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Post-earthquake highway reconstruction: Impacts and mitigation opportunities for New Zealand pinniped population

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ABSTRACT

Knowledge of how roads impact wildlife populations is limited but required to inform management and mitigation. Prioritising sites for mitigation involves identifying the most at-risk areas and populations, particularly after substantial changes to roading infrastructure.

We identify hotspots for New Zealand fur seal (NZFS: *Arctocephalus forsteri*) incidents (live or dead NZFS) on State Highway 1 (SH1) around Kaikōura, on New Zealand's South Island, and analyse whether hotspot locations have persisted following earthquake-induced road reconstruction. We also assess spatial, environmental, and temporal influences of NZFS incidents.

Spatial records of incidents along SH1 were analysed to identify contemporary and former hotspots using Kernel Density Estimation Plus and a Poisson-based method. Spatial, temporal and environmental data were collected to assess these factors' effects on incident location and timing.

Between 2012 and 2022, an average of 59 incidents were recorded annually along 90 km of SH1. Ten significant hotspots accounted for 89% of incidents, along 2.75 km of road. Hotspot concentration shifted following road reconstruction. Incident numbers were significantly positively associated with traffic volumes and windspeed, and significantly negatively associated with temperature and rainfall. Autumn experienced significantly more incidents than any other season. Road-abutting NZFS breeding areas explained most of the spatial variation in incidents.

SH1 is a threat to Kaikōura's NZFS, with its effects changing following an earthquake impacting NZFS distribution, and associated highway reconstruction. Hotspot analysis and current road protections suggest the risks could be substantially reduced by barrier construction along short stretches of road. This type of assessment should continue as climate change raises sea levels and increases storm events globally. This analysis and mitigation approach could be used for any wildlife across numerous landscapes.

1. Introduction

Effectively managing wildlife populations involves understanding threats to their persistence at multiple spatial and temporal scales, from global risks such as climate change to localised stressors such as habitat loss.

1.1. Road ecology

Roads are one such stressor, and may impact wildlife in several ways, including mortality (Ramp and Ben-Ami 2006; Santos et al., 2018); reduced habitat quality (Huang et al., 2009; Koemle et al., 2018; Kunz et al., 2022) disrupted movement (Marsh et al., 2005; Northrup et al., 2012) and gene flow (Benson et al., 2016); and access provision to humans, which can facilitate deleterious interactions (Soofi et al., 2022).

Significant effort has been applied to understanding factors that contribute to wildlife-vehicle collision (WVC) hotspots (Bíl et al., 2019; Özcan et al., 2022; Rendall et al., 2021), and hot moments (Gonçalves et al., 2018; Schalk et al., 2019) – the latter referencing temporal and environmental factors associated with greater incidences of WVCs.

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Research has also assessed the efficacy of measures seeking to mitigate WVC occurrence (Denneboom et al., 2021; Kučas and Balčiauskas 2021).

Data for WVC studies come from sources including systematic surveys (Rendall et al., 2021; Wang et al., 2022), third party databases (Bíl et al., 2019), and call-out data for conservation bodies (Boren et al., 2008). Studies of small species typically require systematic surveys to ensure accuracy, but high detection rates for large mammals make non-systematic approaches comparable (Grilo et al., 2020). Regardless of methodology, the true proportion of a population involved in WVCs is likely to be underestimated, due to phenomena such as scavenging (Schwartz et al., 2018) and carcass decay (Hobday and Minstrell, 2008).

There have been few studies of roads' impacts on pinnipeds (seals and sea lions), with exceptions including Boren et al.'s (2008) study on Kaikōura's New Zealand fur seal (*Arctocephalus* forsteri; NZFS)[1], and a brief report describing vehicle collisions with northern elephant seals *(Mirounga angistirostris)* (Hatfield and Rathbun, 1999). Several ways that roads can impact wildlife, such as impeding dispersion, are unlikely to be relevant to most pinnipeds, which typically remain near to the ocean while ashore. As such, this study focuses on road mortality, as this is likely to be SH1's most immediate impact on Kaikōura's NZFS.

