OPTION VALUE OF APEX PREDATORS: EVIDENCE FROM A RIVER DISCONTINUITY[*]

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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.

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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

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[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)

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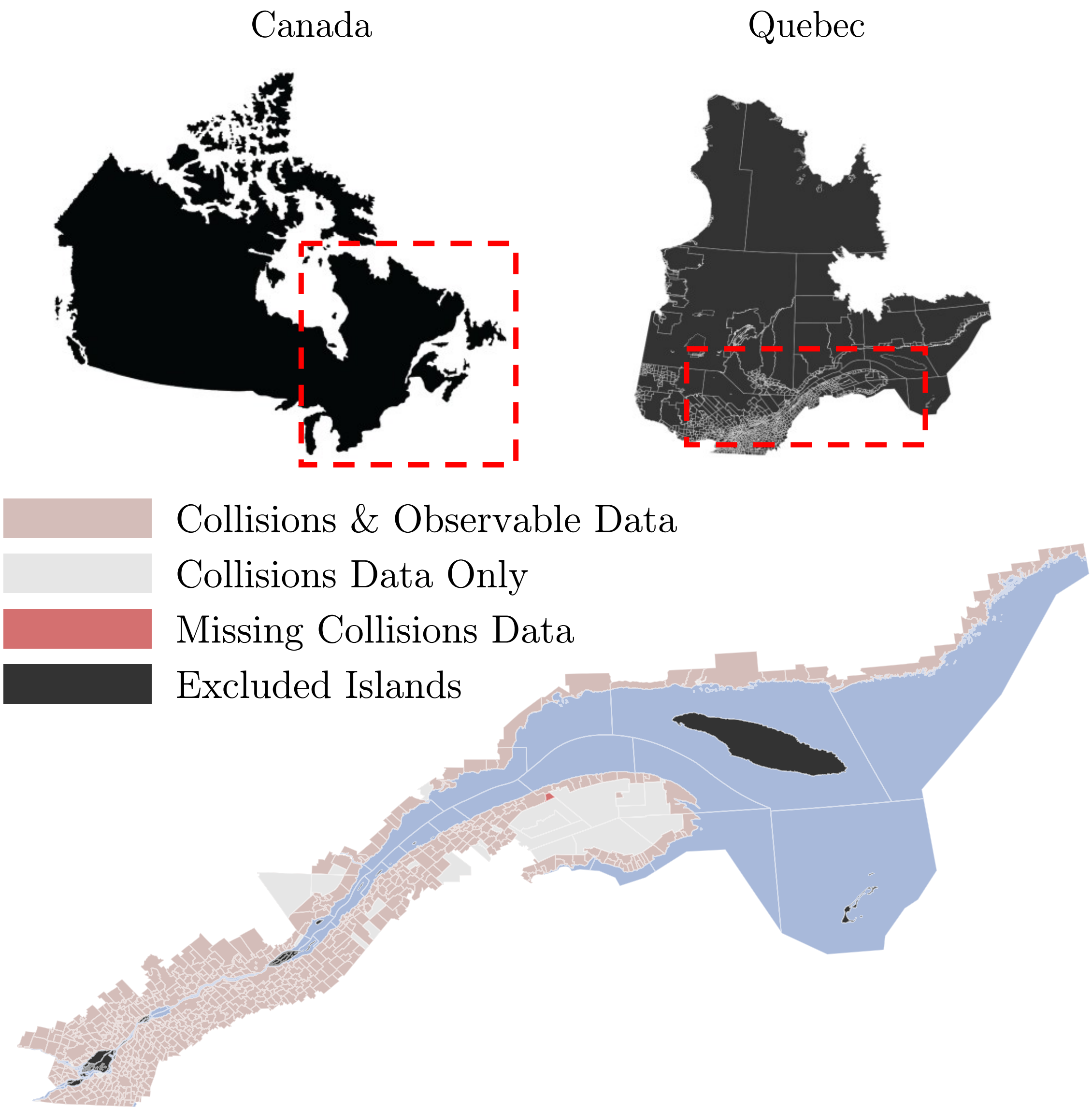
[2] Rare instances when animals do cross the river end up as local news stories. See: https://www.lesoleil.com/2017/06/18/un-orignal-fait-trempette-dans-le-fleuve-1a9e5a106b631546016cd0ca4dee4905/. Accessed: 9/25/2025.

[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

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[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.

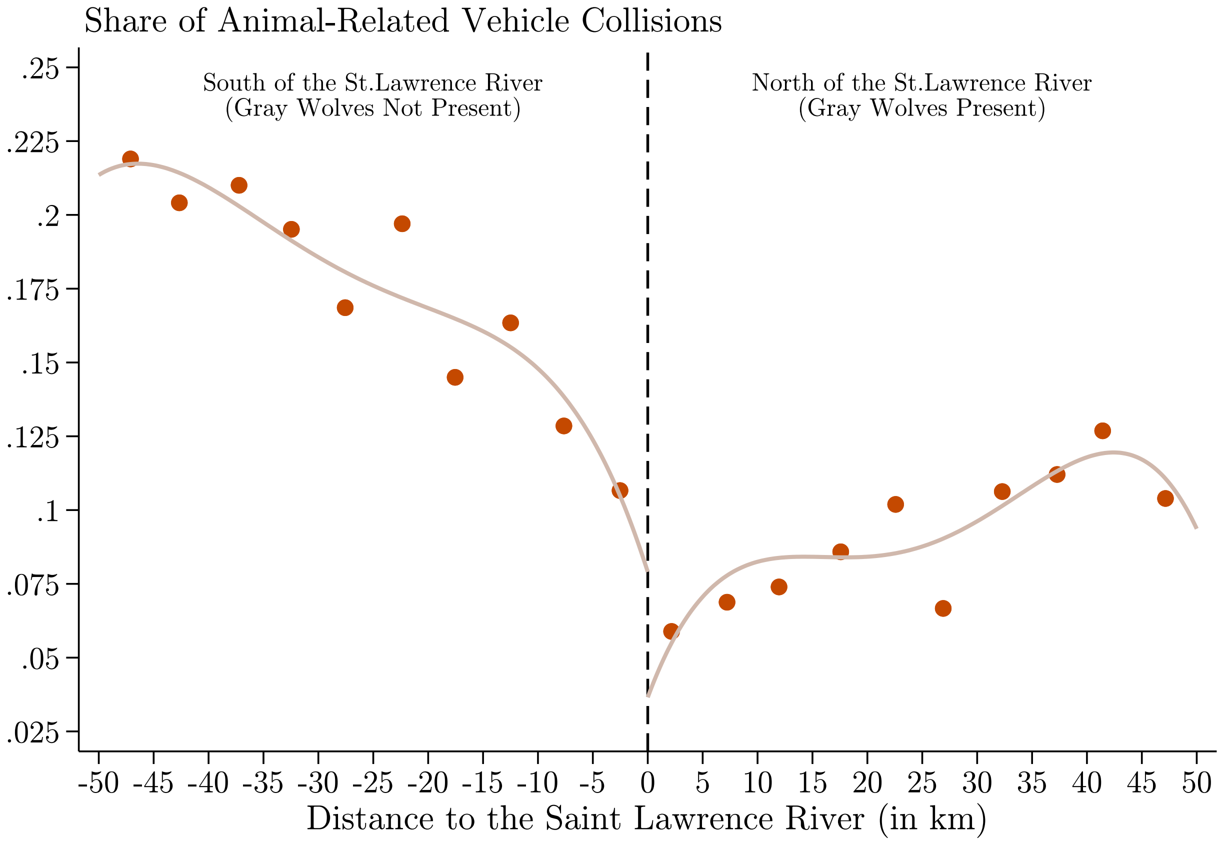
For each municipality, we collect additional socioeconomic and environmental data. We obtain demographic variables from the Canadian Census (e.g., population size, share married, share with a university degree; von Bergmann et al. (2021)), fiscal revenue (Ministère des Affaires Municipales et de l'Habitation 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

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[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.

