precipitation follows a similar declining gradient from south to north, and the elevation and forest land cover follow similar increasing gradients further north of the river, when we examine the balance of covariates around the river (see Section 4.1). These gradients in environmental conditions and in the share of AVCs highlight the local average treatment effect interpretation of the RD estimator. In other words, our analysis focuses on the sharp change in the presence of wolves, and not the continuous change in environmental conditions far from the river.

Figure 2: Share of AVCs Around the Saint Lawrence River



Notes: Binned values (using equally sized intervals) south and north of the St. Lawrence River for the share of animal-related collisions relative to all-cause collisions. Solid lines plot a global four-degree polynomial on each side of the cutoff.

Estimation results from Equation (1) confirm that these sharp changes in AVCs near the river are precisely estimated (Table 1). Arbitrarily setting the bandwidths—for estimation and bias correction—around the river to be either 50 or 25 km leads to a precisely estimated 4 percentage point reduction (Panel A, columns 1, 2 and 3). This estimate reflects a 30 percent reduction relative to the mean in the sample, and a 25 percent reduction relative to the mean south of the river, up to 50 km. Excluding municipalities with high values of the share of AVCs (i.e., above the 95th percentile) drops more municipalities south than north of the river, but recovers the same coefficient with higher precision (Panel A, column 2).

Comparison to Previous Results on Wolves and AVCs.— The estimated effects of wolf presence on AVCs in this study (approximately 30 to 54 percent; Table 1, columns 1-3, and 5) exceed estimates reported by Raynor et al. (2021) (24 percent reduction in deer-vehicle collisions in Wisconsin, USA). One explanation is simply that wolves affect prey populations and their behaviors differently in different settings. However, both settings have largely the same forested habitat and mix of prey species. Therefore, this may be evidence that the long-term effects of wolf presence in an ecosystem exceed the short-term effects. This would be true if, for example, long-run natural selection of deer in the presence of wolves leads to a population that is more adept at avoiding the edges of the forest, near the road, thus reducing collisions.

4.1 Verifying Robustness to Bandwidth Choices, Sample Composition & Controls

Choosing the bandwidths using an optimization routine, rather than arbitrarily, results in the same estimation sample, but a wider bandwidth for the bias correction (75 km instead of 50 or 25 km). This increases the coefficient to 5 percentage points, reflecting a 38.5 percent reduction relative to the mean while also improving estimation precision (Panel A, column 4). We consider this to be our preferred specification and main coefficient we later use in monetizing the effect. The results remain similar in magnitude and precision when we apply a donut approach (D-RDD) and exclude municipalities that are very close to the river (centroid distance of up to 5 km), demonstrating that the reduction in AVCs does not happen only near the boundary of the river (Panel A, columns 5, 6, 8, 9 and 10).

The results are robust to including control variables, weighting by human population, and truncating extreme values. First, we include 15 covariates that control for differences in a set of environmental, demographic, and municipality infrastructure variables discussed above (Panel A, columns 7, 9, and 10). The point estimates are qualitatively similar; however, including all controls reduces statistical power such that we can only reject the null hypothesis of a zero difference between north and south at a 10 percent significance level. Next, we weight the observations by human population and recover a larger effect of a 10 percentage point reduction in the share of AVCs (Panel A, column 8). However, this magnitude is halved once we also include all 15 covariates as controls (Panel A, column 9) and remains unchanged if we truncate the sample to account for extreme values (Panel A, column 10).[6]

The results remain largely unchanged when excluding potential outlier municipalities. We flag outliers with a procedure that uses the 15 standardized covariates. If a municipality has at least three covariates that are two standard deviations larger or smaller than the mean, we exclude it from the sample. Panel B of Table 1 reports results using this restricted sample. There are two cases where the results are slightly different. In column 7, when including all 15 covariates, the coefficient increases from 0.02 in the unrestricted sample to a 0.03. The exclusion of just 19 municipalities increases the precision of the estimates and allows us to reject the null hypothesis of no difference between north and south at the 5 percent significance level. Similarly, the coefficient in column 10 is estimated with higher precision.