NZFS lack natural terrestrial predators in New Zealand (Lalas and Harcourt, 1995), but face threats when ashore including disease transmission (Boren, 2005), and illegal killings (Department of Conservation, 2022). The proximity of many of Kaikōura's NZFS to New Zealand's most significant road, State Highway 1 (SH1; Fig. 1), represents an additional threat to be considered in spatial management decisions (Boren et al., 2008).

1.2. Kaikōura's NZFS and State Highway 1

Between 1996 and 2005, an average of 12 NZFS incidents were recorded annually on SH1, 40% of which were roadkill mortalities (Boren et al., 2008). Pups accounted for 25% of NZFS incidents, and 61% of fatalities, however these figures increased through time.

New Zealand's NZFS population is growing as the species recolonises areas from which it was extirpated by hunting in the 18th and 19th centuries (Lalas and Bradshaw, 2001). Since Boren et al. (2008), Kaikōura's NZFS colonies have increased from an estimated ~600 pups produced at Ōhau Point in 2005 (Boren et al., 2006) to 2471 in 2015 (Gooday 2016). In addition, NZFS now breed both to the north and south of the locations described by Boren et al. (2008) (Hall et al. *unpublished data*) (Fig. 1).

SH1's physical infrastructure has also changed substantially since Boren et al. (2008) , largely due to reconstruction following a Mw 7.8 earthquake that struck the area in November 2016 (Aghababaei et al., 2020). The road was relocated away from the base of inland slopes and closer to the coast, atop newly created seawalls, and roadside barriers were altered from those described by Boren et al. (2008) (discussed below).

1.3. Study aims

We aimed to assess the current effects of SH1 on Kaikōura's NZFS, and to inform possible mitigation measures. This knowledge is not only important for the health of the NZFS population, but also for understanding the dangers posed to motorists.

We first examine the recent trends in NZFS road incidents on SH1, and subsequently undertake analysis to meet the following aims:

1. Where are the contemporary hotspots for NZFS accessing SH1?
2. Which factors contribute to the spatial variability in where NZFS currently access SH1?
3. Have hotspot locations changed over time?
4. Which factors contribute to the temporal variability in when NZFS access SH1?