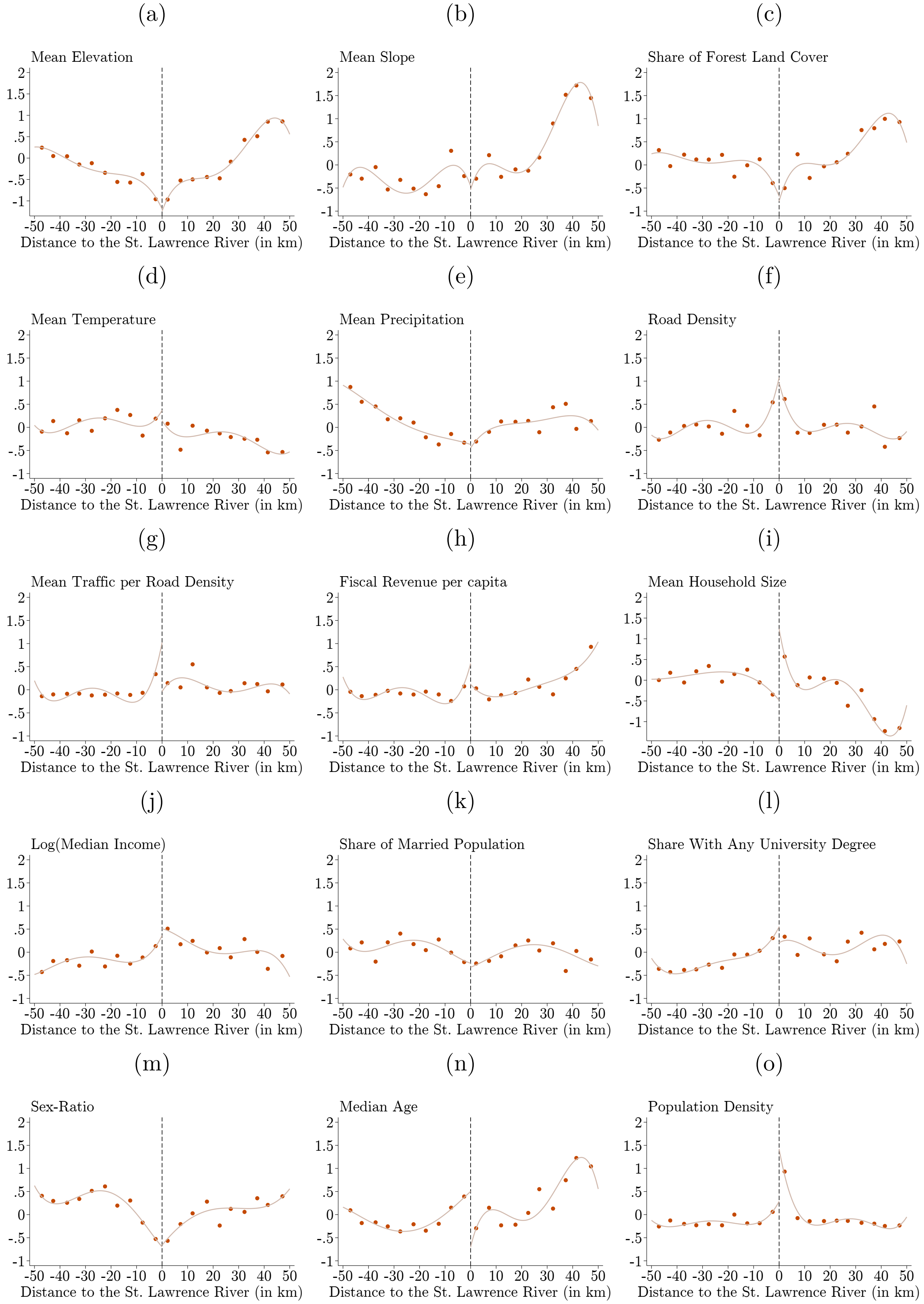
In the Online Appendix, we report additional estimation results that support the internal validity of our analysis. First, we repeat the spatial RD analysis for each covariate when using either: optimally chosen bandwidths, a fixed 50 km bandwidth, and a fixed 50 km bandwidth while excluding the municipalities 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.

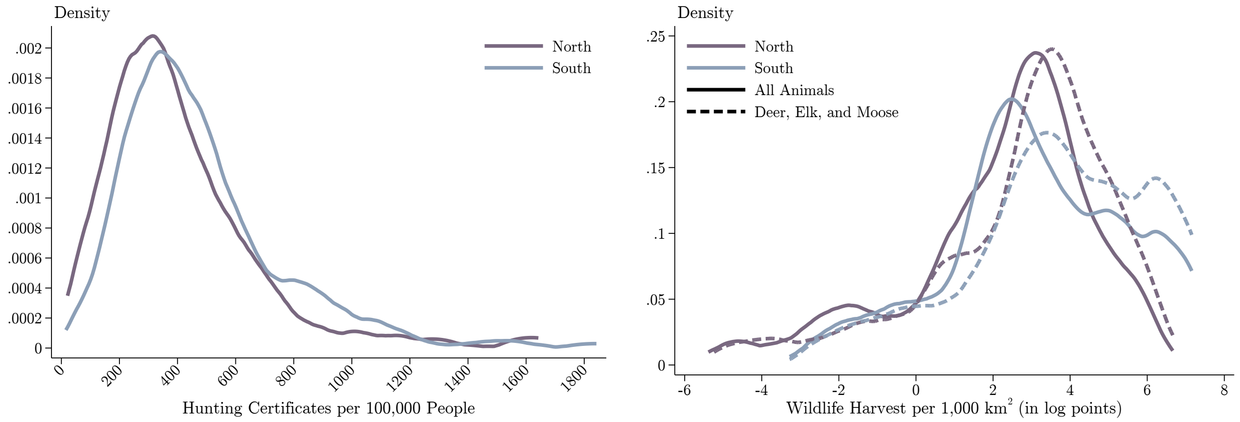
Harvest and hunting certificate data near the river show no meaningful discontinuities across the wolf boundary (Figure 4 and Online Appendix Table A6), and controlling for them does not affect our estimated AVC effect (Online Appendix Tables A6 and A7). This suggests prey abundance explains little of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

A Additional Results

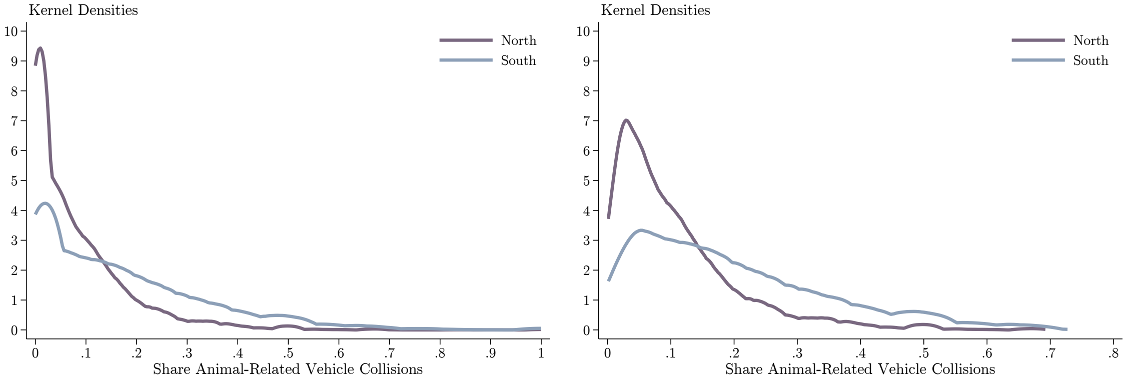
A.1 Summary Statistics for Vehicle Collisions in Quebec

In the main text, we focus on the difference in the share of animal-related vehicle collisions, on average, between municipalities north and south of the Saint Lawrence River. Here we expand on that analysis by describing the distribution of AVCs, how stable it is over time, and whether we observe it solely in animal-related causes.

In Figure A1, we plot the kernel densities for the share of animal-related vehicle collisions, for municipalities that are within 50 km of the river (similar to the sample we use in the main analysis). We report the kernel densities separately for north and south, and we observe that there is a much higher density in the north for low shares of animal-related vehicle collisions than in the south (Panel a). This difference in the distributions is even starker when we truncate the values of the sample at the 1st and 99th percentile values (Panel b).

Figure A1: Distribution of the Share of Animal-Related Collisions

(a) All Municipalities (b) Truncated



Notes: Plotting kernel densities for the share of animal-related vehicle collisions for municipalities that are within 50 km of the Saint Lawrence River. Panel (a) reports the data for all municipalities within that range, while in (b) we truncate at the 1st and 99th percentiles.

In Figure A2, we report the evolution over time of the shares of animal-related vehicle collisions, the share of property damages only (PDO) collisions, and collisions that had at least one injury (each share is calculated separately and categories may overlap).[7] We report the mean shares, by year, for all municipalities either north or south of the river, in either the full sample or the sample of municipalities within 50 km of the river. The first stylized fact that emerges from the top row of the figure is that the share of animal-related vehicle collisions is higher in the south relative to the north, and it has been persistently higher over the span of 2000 to 2019. The second stylized fact is that we *fail* to observe any differences in the share of PDO collisions, or collisions that had at least one injury. With respect to those shares, municipalities north and south of the river exhibit nearly identical shares, on average, over time.