To check whether the municipalities are exhibiting any other discontinuities along the river, we examine how a variety of characteristics change at the border. In Figure 3, we report the same RDD-style plot as in Figure 2. These figures reveal a few key insights about how environmental conditions, demographic variables, and municipality infrastructure change across the river boundary. First, in the cases where there is a discontinuity in some demographic variables, it is strictly driven by the municipalities in the zero to five kilometer range north of the river (panels i, n, and o). Second, the median age (panel n) increases sharply beyond 25 km north of the river. Third, municipalities that are within 5 km of river do not exhibit a discontinuity but do appear to be different than those that are further away in terms of road density and sex-ratio (panels f and m). We consider these differences in

[6] With the truncated sample, we only report results for the manually set bandwidth of 50 km because when we use population weights and allow the MSERD procedure to choose the optimal bandwidth, the sample size becomes extremely small as the selected bandwidth ends up being less than 10 km.

Table 1.
Estimation Results for Share of Animal-Related Vehicle Collisions

Panel A. Full Sample

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
N. Dummy	-0.04	-0.04	-0.04	-0.05	-0.06	-0.06	-0.02	-0.10	-0.05	-0.05
	(0.02)	(0.01)	(0.02)	(0.01)	(0.03)	(0.03)	(0.01)	(0.04)	(0.03)	(0.03)
$\overline{Y}$	0.13	0.13	0.11	0.13	0.11	0.13	0.13	0.04	0.04	0.04
BW	50.0	50.0	25.0	49.7	31.2	50.0	50.0	50.0	50.0	50.0
N South	433	400	273	433	225	339	385	328	308	279
N North	255	253	198	255	127	170	223	166	158	158

Panel B. Excluding Outlier Municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
N. Dummy	-0.04	-0.04	-0.04	-0.05	-0.06	-0.06	-0.03	-0.10	-0.05	-0.05
	(0.02)	(0.01)	(0.02)	(0.02)	(0.03)	(0.03)	(0.01)	(0.04)	(0.03)	(0.02)
Truncated		X								X
Op. BW				X	X					
Donut					X	X		X	X	X
Covs.							X		X	X
Pop. W.								X	X	X
$\overline{Y}$	0.13	0.13	0.11	0.13	0.12	0.13	0.13	0.04	0.04	0.04
BW	50.0	50.0	25.0	47.2	31.0	50.0	50.0	50.0	50.0	50.0
N South	425	393	268	410	217	333	379	322	304	276
N North	230	228	178	227	119	158	210	154	150	150

Notes: Estimation results using the specification in Equation (1). We report the robust coefficient following Calonico et al. (2014). Truncated samples exclude municipalities with a share of animal-related collisions above the 95th percentile. Optimal bandwidths use the MSERD procedure with triangular kernel. Donut samples exclude municipalities whose centroids are closer than 5 km to the river. When including covariates, we include all 15 environmental, demographic, and municipality infrastructure variables. In Panel B, we exclude municipalities with at least three covariates that deviate by more than two standard deviations. Population weights use the 2011 census data. Standard errors are clustered at the municipality level.

some variables as additional justification for the D-RDD approach.