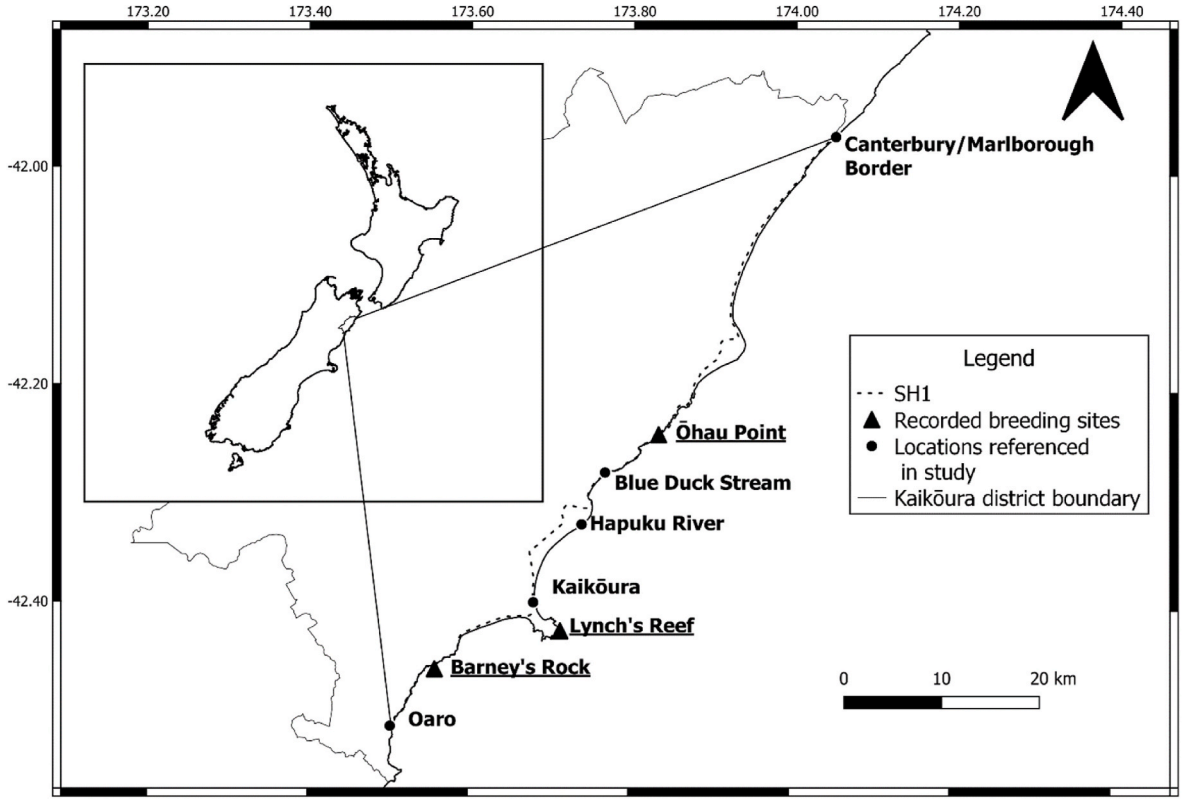

Fig. 1. Key locations in the study area, including the three previously recorded New Zealand fur seal breeding sites in the Kaikōura region: Ōhau Point, Lynch's Reef and Barney's Rock (Boren et al., 2008).

2. Materials and methods

2.1. Study site

This study focused on ~90 km of SH1 between Oaro and the north-eastern extent of the Canterbury region, where it borders the Marlborough region on the east coast of New Zealand's South Island (Fig. 1). SH1 is New Zealand's longest and most significant national highway, running the length of the country. In the Kaikōura region, it is a two-lane, bidirectional highway which, in many places, runs within metres of the coastline. The relevant portion of SH1 experiences an annual average daily traffic (AADT) volume of greater than 2500 vehicles, of which approximately 10% are heavy vehicles (gross vehicle mass of over 3.5 tonnes) (Aghababaei et al., 2020). The methodology is described in sections relating to the research aims in Section 1.3.

2.2. NZFS road incident data collection

Data on live or dead NZFS on SH1 ('NZFS incidents'), were collected by the New Zealand Transport Authority (NZTA). Since 2012, NZTA has been permitted by the New Zealand Department of Conservation (DOC) to both herd live NZFS off SH1 and dispose of NZFS carcasses on SH1. This is typically done in response to callouts, or while road maintenance is being undertaken. As such, it is unlikely that any NZFS incident reflects the time, and perhaps also the location, where the animal first entered the road. NZTA staff record each incident and produce annual reports. This study analyses data from May 2012–April 2022. There are, however, recording gaps, most notably between the November 2016 earthquake until June 2018, when data were collected by another body in a different format.

To spatially record NZFS incidents, NZTA uses a linear referencing system (Location Referencing Management System; 'LRMS'). When a NZFS incident occurs, the location is recorded using Mobile Road (current version 3.2.3, NZTA, Wellington) a smart device app.

2.3. Contemporary NZFS incident hotspot identification

Bíl et al.'s (2013, 2016, 2019) Kernel Density Estimation Plus (KDE+) method was used to identify NZFS incident hotspots. We used the KDE + software package (vers. 2.5, Transport Research Centre, Olomouc, Czechia) available for download as freeware (http://www.kdeplus.cz/en/download), which analyses between-intersection segments of road (Bíl et al., 2016; 2019). Two input CSV files were created; one containing the lengths of the between-intersection road segments, and the second the locations of NZFS incidents in each segment, given by their distance from the segment start point.

For the contemporary hotspot analysis, NZFS incident data were limited to January 2021–April 2022 to reflect the current state of SH1's infrastructure. Measurements of between intersection segment lengths and the position of incidents were conducted in QGIS (QGIS Development Team, 2022).

In the KDE + software, a kernel bandwidth of 150 units was chosen, and 'Accurate (GPS)' was selected under the software's 'Data Accuracy' options.

2.4. Current spatial drivers of NZFS incidents on SH1

SH1 was divided into 250-m segments (Rendall et al., 2021) to determine factors that may explain the spatial distribution of NZFS incidents. For each segment, a binary response variable was created indicating whether it contained at least one NZFS incident. Again, the NZFS incident data were limited to January 2021–April 2022.