In addition to summarizing the share of collisions, we also describe how the different collision rates, per 1,000 people, change over time, between the municipalities north and south of the river. In Figure A3, we plot (in the first row) the population-weighted all-cause collision rate per 1,000 people. While we see an overall declining trend, especially after 2009, the all-cause collision rate is persistently very similar between the south and the north. When we decompose the all-cause collision rate to animal-related and non-animal-related collision rates (middle and bottom rows, respectively), the key stylized fact that emerges is that within the 50k km estimation bandwidth, there is a striking difference strictly in the animal-related collision rate. In the full sample, there appears to be a reversal between the two rates: animal-related collisions are higher in the south, while non-animal-related collisions are lower in the south. In the restricted sample (within 50 km from the river), we only observe a higher animal-related collision rate in the south relative to the north, while the non-animal-related collision rate essentially overlaps between the south and the north.

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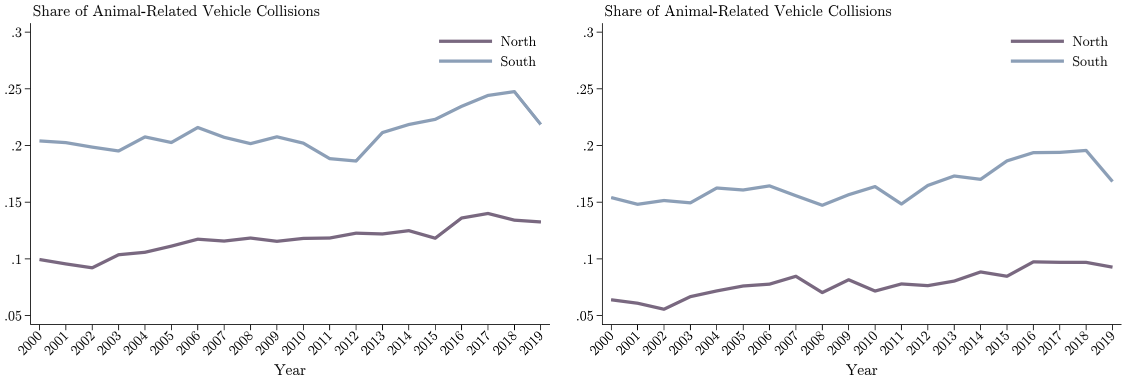
[7] Share or animal-related vehicle collisions are the number of animal-related relative to all vehicle collisions; PDO collisions are all PDO collisions, animal-related or not, relative to all collisions; and collisions with at least one injury are also measured, animal-related or not, relative to all collisions.

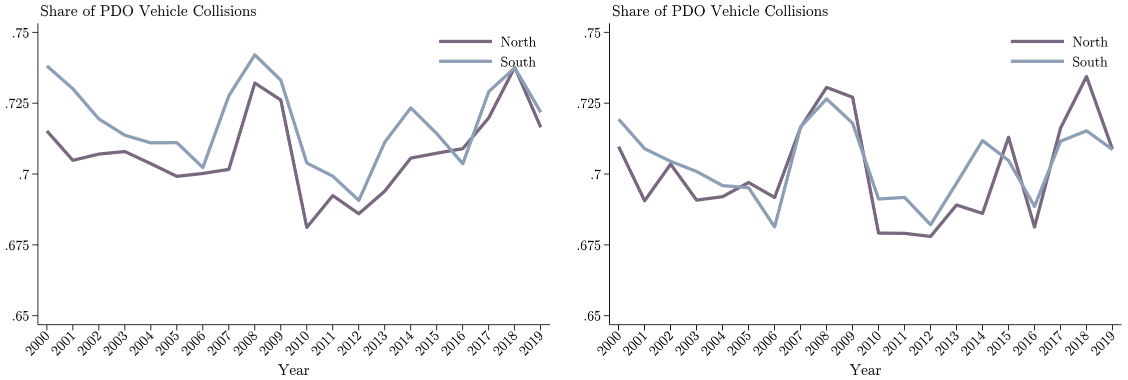
Figure A2: Comparing Collision Shares Over Time

All Municipalities *Within 50 km of the River*

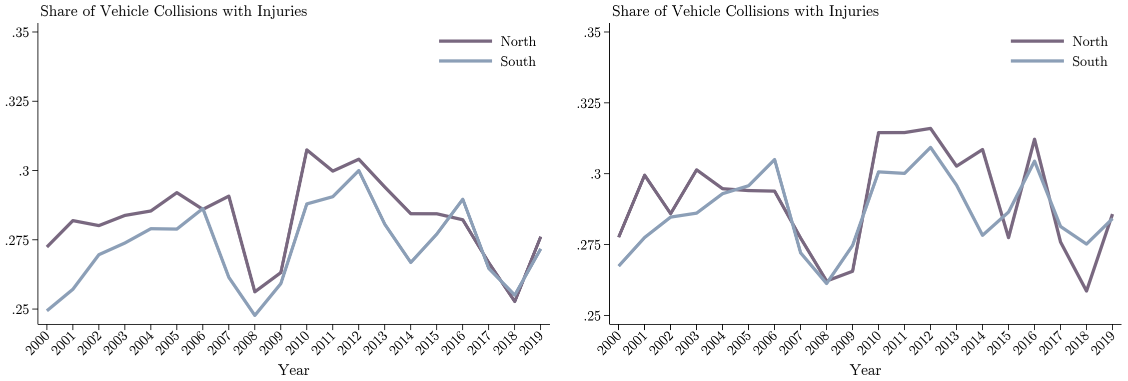
(a) Animal-Related (b) Animal-Related



(c) PDO Collisions (d) PDO Collisons



(e) Collisions with Injuries (f) Collisions with Injuries

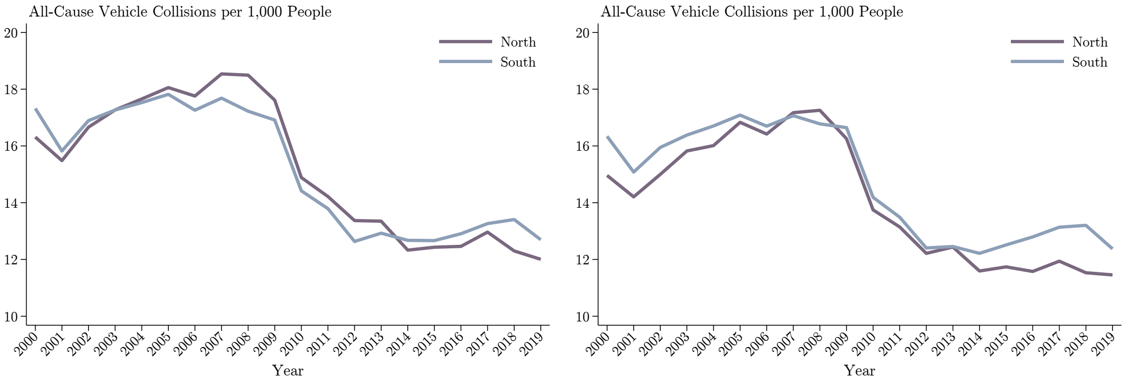


Notes: Mean shares of animal-related, property damages only (PDO), or vehicle collisions that had at least one injured person reported, relative to all-cause collisions, north or south of the Saint Lawrence River. The left column of figures includes all the municipalities in Quebec (n = 1,232), and the right column restricts the municipalities to 50 km from the river (n = 689).

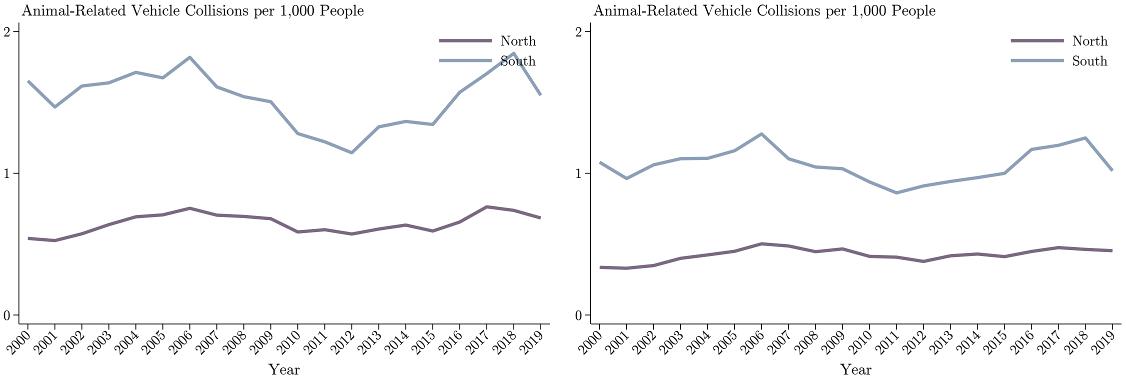
Figure A3: Vehicle Collision Rates Over Time