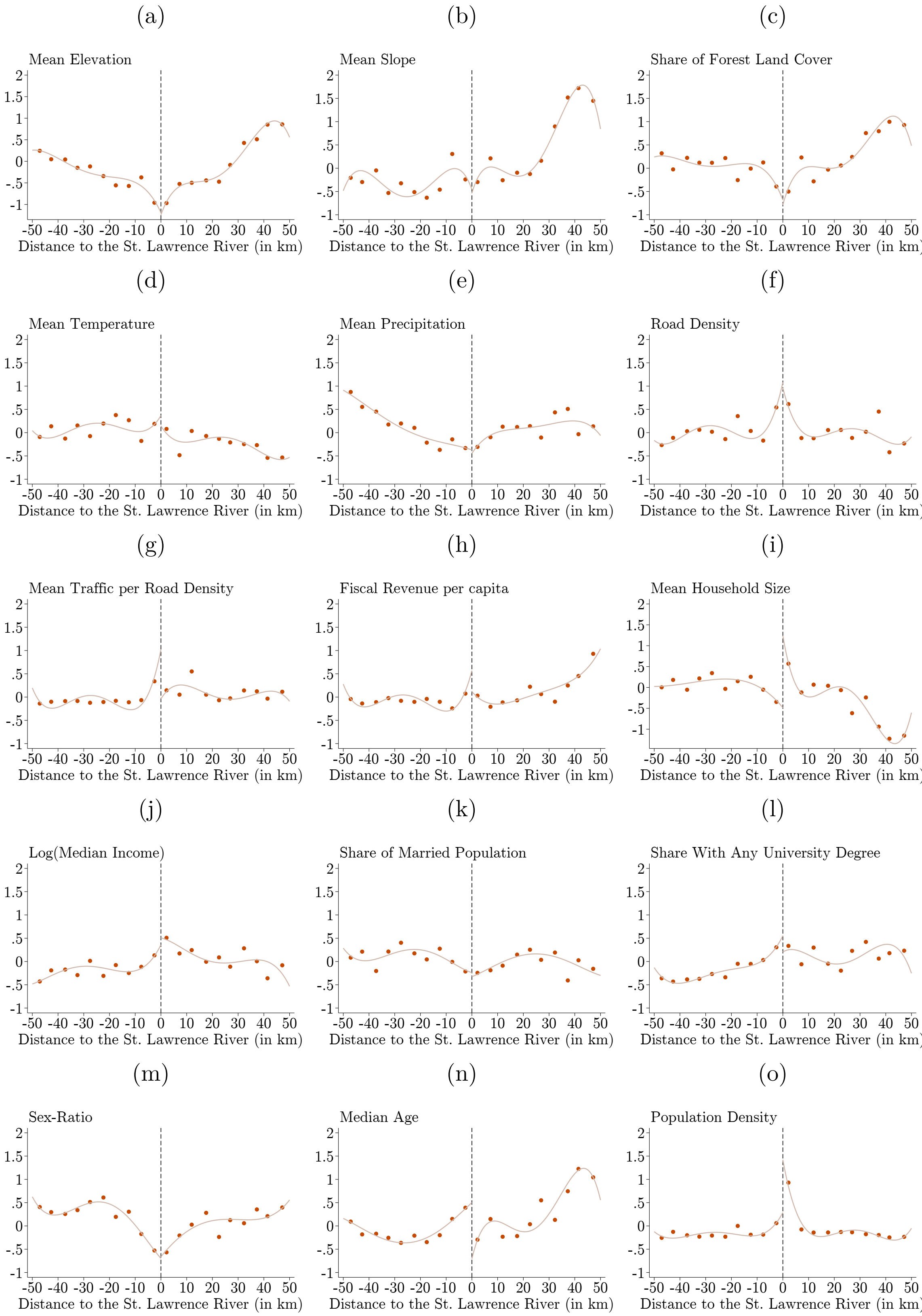
In the Online Appendix, we report additional estimation results that support the internal validity of our analysis. First, we repeat the spatial RD analysis for each covariate when using either: optimally chosen bandwidths, a fixed 50 km bandwidth, and a fixed 50 km bandwidth while excluding the municipalities near (5 km or less) the river (Table A1). Second, we also include each of the 15 covariates separately in the regression where the share of AVCs is the outcome (Table A2). See Online Appendix, Section A.3, for a detailed discussion of those results. Third, we verify the results are not driven by outlier municipalities by reporting the distributions of a set of leave-one-out estimation procedures (Figure A4). Fourth, we verify that if we displace the true location of the river, we fail to obtain the result we report when using the true location of the river (Figure A5). Fifth, we verify that clustering the standard errors at geographic levels above the municipality—to account for spatial clustering of the standard errors—does not meaningfully reduce the precision of the estimates (Table A3).

4.2 Mechanisms & Adaptations

Wolves may reduce AVCs through two main channels: (i) by lowering prey populations and (ii) by altering prey behavior in ways that reduce their presence near roads. Likewise, humans might adapt to the absence of wolves either by managing prey abundance through more aggressive hunting or by exercising defensive driving to lower AVC risk. We discuss each mechanism in turn, then consider evidence for human adaptations.

Mechanism I: Prey Abundance.— We first ask whether wolves reduce AVCs simply by reducing deer and moose populations. Because we lack direct population counts, we rely on two widely used proxies for wildlife abundance: hunting harvests per area (from 45 hunting zones, spanning 1971-2024), and hunting certificates per capita (at the municipality level, spanning 2000-2019). In most North American jurisdictions, harvest levels are strongly correlated with underlying prey populations because hunting quotas and hunter success rates

Figure 3: Environmental, Infrastructure & Demographic Variables



Notes: Same as in Figures 2, but for each separate observable characteristic of the municipality. Each outcome is a z-score of a different observable characteristic.

rise with animal density (Stephens et al. 2015; Priadka et al. 2020). Similarly, the number of hunting certificates per capita reflects the expected returns to hunting, as demand is proportional to game abundance. These measures are routinely employed by wildlife managers to infer trends in ungulate populations when costly population surveys are infeasible.