Twenty-six road segments contained at least one NZFS incident, and, to permit modelling of spatial variables, 52 incident-free segments were randomly selected for comparison. To qualify for selection, an incident-free segment had to run within 100 m of a beach head (measured in QGIS) in at least one location, and not be in a residential area, to reduce any likelihood of selecting segments with multiple obstructions between the road and the coast. For each segment, a suite of variables was recorded for use in the models (Tables 1 and 2).

Roadrunner (Argonaut Ltd, Wellington) was used to determine the presence/absence of different road barrier types and sea walls, the percentage coverage of roadside vegetation, the relative position of the railway tracks and the distance to the nearest bend capable of visually obstructing a driver. Roadrunner is a dash-cam style video viewer used by NZTA, with an associated indication of location, based on the LRMS. Segment heights were recorded using BackCountry Navigator PRO v. 7.2.8, (CritterMap Software LLC, Washington), and were measured by AAH at segment mid-points. Road width measurements were taken in Mobile Road v. 3.2.3 (NZTA, Wellington), also at segment mid-points. QGIS was used to measure distance to the nearest culvert/stream and beach head from segment midpoints, while distance to the nearest bend was measured in RoadRunner, as this was deemed to provide a more accurate method of identifying the bend closest to a section midpoint which would obscure a driver's vision. All measurements were taken from section midpoints. Coastal substrates were determined using Google Earth®. The presence/absence of NZFS breeding sites was based on direct counts of pups in the 2021/22 breeding season. Ideally, slope would have been included as a variable in this analysis, however, collecting this data was deemed unsafe for researchers due to the risk posed by traffic, and so segment height was used instead (see supplementary material).

Pearson correlation coefficients tested for correlations among continuous explanatory variables and the response variable. Initially, this included continuous measurements of the lengths of different barrier types, which were later converted to categorical binary variables (Table 2).

Chi-squared tests were used to determine any statistically significant relationships between categorical variables.

Low to moderate associations existed between many of the explanatory variables and the response. These relationships were explored further using chi-squared tests and cross tabulated data between the categorical explanatory variables and the response. The test results indicated that one explanatory variable explained such a large majority of the spatial variation in NZFS incidents that a full logistic regression was not required. All statistical testing was conducted in R (R Core Team, 2022).

2.5. Hotspot persistence analysis

To assess 2012–2022 hotspot persistence, incidents were aggregated into kilometre segments (Lee et al., 2006) and their observed spatial distribution compared with the expectation from a random scenario, where the probability of incidents per segment should follow a Poisson distribution (Boots and Getis 1988).

Kilometre segments were used as, prior to 2019, this was the typical precision with which incidents were recorded. As the analysis requires equal-length segments (Malo et al., 2004), some stretches of SH1 were excluded where they did not constitute complete kilometres. Only one NZFS incident was omitted as a result.

This methodology (Lee et al., 2006; Malo et al., 2004) requires

Table 1
Continuous variables analysed in the assessments of the spatial drivers of New Zealand fur seal incidents.

Variable	Values
Road width	Metres
Distance to the nearest bend	Metres
Distance to the nearest stream/culvert	Metres
Road segment height	Metres
Distance to beach head	Metres

Table 2
Categorical variables analysed in the assessments of the spatial drivers of New Zealand fur seal incidents.

Variable	Values
Roadside vegetation coverage (within 5 m of road)	0–24%, 25–49%, 50–74%, 75–100%
Location of railway line relative to road	Coastal/inland
Road segment abuts known NZFS breeding area	Yes/no
Coastal substrate type	Sand or pebble beach/rocky shore
Non-barriered road	Present/absent
Single guard rail	Present/absent
Single guard rail combined with plastic mesh safety fencing (PMSF)	Present/absent
Motorcycle protection railing (MPR)	Present/absent
Agricultural fencing	Present/absent
Standalone PMSF	Present/absent
Sea wall	Present/absent

calculating the mean number of incidents per segment (λ), allowing the probability of a segment containing a given number of incidents (x) to be calculated as follows:

$$p(x) = \frac{\lambda^x}{(x!e^{\lambda})}$$

An α of 0.01 was selected (Lee et al., 2006), and separate analyses were conducted for each period. Although 2012, 2016; 2022 were not complete calendar years, because individual analyses were conducted per period, each segment always had an equal opportunity to accumulate incidents. Data for 2017 were not available, and 2018 was excluded as only four incidents were recorded. Data were also omitted where incident locations were illegible, or where precision was insufficient.