All Municipalities *Within 50 km of the River*

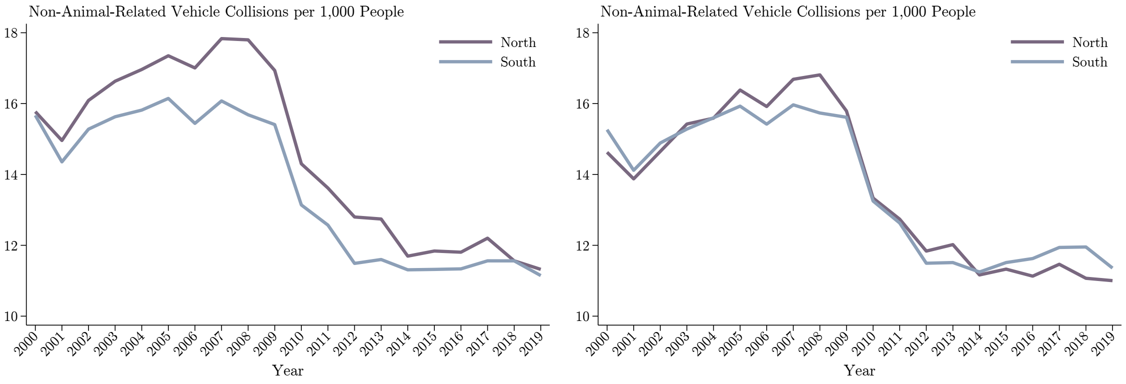
(a) All-Cause (b) All-Cause



(c) Animal-Related (d) Animal-Related



(e) Non-Animal-Related (f) Non-Animal-Related



Notes: Population-weighted mean vehicle collision rates, per 1,000 people, north or south of the Saint Lawrence River. The left column of figures includes all the municipalities in Quebec (n = 1,232), and the right column restricts the municipalities to 50 km from the river (n = 689).

A.2 Jackknife Estimation Results

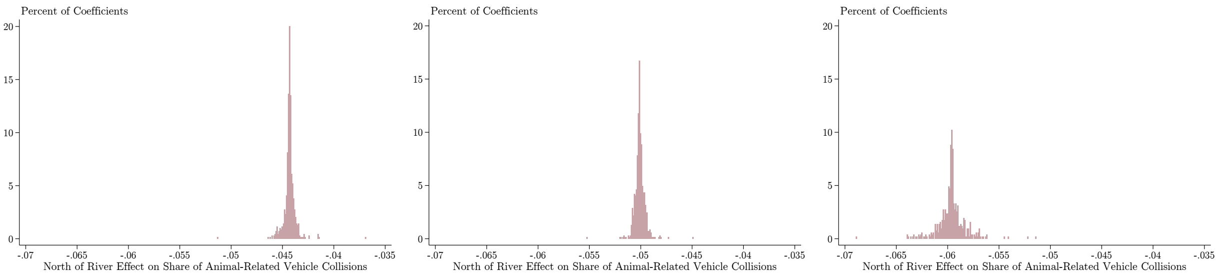
We run the estimation in Equation (1) while leaving one municipality out of the sample each time. In Figure A4, we report the distributions of the coefficients for the cases where we set the bandwidth at 50 km, allow the bandwidth to be chosen optimally, or use the optimal bandwidth when using the donut sample (i.e., that leaves out the municipalities whose centroid is less than 5 km away from the river). Overall, all the coefficients are narrowly distributed, have the same sign, and are of similar qualitative magnitude.

We make two adjustments to the jackknife procedure to avoid artificially inflating the jackknife results. One concern is that because in most cases, the optimally chosen bandwidth is below 50 km, any municipality we exclude that is more than 50 km away from the river would not change the estimation result—as that municipality would not get chosen by either the fixed 50 km bandwidth rule, or the optimal bandwidth procedure. The adjustment we make in this case is to skip the estimation if the chosen leave-one-out municipality is more than 50 km away from the river. We do this instead of restricting the sample to municipalities that are within 50 km as the optimal bandwidth procedure relies on variation from municipalities in the full sample. The other concern is that when excluding any municipalities that are less than 5 km from the river (the donut sample), any chosen leave-one-out municipality within that range will not change the estimation results. Similarly in this case, the adjustment we make is to skip the estimation if the chosen leave-one-out municipality is within 5 km to the river.

A.3 Examining Environmental & Demographic Variables Around the Saint Lawrence River

In the main text, we describe the collection of different observable characteristics (Section 3), how we standardize each of the 15 variables, and include them as controls in the estimation (Table 1), or plot how they change flexibly around the border of the river (Figure 3). Here we report detailed regression results for each of the 15 variables, which estimate whether

Figure A4: Jackknife Estimation Results



(a) BW=50 (b) Op. BW (c) Op. BW & 5 km Donut

Notes: Distribution of the RDD-jackknife estimation. See text for more details.

they change sharply at the river boundary, or whether they change the estimation results when included as a control variable.

In Table A1, we report a different variable in each column. We repeat the analysis in three variations. First, we use the full sample and allow the bandwidths (for estimation and bias correction) to be selected optimally (Panel A). Next, we set a fixed bandwidth of 50 km, for both estimation and bias correction (Panel B). Finally, we set the same fixed 50 km bandwidth, but also impose a Donut-RDD (D-RDD) approach where we exclude the municipalities that have a centroid distance below 5 km to the river (Panel C).

We fail to detect meaningful differences for most of the coefficients with exceptions in the cases of four variables: mean temperature (column 4), mean household size (column 9), median age (column 14), and population density (column 15). In all four cases, the optimally chosen bandwidth is below 10 km. When we set a fixed 50 km bandwidth (Panel B), the magnitude of all four differences becomes smaller. In the case of mean temperature, there is no longer a meaningful difference. However, the remaining three demographic variables still exhibit a potentially concerning magnitude with respect to the mean difference north versus south of the river. Those three differences shrink by about 75% when we exclude the municipalities closest to the river in the D-RDD sample (Panel C). In short, while three out of 15 variables exhibit potential differences once we allow for a sufficiently wide bandwidth, those differences get attenuated if we exclude the locations closest to the river. This analysis motivates why we report the D-RDD results in the main text. In Table 1, the results between the non-donut (columns 1 to 5) and the donut samples (columns 6 and 7) are nearly identical in terms of magnitude and precision.

In the main text, we include all 15 variables as controls (Table 1, columns 7, 9, and 10). Here we include each variable separately as a control to focus on which municipality characteristic has a larger influence on the estimated discontinuity. We repeat the process we detailed above for Table A1, only we set each characteristic as a control variable instead of the outcome variable. In Table A2, we report the results for the RDD estimation for the share of animal-related vehicle collisions. Across all panels and columns, the coefficients are always negative, and often within the range of a four to six percent drop in the share of animal-related vehicle collisions north relative to south of the river.

A.4 Displacing the True Saint Lawrence River Border

We perform a falsification test by displacing the river border south or north by varying distances (Ebenstein et al. 2017). In each iteration, we either move the river border north, or south, by the same distance. When displacing the river to the south, we effectively are switching some of the municipalities that are truly south of the river to be considered as north of the displaced river. In other words, we are moving control units (no wolf presence) into the treatment group (wolf presence). If we displace the river to the north, we are shifting municipalities that were north of the river (treatment) to be south of the displaced river (control). Displacement in either direction makes the mean share of AVCs more similar across the treatment and control units, and as a result, attenuates the results.