Harvest and hunting certificate data near the river show no meaningful discontinuities across the wolf boundary (Figure 4 and Online Appendix Table A6), and controlling for them does not affect our estimated AVC effect (Online Appendix Tables A6 and A7). This suggests prey abundance explains little of the 38% difference in AVCs.

Mechanism II: Prey Behavior.— A second mechanism may be more important but is difficult to measure. Wolf presence can cause behavioral changes in prey leading them to avoid areas where predation risk is high ("landscape of fear") (Ripple and Beschta 2004; Gable et al. 2020; Zanette and Clinchy 2020; Allen et al. 2022; Ganz et al. 2024), and in the long-run improve their genetic fitness in avoiding predation. Radio-collar evidence indicates that wolves favor traveling along linear corridors and forest edges, including roadways, and that prey respond by avoiding these areas (Fortin et al. 2005; Dellinger et al. 2019). We lack data on wolf and prey movement around the Saint Lawrence River, but we hope that future research examines this channel more closely.

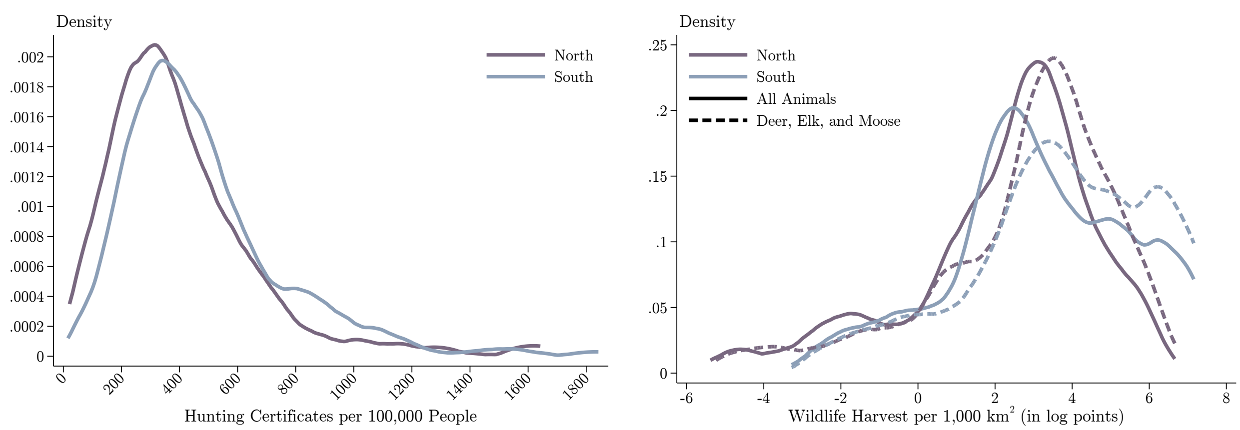
Human Adaptations.— We emphasize that AVCs are higher in the south despite any human adaptation to a landscape lacking wolves. Drivers could attempt to reduce AVC risk by changing when or how they drive. We find no evidence that drivers south of the river shifted driving times to avoid periods of known animal movement (Figure A6 and Table A4). We do, however, find weakly suggestive evidence that drivers north of the river drive smaller and lighter vehicles (Table A5), suggesting that more drivers in the south are choosing larger cars possibly to reduce their risk of injury from AVCs. Finally, as indicated above, there is no evidence that more aggressive hunting effort has offset wolf effects where they are absent.

Interpretation and Discussion.— Taken together, the results do not support the notion that wolves reducing prey population is the primary mechanism that lowers AVCs. Instead, prey changing their behavior remains a more compelling, yet untested, mechanism. Despite the large (38%) effect of wolf presence on AVCs, human adaptation to their absence appears to have been minimal, at least as measured by data on driving behavior and hunting effort. The finding that human adaptation to predator absence has been incomplete suggests that it has been difficult and costly, at least in terms of road safety. Overall, the results underscore how a predator's option value depends not only on its role in affecting prey population numbers and behavior, but also on the costs of human adaptation to its absence. Further study of these costs should help scientists understand which predators offer ecosystem services that are unlikely to be replicated by humans.