As the high number of zero incident segments resulted in a low threshold for significance, the analysis was repeated, including only segments containing at least one incident.

2.6. Temporal and environmental drivers of NZFS incidents on SH1

To model environmental and temporal drivers of NZFS incidents, daily values of traffic volume, wind speed (km/hour), precipitation (mm), average temperature (°C), tide height (m), and significant wave height (m) were obtained and averaged across the month from which they were recorded for use as model covariates. An additional season variable was created to determine whether season impacted NZFS incident numbers. All available NZFS incident records made since data collection restarted post-earthquake in June 2018 were analysed.

Traffic volume was extracted from NZTA's Traffic Monitoring System and originated from a telemetry site north of the Hapuku River (ID: 01S00144; Fig. 1). Wind speed, precipitation and temperature data were extracted from the National Institute of Water and Atmospheric Research (NIWA)'s CliFlo database (https://cliflo.niwa.co.nz/) and originated from a weather station on the Kaikōura Peninsula (no. 4506, name: Kaikōura Aws). Maximum daily tide height (metres above lowest astronomical tide) for each 24-h period in Kaikōura was extracted from NIWA's Tide Forecaster (https://niwa.co.nz/information-services/tide-forecaster). Significant wave height was extracted from the Historic Forecast of MAGICSEAWEED.com (https://magicseaweed.com/). A daily average significant wave height (the largest third of all waves) was derived from the mean of the eight three-hourly forecasts per day. Forecasts were taken from the Blue Duck Stream site (Fig. 1.).

Poisson regression models were used to identify environmental and temporal drivers of NZFS incidents on SH1.

Pearson correlation coefficients tested for correlations among continuous explanatory variables and the response variable, and ANOVAs investigated possible correlations between the season variable and the continuous variables. Variance inflation factor (VIF) tests were used to test for multicollinearity.

Due to the time series nature of the data, models with and without the season variable were compared to determine the impact on autocorrelation. Autocorrelation function plots and Durbin-Watson tests were used to determine whether autocorrelation was a concern in each model.

The substantial difference between the mean (4.4) and the variance (60.6) of the response variable suggests overdispersion. To determine whether this was problematic, a comparison of residual deviance and degrees of freedom, and a dispersion test on the fitted model were conducted. A residual deviance and degrees of freedom with a ratio around 1:1 is considered appropriately dispersed. If the ratio is larger, and the dispersion tests yield a significant p-value, a Quasi-Poisson model could be considered an appropriate alternative. Quasi-Poisson models were compared to the standard Poisson model to determine whether there was a considerable difference, however final model selection was based on the dispersion test.

Diagnostic plots assessed whether there was a linear relationship between the log value of the response and the explanatory variables.

3. Results

3.1. Overview

Between May 2012–April 2022, 393 dead and 57 live NZFS were recorded on SH1 within the study area in 307 NZTA records (Fig. 1; Table 3).

For years with data for all 12 months ('complete years'; 2013–2015 incl. and 2019–2021 incl.), an annual average of 49 (±9.2 s.d.) dead and 9 (±9.8 s.d.) live NZFS were recorded. The average number of NZFS incidents in complete years was 59 (±16.9 s.d.). The most NZFS were killed in 2020 (59) while the fewest NZFS (37) were killed in 2019. The number of NZFS killed on SH1 between January–April 2022 (36) was higher than all the previous years for which comparable data are available (n = 7).

For incidents with an associated indication of the individual's age cohort (n = 387), pups accounted for 83.7% of NZFS recorded on SH1. For mortalities with an associated indication of the individual's age cohort (n = 350), pups accounted for 87.8% of NZFS road mortality on SH1. In the final three complete years, pups accounted for an average of 95.7% of NZFS road mortality.

3.2. Contemporary NZFS incident hotspot identification

Forty-seven between-intersection segments of SH1 (labelled A through UU) were analysed, totalling 88.24 km. From the 91 NZFS incidents between January 2021–April 2022 (incl.), 10 significant clusters were identified, accounting for 89% of the analysed incidents (81/91).