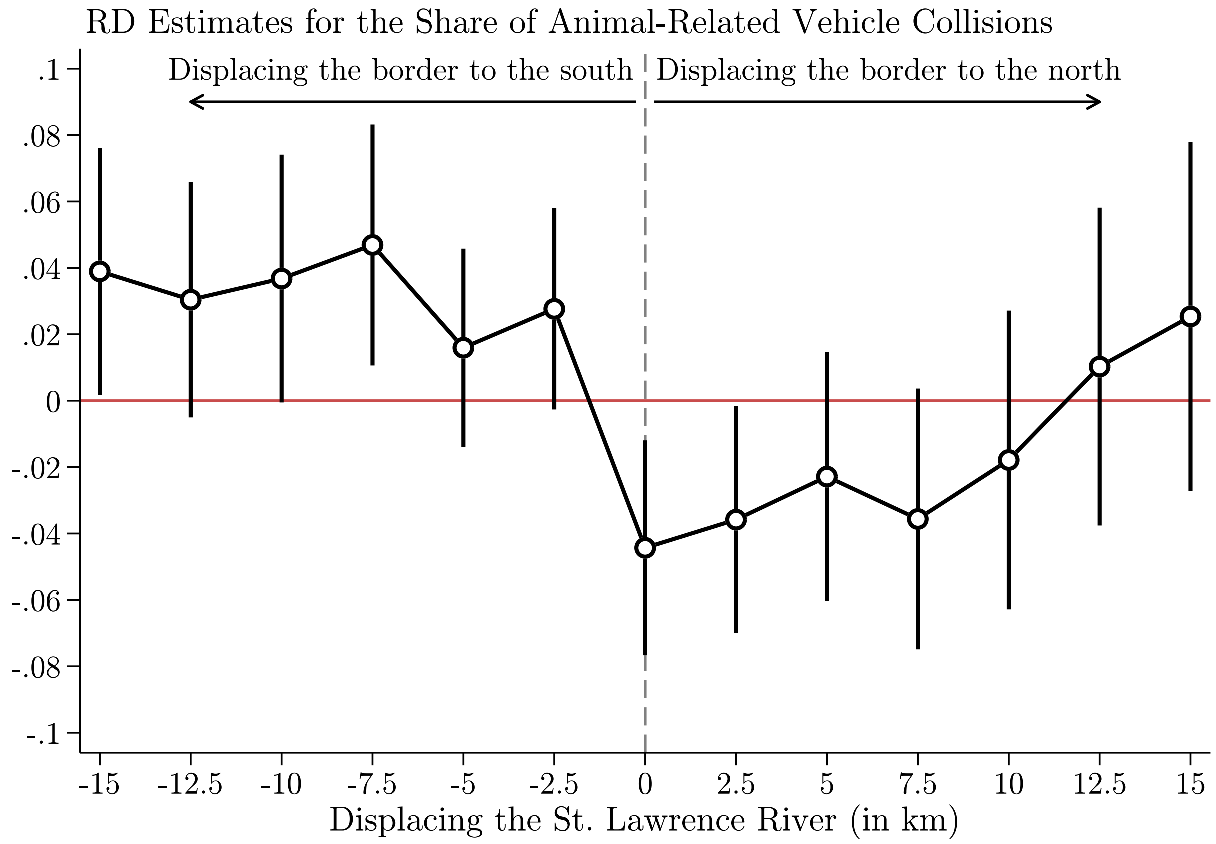
In Figure A5, we report that we only observe the discontinuous difference in the share of AVCs between north and south of the Saint Lawrence River when using the correct border. When we displace the river, the results attenuate, and as we continue to displace the river, the coefficient flips signs. This exercise helps to verify that the main coefficient we report for the discontinuous change in the share of AVCs is not a spurious effect that is estimated at arbitrary divisions of north and south.

The coefficient changes more sharply when we displace the river to the south than to the north (left relative to the right of the dashed line). Displacing the river south means that the right-hand local regression, estimated with a 50 km bandwidth, straddles the *true* river and therefore mixes high- and low-AVC observations. As a result, this contamination biases the fitted intercept downward and can reverse the sign even when the south-side slope is negative. This is because the share of AVCs is higher south of the river, and increases further away from the river, as can be seen in Figure 2, making it such that the difference at the displaced boundary is positive. Changes in the share of AVCs north of the river are more subtle, such that the estimated discontinuity at the displaced river shrinks and gets closer to zero with larger displacements.

A.5 Examining the Precision of the Results Using Alternative Clustering Schemes

In the main text, we cluster the standard errors at the unit of observation—the municipality. Here, we evaluate how the precision of the north dummy coefficient changes when we cluster at two alternative levels. The first change we make is clustering at a higher administrative region that nests the municipality: the regional county municipality. The 688 municipalities that are within 50 km are nested by 79 regional county municipalities. The second clustering alternative we evaluate is to cluster at the admin region by hunting zone level. Hunting zones allow us to capture geographical and environmental differences instead of only relying on administrative boundaries. However, because the number of hunting zones that are within 50 km of the river is low, we split a hunting zone if it extends over more than one administrative region. This provide a more granular level of clustering than using the hunting zones alone, but is still a coarse and very conservative level of clustering. For comparison, the 688 municipalities that are within 50 km of the river are nested by just 37 admin region by hunting zone areas.

Figure A5: Displacing the Saint Lawrence River



Notes: We displace the river in increments of 2.5 km either north or south of its true location. This shift municipalities that were previously treatment to be control units, and vice versa. For each such displacement, we estimate the specification in Equation (1) using a fixed bandwidth of 50 km. At zero displacement, we observe the coefficient we report in Table 1, Panel A, column 1. As we displace the river, the result attenuates, verifying that we only observe it at the true river boundary.

The alternative clustering levels help to assess whether clustering at the municipality level overestimates the precision of the coefficient for the north dummy because of the spatial correlation of the error term. In Table A3, we report the three different levels: the baseline one and the two alternatives. Precision remains largely unaffected by the changes to the level of clustering. This holds whether we set the bandwidth manually at 50 km (columns 1, 2, and 3), truncate the sample (columns 2, 5, and 7), exclude the municipalities that are close to the river (columns 3, 6, and 7), or use the optimally chosen bandwidth (columns 4, 6, and 7). In cases where we meaningfully see a decline in the precision of the coefficient, we can still reject the null hypothesis of no discontinuous change at the river border at the 10 percent significance level (columns 5 and 7), whereas the estimate becomes less precise than that in the case of the donut sample when we do not truncate the sample (columns 3 and 6).

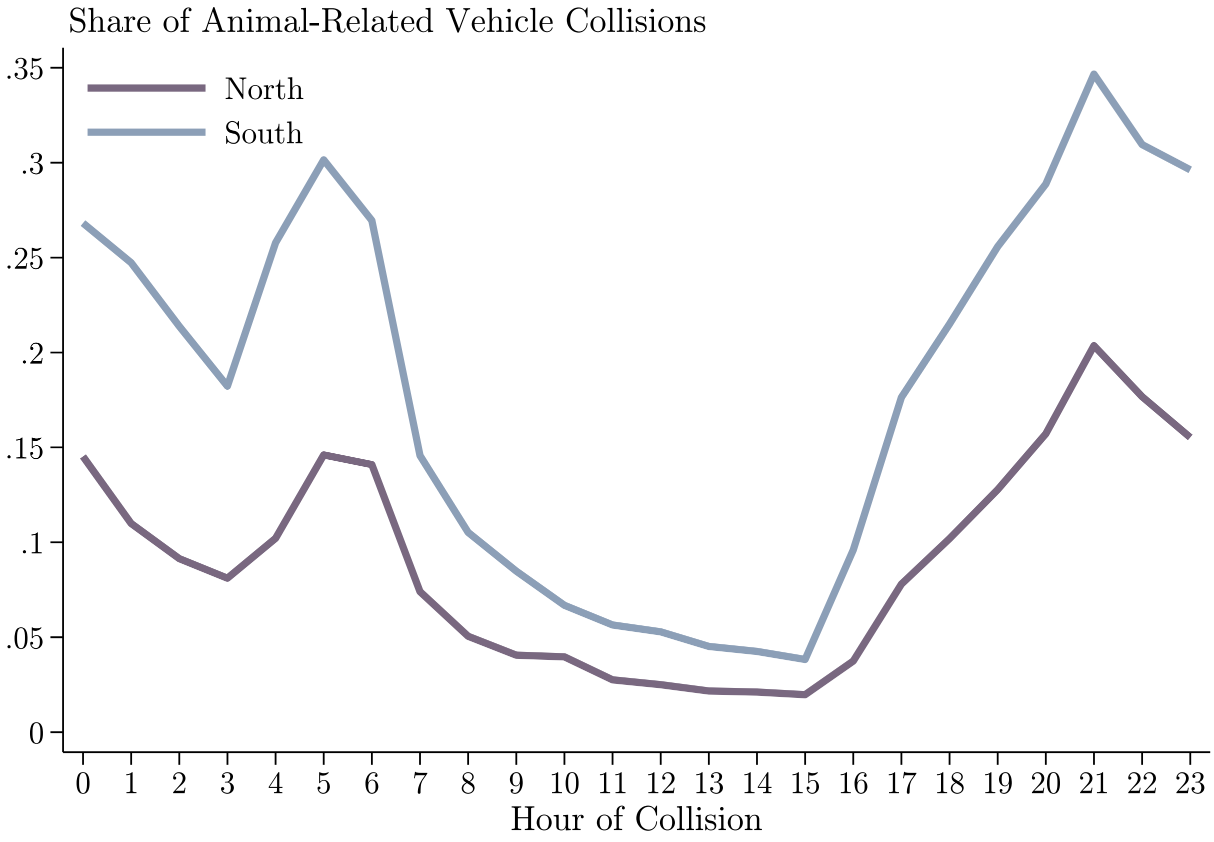
A.6 Examining Heterogeneity With Respect to Time of Day of Collisions

In the main text, we pool all vehicle collisions throughout all years, months, and hours of the day. Here we examine if there is meaningful heterogeneity, north versus south of the river, in when vehicle collisions happen relative to the time in the day. To do so, we re-aggregate our data in four-hour intervals. First, we estimate whether the share of all-cause collisions (collisions in a four-hour interval relative to all collisions) changes at the river border. This allow us to examine if there is suggestive evidence that drivers might be shifting the time they are on the road. For example, if drivers are adapting by driving less when it is dark, we would expect to see a lower share of total vehicle collisions. Second, we re-estimate our main outcome, the share of animal-related collisions (animal-related collisions relative to all-cause collisions in the same four-hour interval). This allows us to examine whether the presence of wolves north of the river lowers AVCs more so during some parts of the day than others. For example, if AVCs are more likely to happen when it is dark, we would expect to see a larger reduction north of the river in AVCs that happen in the evenings, nights, and early mornings.