Figure 4: Hunting Harvests & Certificates Around the Saint Lawrence River

(a) Wildlife Hunting Certificates

(b) Wildlife Harvest Densities



Notes: We plot the kernel densities for the mean number of hunting certificates per capita for municipalities within 50 km of the river, truncated at the 99th percentile (a), and the wildlife harvest data in the hunting zones whose borders are within 50 km of the river (b).

4.3 Monetizing the Benefits of Wolf Presence

To quantify the road safety benefit of having wolves north of the Saint Lawrence River, we combine the RDD estimates with additional data on monetized damages in a simple back-of-the-envelope calculation. First, we note that the mean number of collisions per municipality and year north of the river is 132.7 for total collisions and 4.02 for AVCs. Converting the difference of 5 percentage points (Table 1, column 4) to the number of averted AVCs relative to the counterfactual of no wolves north of the river (up to 50 km from the river) generates an annual estimate of 7.2 averted collisions per municipality. There are 255 municipalities north of the river, within 50 km, resulting in a total annual benefit of 1,836 averted collisions. Most of the AVCs are non-fatal (99.9 percent) and result in property damages only (90.3 percent), while 9.6 percent of collisions include at least one injured person and 0.1 percent caused at least one human fatality. Using these estimates, we calculate that each year, the presence of wolves north of the river prevents 1,658 property damage only collisions, 176 collisions with at least one human injury, and 1.8 collisions with at least one human fatality, due to animal-related causes. We use monetized damage estimates from Transports Canada – Direction générale de l'analyse économique (2007) based on 2000 data, and multiply these counts to arrive at a total *annual* benefit of 41.7 million 2024 CAD (29 million 2024 USD).

To put this magnitude in context, consider how it compares to expenditures on road infrastructure in Quebec (see Online Appendix A.10 for details): our full account of annual averted damages amounts to 5.4 percent of annual realized road infrastructure expenditures, or alternatively, 3.7 percent of the annual projected road infrastructure expenditures.

We can also place this number in a broader context for North America, and extrapolate the back-of-the-envelope calculation to all of Canada and all of the United States (see Online Appendix A.10 for details). We obtain 564,274 and 128,682 averted AVCs in the United States and Canada, respectively, and convert it to \$5.12 and \$1.24 billion in total or \$15.1 and \$30 in per capita terms, respectively, in 2024 USD. In total, our extended back-of-the-envelope calculation suggests that the presence of wolves in North America has the potential to reduce damages from AVCs by \$6.36 billion per year or population-weighted value of \$16.7 per person per year, in 2024 USD. This assumes that the effect of wolf presence is homogeneous regardless of wolf density, prey composition and density, road density, and other management and defensive expenditure actions.

5 Conclusions

Ongoing endeavors to reintroduce large predators raise questions about how they will affect human well-being. Here, we identify a key effect from gray wolves that has broad economic relevance—the reduction in animal-vehicle collisions. Exploiting a stable discontinuity in the presence of wolves across the Saint Lawrence River in Quebec, Canada, we find evidence that wolf presence has caused a 38 percent reduction in the share of AVCs relative to all collisions, an estimate larger than short-run effects found in previous research (Raynor et al. 2021). The back-of-the-envelope calculation of benefits derived from wolves highlights the potential social benefits from reintroductions of apex predators such as wolves in other settings where ungulates are also overabundant and operating in landscapes free of fear from predators.

More generally, the 100-year-old extermination of wolves to the south but not the north of the Saint Lawrence River provides a rare opportunity to evaluate the theoretical idea of quasi-option value with a concrete empirical realization. The focus on gray wolves is powerful because they were, for good reason, considered a pest throughout much of human history. Yet had historical efforts to exterminate them led to global extinction, their option value in controlling modern damages from overabundant deer, elk, and moose would have gone unrealized. While the near-total extermination of costly predators such as wolves until the 20th century reduced large, known costs of wolves to humanity, its incompleteness preserved the option to later return them to areas inhabited by humans and deliver valuable ecosystem services difficult for past generations to imagine.

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