Our analysis reveals meaningful heterogeneity in the reduction of AVCs, but not in the overall share of all-cause collisions. We summarize the results of these regressions in Table A4. In Panel A, we see small and noisy coefficients. We interpret this as a lack of strong evidence that drivers south of the river have adapted to the absence of wolves by driving at different times of the day. It is very likely that the decisions regarding when to drive are based on other, more pressing, schedule considerations. It is still possible that drivers south of the river are adapting by driving more slowly in certain hours, but we do not observe that in our data.

In Panel B, we find that the share of AVCs is lower north of the river throughout the different hourly bins, however, the effect is suggestively larger from midnight to morning, and from the late afternoon to the evening. While each coefficient is precisely estimated, our coefficients are not sufficiently precise to allow us to reject that they are equal. The findings in Panel B align with the more descriptive summary in Figure A6 of when and where the share of AVCs is higher.

Figure A6: Distribution of AVCs During the Day by Hour of Accident



Notes: We plot the mean share of animal-related vehicle collisions throughout the time of day, by the hour of the accident. We use the sample of municipalities that are within 50 km of the river.

A.7 Examining Differences in Vehicle Type & Weight

In addition to testing whether drivers potentially adapt by driving at different hours, we also test whether drivers choose different vehicle classes, north versus south of the river. We use data on the registered vehicles (Société de l'assurance automobile du Québec 2022), as of 2022, and calculate for each municipality the share of vehicles that are: (i) cars or light trucks, (ii) trucks or tractors, (iii) snowmobiles, (iv) special equipment vehicles, (v) or all terrain vehicles. These five categories account for 98.5 percent of the seven million vehicles in the data.

In Table A5, we report the estimation results for the RDD when using a bandwidth of 50 km around the river. The two categories for which we find a meaningful and precisely estimated difference are cars or light trucks, and special equipment vehicles. The share of cars or light trucks is 5.8 pp higher north of the river, relative to the south. At the same time, special equipment vehicles are 5.6 pp lower north of the river. Cars or light trucks are by far the most common category, accounting for 64 percent of all vehicles in the 50 km around the river, while special equipment vehicles are only 11 percent. We also estimate a negative coefficient for all-terrain vehicles, but it is imprecisely estimated.

Vehicles north of the river are lighter, on average, by 100 kg (column 6, imprecisely estimated), or by 6.1 percent (column 7, precisely estimated). This suggests that drivers north of the river are less concerned about the weight of their vehicle and the potential for collision, as previous research has documented that drivers attribute higher safety to heavier vehicles (Anderson and Auffhammer 2014). We interpret these results on vehicle types and weight as suggestive evidence that drivers have adapted to the absence of wolves south of the river by driving cars in larger categories, as well as driving heavier vehicles.

A.8 Wildlife Hunting Certificates Around the Saint Lawrence River

In the main text, we plot the distribution of the mean number of hunter's certificates per 100,000 people across municipalities north and south of the river (Figure 4a). Here, we report RDD estimation results using that variable as the outcome, as well as using it as a control when the share of AVCs is the outcome. We report the estimation results in Table A6. We do not find precisely estimated differences at the river border in the mean number of hunters' certificates per 100,000 people (columns 1 to 4). More importantly, when we include hunters' certificates as a control in the analysis of the share of animal collisions, we continue to recover meaningful and precisely estimated negative effects for the discontinuity coefficient (columns 5 to 9). To summarize, we fail to find that wildlife management, through the channel of wildlife hunters' certificates, effectively explains the difference in the share of animal collisions between municipalities north and south of the Saint Lawrence River.

A.9 Wildlife Harvest Densities Around the Saint Lawrence River

In the main text, we plot the kernel densities of comparing the hunting harvests between north and south of the river (Figure 4b). Here, we report how including the data on harvests affects the estimation results. To do so, we first match each municipality to a hunting zone based on the location of the municipality centroid. We assign to each municipality the hunting data of its linked hunting zone for the years 2000 to 2019 (so it matches the span of the vehicle collision data). Then, we collapse the data into a cross-sectional of means for the vehicle collision data, harvest densities, hunting certificates, and the 15 environmental, demographic, and infrastructure variables. In Table A7, we report results for the baseline sample (column 1), and how including additional controls affects the magnitude and precision of the estimates. If we include the mean number of all animals hunted per square kilometer or only the ungulate species, we find no difference in the estimated discontinuity in the share of AVCs (columns 2 and 3). Adding more controls in the form of the hunting certificates data, or the additional covariates, results in a precisely estimated drop in the share of AVCs of 0.06 or 0.03 percentage points (columns 4 and 5). Controlling for the harvest densities, the hunting certificates, the additional covariates, and setting the bandwidth to be 25 km instead of 50 km, results in a precisely estimated drop in the share of AVCs of 0.04 percentage points (column 6). If we allow the bandwidth to be chosen optimally, the decline in the share of AVCs north relative to just south of the river is precisely estimated to be 0.05 percentage points (column 7).

A.10 Details on the Monetized Damage Calculation

In the main text, we report that we estimate monetized prevented damages from the presence of wolves north of the river at 41.7 million 2024 CAD. Here we describe this calculation in more detail. First, to arrive at the number of 7.2 averted collision per municipality, we use the following conversion that relies comparing of the share of animal-related collisions without wolves versus with wolves (corresponding to β_1 in Equation 1): $\frac{A+X}{T+X} - \frac{A}{T} = 0.05$. Where we denote the number of animal collisions with wolves present as A, the number of total collisions with wolves present as T, and the additional collisions that *would have happened* if wolves were absent as X. Solving for X results in: $X = \frac{0.05T^2}{(0.95T-A)}$.

The most detailed, complete, and recent account of monetized estimates for vehicle collisions for the setting of Quebec, Canada comes from Transports Canada – Direction générale de l'analyse économique (2007). We use the following central estimates from the report (calculated for the year 2000) of 4,787,000 CAD for a crash with a fatality; 29,000 CAD for a crash with injuries only; and 6,500 CAD for a crash with PDO. We then use the estimates for the averted collisions (1,836 annually), and the share of collisions with injuries only or PDO, for the municipalities that are 50 km north of the river and arrive at the following value:

$$
\begin{aligned}
&0.903 \times 1,836 \times 6,500\$ + \\
&0.096 \times 1,836 \times 29,000\$ + \\
&(1 - 0.903 - 0.096) \times 1,836 \times 4,787,000\$ \\
&= 24,676,758\$
\end{aligned}
$$

We then convert the values from 2000 CAD to 41,720,997 2024 CAD.[8] We use the exchange rate of December 2024 to convert those into 29,033,641 2024 USD.[9] Similarly, if we focus on the averted damages that exclude the small fraction of crashes with fatalities, we obtain values of 15,887,826 2000 CAD, 26,861,549.08 2024 CAD, and 18,692,952 2024 USD.

To put this magnitude in context, we also show how it compares to expenditures on road infrastructure. While municipality level data on road budgets in Quebec are not available, we do know that, in the budget period of 2005 to 2006, Quebec spent 1.94 billion 2024 CAD on road infrastructure for the entire province.[10] If we take into account that, on average, Quebec's population north of the river within 50 km reflects 39.6 percent of the total population in the province, and public expenditure is proportional to the population share, then our full account of annual averted damages amounts to 5.4 percent of annual realized road infrastructure expenditures.

We also compare averted damages to planned expenditures. This is important because the provincial government of Quebec is planning an ambitious public infrastructure program, of which 31.3 billion 2024 CAD are allocated to road improvements over the 2022 to 2032 period.[11] Making the same population share adjustment as above, our estimated averted

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[8] We use the Bank of Canada inflation calculator: https://www.bankofcanada.ca/rates/related/inflation-calculator/. Accessed: September 25, 2025.

[9] Specifically, we use the exchange rate of December 23, 2024: 1 CAD = 0.6959 USD. Obtained from https://www.exchange-rates.org/exchange-rate-history/cad-usd-2024-12-23. Accessed September 25, 2025.

[10] See page 25 of: www.budget.finances.gouv.qc.ca. Accessed September 25, 2025.

[11] For more details, see https://www.caaquebec.com/en/news/news/article/a-look-at-the-2022-2023-provincial-budget-a-half-baked-budget-for-motorists. Accessed September 25, 2025.

damages reflect 3.7 percent of the annual projected road infrastructure expenditures.

To place this number in a broader context for North America, we extrapolate the back-of-the-envelope calculation to all of Canada and all of the United States. To do so, we use the total number of vehicle collisions, obtained from Pitel and Solomon (2013), and the total number of AVCs by severity in Canada in 2003, obtained from Canada Transport (2020). We apply the same approach to recover the increase in AVCs, assuming that the same effect persists throughout the country. For the United States, we use the estimated number of all vehicle collisions, obtained from Weiss et al. (2011), and the number of estimated AVCs for 2008, obtained from Huijser et al. (2008). To monetize the costs in a comparable manner in both settings, we use the severity-weighted value for the monetized cost of a vehicle collision in the United States of $9,078 (2024 USD), using the damage estimates in Huijser et al. (2008). For Canada, we calculate a similar severity-weighted value of $9,634 (2024 USD) using the monetized costs per severity category, and the proportion of accidents in each category.[12] We convert the number of averted AVCs in the United States and Canada, 564,274 and 128,682, to $5.12 and $1.24 billion in total or $15.1 and $30 in per capita terms, respectively. 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 AVC by $6.36 billion per year or a population-weighted $16.7 per person per year. 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.

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[12] This calculation implies two important and non-trivial assumptions: (i) that Canada and the United States have the same distribution of deer, elk, and moose crashes as a percent of AVCs; and (ii) that they also have the same distribution of injury types. In other words, the difference in values arises only from the differences in the estimates of the monetized costs.

Table A1.
Estimation Results for Standardized Covariates

Panel A. Results Using Optimally Chosen Bandwidths

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
N. D.	-0.12	-0.10	0.01	-0.68	0.08	0.03	-0.19	-0.09	1.77	0.21	-0.03	-0.36	0.08	-1.10	1.02
	(0.09)	(0.17)	(0.23)	(0.36)	(0.21)	(0.25)	(0.37)	(0.22)	(0.50)	(0.30)	(0.35)	(0.32)	(0.28)	(0.36)	(0.42)
$\overline{Y}$	-0.44	-0.20	-0.23	-0.01	-0.22	0.15	0.05	-0.03	0.04	0.13	-0.09	0.17	-0.35	0.09	0.16
BW	47.4	32.2	9.3	8.5	11.4	41.1	42.6	51.3	9.3	17.3	17.0	12.7	12.4	11.1	16.0

Panel B. Results Using a Fixed Bandwidth of 50 km

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
N. D.	0.00	-0.11	-0.03	-0.16	-0.01	0.01	-0.34	-0.12	1.09	0.39	-0.08	-0.09	0.11	-0.84	0.95
	(0.09)	(0.17)	(0.15)	(0.20)	(0.15)	(0.28)	(0.48)	(0.31)	(0.25)	(0.22)	(0.25)	(0.21)	(0.18)	(0.22)	(0.30)
$\overline{Y}$	-0.41	-0.11	0.00	-0.00	0.00	0.11	0.04	-0.03	-0.00	-0.00	0.00	-0.00	0.00	-0.00	-0.00

Panel C. Results Using a Fixed Bandwidth of 50 km & 5 km Donut

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
N. D.	0.00	-0.17	0.36	-0.46	0.15	-0.07	0.39	0.04	-0.04	0.62	-0.32	-0.09	0.33	-0.21	0.21
	(0.32)	(0.50)	(0.35)	(0.38)	(0.46)	(0.32)	(0.24)	(0.17)	(0.43)	(0.42)	(0.46)	(0.40)	(0.36)	(0.40)	(0.19)
$\overline{Y}$	-0.41	-0.11	0.00	-0.00	0.00	0.11	0.04	-0.03	-0.00	-0.00	0.00	-0.00	0.00	-0.00	-0.00

Notes: Estimation results using the specification in Equation (1). We report the robust coefficient following Calonico et al. (2014). Each outcome is a z-score of a different observable characteristic, or the mean of all the z-scores. We calculate the z-scores using the full sample, and report the mean of each outcome to help convey how different, if at all, the sample contained in the chosen bandwidth is from the full sample (the closer the mean is to zero, the smaller the difference is). In each column, we report the following: mean elevation (1); mean slope (2); share of forest land cover (3); mean temperature (4); mean precipitation (5); road density, length over area (6); mean traffic per road density (7); fiscal revenue per capita (8); mean household size (9); natural log of median income (10); share married (11); share with any university degree (12); sex-ratio (13); median age (14); and population density (15).

Table A2.
Estimation Results for Share of Animal-Related Collisions With Standardized Covariates

Panel A. Results Using Optimally Chosen Bandwidths

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
N. D.	-0.04	-0.04	-0.05	-0.07	-0.07	-0.04	-0.04	-0.04	-0.05	-0.06	-0.07	-0.07	-0.07	-0.05	-0.03
	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)
BW	39.8	40.5	13.4	11.1	11.5	35.9	37.5	40.7	12.2	12.0	10.8	11.3	10.5	12.8	14.1

Panel B. Results Using a Fixed Bandwidth of 50 km

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
N. D.	-0.04	-0.04	-0.05	-0.06	-0.06	-0.04	-0.05	-0.04	-0.04	-0.05	-0.05	-0.05	-0.06	-0.04	-0.03
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)

Panel C. Results Using a Fixed Bandwidth of 50 km & 5 km Donut

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
N. D.	-0.04	-0.04	-0.07	-0.06	-0.06	-0.04	-0.03	-0.04	-0.05	-0.04	-0.05	-0.05	-0.06	-0.04	-0.04
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)

Notes: Estimation results using the specification in Equation (1). We report the robust coefficient following Calonico et al. (2014). Each column is a regression of the same outcome, the share of animal-related collisions, while controlling for a different a z-score of a different observable characteristic. We calculate the z-scores using the full sample, In each column, we control for the following: mean elevation (1); mean slope (2); share of forest land cover (3); mean temperature (4); mean precipitation (5); road density, length over area (6); mean traffic per road density (7); fiscal revenue per capita (8); mean household size (9); natural log of median income (10); share married (11); share with any university degree (12); sex-ratio (13); median age (14); and population density (15).

Table A3.
Clustering Standard Errors at Different Administrative Levels

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
N. Dummy	-0.04	-0.04	-0.06	-0.05	-0.04	-0.06	-0.05
Clustering Level:							
Municipality	(0.02)	(0.01)	(0.03)	(0.01)	(0.01)	(0.03)	(0.02)
Regional County Municipality	(0.02)	(0.02)	(0.05)	(0.02)	(0.02)	(0.04)	(0.03)
Admin Region-Hunting Zone	(0.02)	(0.02)	(0.04)	(0.02)	(0.02)	(0.04)	(0.03)
Truncated		X			X		X
Donut			X			X	X
Op. BW				X	X	X	X
$\overline{Y}$	0.13	0.13	0.13	0.12	0.11	0.11	0.11
BW	50.0	50.0	50.0	37.4	29.4	26.4	31.2
$\text{Clusters}_{\text{M}}$ South	433	400	339	364	296	187	213
$\text{Clusters}_{\text{M}}$ North	255	253	170	228	208	119	126
$\text{Clusters}_{\text{RCM}}$ South	46	46	40	47	41	41	46
$\text{Clusters}_{\text{RCM}}$ North	33	33	30	33	30	30	32
$\text{Clusters}_{\text{ARHZ}}$ South	17	17	13	15	14	10	10
$\text{Clusters}_{\text{ARHZ}}$ North	20	20	17	18	18	15	15

Notes: Same as in Table 1, but we report how alternative clustering, at higher administrative levels, affects the precision of the coefficient. For comparison, we report the standard errors when clustering at the municipality (M) level, as we do in the main text. In addition, we cluster at a higher level of administrative boundary, the regional county municipality (RCM), or we cluster at the admin region by hunting zone (ARHZ) level.

Table A4.
Estimation Results for Hourly-Binned Collisions

	00:00-03:59	04:00-07:59	08:00-11:59	12:00-15:59	16:00-19:59	20:00-23:59
Panel A. Share of All-Cause Collisions in Hourly Bin						
	(1)	(2)	(3)	(4)	(5)	(6)
N. Dummy	0.002	0.000	-0.009	-0.009	0.012	0.004
	(0.007)	(0.011)	(0.012)	(0.012)	(0.010)	(0.009)
$\overline{Y}$						
N South	433	433	433	433	433	433
N North	255	255	255	255	255	255
Panel B. Share of Animal-Related Collisions in Hourly Bin						
	(1)	(2)	(3)	(4)	(5)	(6)
N. Dummy	-0.056	-0.086	-0.035	-0.019	-0.051	-0.081
	(0.024)	(0.026)	(0.009)	(0.007)	(0.018)	(0.027)
$\overline{Y}$						
N South	422	423	424	426	427	423
N North	251	252	253	252	254	253

Notes: Estimation results using the specification in Equation (1). We report the robust coefficient following Calonico et al. (2014). We use a 50 km bandwidth for all regressions. In Panel A, we report results for the outcome of the share of the mean all-cause collisions in the four-hour interval bin, relative to the mean total number of collisions in the municipality. In other words, the numerator is the mean number of all-cause collisions in the four-hour interval, and the denominator is the mean of the total number of all-cause collisions in the municipality. In Panel B, we report the results for the outcome of the mean number of animal-related collisions in the four-hour interval bin, relative to the mean number of all collisions in the municipality. In other words, the numerator is the mean number of animal-related collisions in the four-hour interval, and the denominator is the mean number of all-cause collisions in the same four-hour interval bin. Standard errors are clustered at the municipality level.

Table A5.
Estimation Results for Vehicle Types & Weight

	Share of Vehicle Type					Vehicle Weight	
	Car or Light Truck	Truck or Tractor	Snowmobile	Special Equipment	All Terrain	Levels (kg)	Logged
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
N. Dummy	0.058	0.003	0.012	-0.056	-0.015	-99.049	-0.061
	(0.022)	(0.005)	(0.009)	(0.009)	(0.010)	(69.164)	(0.030)
$\overline{Y}$	.64	.026	.066	.11	.13	1,932	7.5
N South	395	395	395	395	395	395	395
N North	231	231	231	231	231	231	231

Notes: Estimation results using the specification in Equation (1). We report the robust coefficient following Calonico et al. (2014). We use a 50 km bandwidth for all regressions. We report results for the outcome of the share of vehicle types, columns 1-5, and mean vehicle weight, in levels or in log points, columns 6 and 7. Standard errors are clustered at the municipality level.

Table A6.

Estimation Results for Hunting Certificates as the Outcome and as a Control Variable

	Hunting Certificates				Share of Animal Collisions				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
N. Dummy	66.44	11.85	42.44	14.91	-0.06	-0.07	-0.03	-0.08	-0.05
	(71.25)	(39.07)	(48.18)	(17.65)	(0.02)	(0.02)	(0.01)	(0.03)	(0.02)
Covs.		X		X			X		X
Pop. W.			X	X					
Hunting Certificates					X	X	X	X	X
Op. BW								X	X
$\overline{Y}$	474.62	474.62	474.62	474.62	0.13	0.11	0.13	0.09	0.10
BW	50.0	50.0	50.0	50.0	50.0	25.0	50.0	11.6	13.2
N South	390	368	390	368	390	253	368	154	152
N North	231	218	231	218	231	176	218	121	116

Notes: Estimation results using the specification in Equation (1). We report the robust coefficient following Calonico et al. (2014). Optimal bandwidths use the MSERD procedure with trinangular kernel. In columns 1 to 4, we report results when the outcome is the mean number of hunting certificates per 100,000 people. In columns 5 to 9, we report results for the share of animal collisions when controlling for the mean number of hunting certificates per 100,000 people. When including covariates, we include all 15 environmental, demographic, and municipality infrastructure variables. Population weights use the 2011 census data. Standard errors are clustered at the municipality level.

Table A7.
Estimation Results for Share of AVCs When Controlloing for
Hunting Certificates & Densities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
N. Dummy	-0.04	-0.04	-0.04	-0.06	-0.03	-0.04	-0.05
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)
Harvest Densities (All Species)		X		X	X	X	X
Hunting Densities (Ungulate Species)			X				
Hunting Certificates				X	X	X	X
Covariates					X	X	X
Op. BW							X
BW	50.00	50.00	50.00	50.00	50.00	25.00	13.56
N South	433	433	433	391	369	238	158
N North	255	255	255	234	221	168	119

Notes: Estimation results using the specification in Equation (1). We report the robust coefficient following Calonico et al. (2014). Optimal bandwidths use the MSERD procedure with trinangular kernel. When including covariates, we include all 15 environmental, demographic, and municipality infrastructure variables. Standard errors are clustered at the municipality level.

B Data Sources

B.1 Collisions Data

Collisions data are gathered by the Société de l'Assurance Automobile du Québec (SAAQ). We use the universe of vehicle collisions at the crash record level, 2000-19. It comprises all crashes *involving at least one authorized vehicle* that led to either physical injury or at least CAD 2,000 in property damage.[13] We classify accident codes 15, 35, 36, or 37 as animal-related vehicle collisions.

B.2 Data Sources for Observables

Population at the municipalité level in Québec are obtained from the Government of Québec's Ministère des Affaires municipales et de l'Habitation.[14] Census data is also obtained from the government of Canada, via R package 'cancensus' (von Bergmann et al. 2021); it provides further detail on gender, age, household makeup (size, share married), income, education.

Administrative boundaries at a 1/1,000,000 scale are obtained from the Base de données géographiques et administratives (spatial and administrative database), from the Ministère de l'Énergie et des Ressources naturelles of Québec.[15]

Elevation and slope are obtained and processed through the Google Earth Engine, from a digital elevation model (DEM) produced by NASA / USGS / JPL-Caltech (USGS/SRTMGL1_003, a global DEM at a ground resolution of resolution of 1 arc-second, i.e., about 30 m at the Equator, 20 m at 50° latitude (Farr et al. 2007; NASA 2015)).

Temperature and precipitation are obtained and processed through the Google Earth

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[13] This threshold has been stable since March 18, 2010, see donneesquebec.ca/recherche/dataset/rapports-d-accident. Accessed: May 30, 2025.

[14] https://donneesouvertes.affmunqc.net/, see https://www.donneesquebec.ca/recherche/dataset/repertoire-des-municipalites-du-quebec/ for more information.

[15] https://www.donneesquebec.ca/recherche/dataset/base-de-donnees-geographiques-et-administratives/

Engine from the ERA5 reanalysis data (Muñoz Sabater 2019).[16] Specifically total precipitation [m] and mean temperatures [K|°C] at the monthly level 2000-2019 are aggregated in space (ERA5 pixel size: 11132 m) and over time (averaged).

Forest cover is calculated by summing the forest pixels in each municipality (then converted into square kilometers) in the NALCMS Land Cover layer (Commission for Environmental Cooperation 2024) via Google Earth Engine,[17] and then dividing by municipality area.

Road and traffic densities ("débit de circulation") is taken from Quebec's Ministère des Transports et de la Mobilité Durable (2017).[18]

Fiscal revenue base ("richesse foncière uniformisée," RFU) by sector for the year 2021 is obtained from the Ministère des Affaires municipales et de l'Habitation of Québec (Ministère des Affaires Municipales et de l'Habitation 2017). It enables us to measure and compare the ability of municipalities to generate tax revenue (or assimilated); we focus on the total RFU, and RFU disaggregated at the sectoral level for agriculture, industry, and housing.[19]

B.3 Data Sources for Prey Density and Hunter's Certificates

Hunting and trapping statistics 1971-2024 are obtained from Ministère de l'Environnement (2025a) at the hunting zone and year level for big game (deer, elk, moose), wild turkey and black bear.

Game management zones (as defined by the *Règlement sur les zones de pêche et de chasse* (C-61.1, r. 34) and in the *Règlement sur la chasse* (C-61.1, r. 12)) are used to spatialize the statistics, and, importantly, assign them to one side of the river or the other, and determine whether they lie within 50 km of the river. The shapefiles were

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[16] ERA5-Land Monthly Aggregated - ECMWF Climate Reanalysis, https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR.

[17] Land Cover of North America at 30 meters, 2020, https://developers.google.com/earth-engine/datasets/catalog/USGS_NLCD_RELEASES_2020_REL_NALCMS.

[18] https://www.donneesquebec.ca/recherche/dataset/debit-de-circulation.

[19] Data set: https://donneesouvertes.affmunqc.net/rf/rfu-2021.csv, and metadata: https://www.donneesquebec.ca/recherche/dataset/richesse-fonciere-uniformisee/resource/81028389-ce08-47ed-907e-a95c81dae23f.

obtained by direct request to the Ministry of the Environment of Québec. The zones can be visualized at quebec.ca/tourisme-et-loisirs/activites-sportives-et-de-plein-air/chasse-sportive/cartes-zones.

Valid hunter's certificates (details at quebec.ca/tourisme-et-loisirs/activites-sportives-et-de-plein-air/chasse-sportive/permis-certificat/certificat-chasseur) 2000-2019 from Ministère de l'Environnement (2025b) at the municipality of residence and year level are obtained through Quebec's "Act respecting Access to documents held by public bodies and the Protection of personal information" (*Demande d'accès n° 2025-06-050*). We take the average over the period at the municipality level.

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