Significant cluster sizes ranged from two incidents (n = 2, O1 and O3) to 35 (n = 1, TT1) (Fig. 2; Table 4). Cluster lengths ranged from 90 m (O3) to 1.74 km (TT1). The combined cluster length was 2.75 km,

Table 3
Interannual comparison of New Zealand fur seal (NZFS) incidents on State Highway 1, Kaikōura, New Zealand. * denotes complete years of data.

Year	No. of live NZFS on SH1	No. of dead NZFS on SH1	Total NZFS incidents	Pups as percentage of annual road mortality
2012	2	21	23	60%
2013*	3	40	43	97.1%
2014*	17	52	69	94.1%
2015*	25	58	83	58.6%
2016	0	34	34	84.4%
2018	1	3	4	100%
2019*	1	37	38	94.3%
2020*	6	59	65	96.6%
2021*	2	53	55	96.2%
2022	0	36	36	97.2%

Table 4
Statistically significant clusters of New Zealand fur seal incidents identified using Kernel Density Estimation Plus.

Road section ID	Cluster ID	No. incidents/cluster	Cluster strength	Cluster length (metres)	Incident density per 100 m of cluster	Segment strength
O	O1	2	0.125	100	2	0
O	O2	4	0.559	220	1.8	1
O	O3	2	0.125	90	2	0
O	O4	5	0.601	230	2.2	1
Q	Q1	11	0.671	460.62	2.4	1
TT	TT1	35	0.673	1073.81	3.3	1
TT	TT2	6	0.348	150	4	0
TT	TT3	7	0.434	193.73	3.6	0
TT	TT4	5	0.133	145.89	3.4	0

3.1% of the analysed portion of SH1. The strongest cluster was TT1 (cluster strength = 0.671, incident count = 35), and the weakest was TT5 (cluster strength = 0.108, incident count = 4).

The KDE + software provides a more stringent test called the segment test (Bíl et al., 2016). Four clusters met the threshold for the segment test: O2, O4, Q1 and TT1 (Fig. 2; Table 4).

3.3. Spatial drivers of NZFS incidents on SH1

Pearson correlation tests found several predictor variables showing low-moderate, statistically significant correlations. These included: distance to beach head and distance from nearest bend (Pearson correlation coefficient = 0.69, $p < 0.001$), distance to beach head and road width (Pearson correlation = −0.52, $p < 0.001$) road width and distance to nearest bend (Pearson correlation coefficient = - 0.4, $p < 0.001$), single guard rail and non-barriered road (Pearson correlation coefficient = - 0.763, $p < 0.001$), MPR and non-barriered road (Pearson correlation coefficient = - 0.388, $p < 0.001$), sea wall and non-barriered road (Pearson correlation coefficient = - 0.309, $p < 0.01$), sea wall and single guard rail (Pearson correlation coefficient = - 0.333, $p < 0.01$) and sea wall and agricultural fencing (Pearson correlation coefficient = 0.239, $p < 0.05$).

Chi-squared tests revealed statistically significant relationships between several categorical variables, including: known breeding area and single guard rail combined with PMSF (binary) ($x^2 = 5.567$, $p = 0.018$), known breeding area and MPR (binary) ($x^2 = 9.152$, $p = 0.002$), MPR railing and agricultural fencing ($x^2 = 4.537$, $p = 0.033$), agricultural fencing and sea wall ($x^2 = 10.954$, $p = 0.001$).

Additional chi-square tests of the binary variables and the response, and the cross-tabulated data indicated that known breeding area explained most of the variation in NZFS incidents. Cross-tabulation indicated that known breeding area correctly classified NZFS incidents in 74 out of 78 observations, and the chi-squared test between NZFS incidents and known breeding area was statistically significant ($x^2 = 57.123$, $p < 0.00001$). The significance of this chi-squared result is sufficient to represent the relationship between the two variables.

3.4. Hotspot persistence analysis

Both persistence analyses used data from 2012 to 2022, with 428 NZFS incidents available for analysis. Across the study period, 25 segments contained at least one NZFS incident.

The first persistence analysis returned 39 non-unique significant segments. The most persistent individual kilometre segment, 118.12, was significant in the eight analysed years between 2012 and 2021 (incl.), and contained the greatest number of incidents (78, 18.2% of the total), followed by 118.11, 163.06, 163.07 and 163.08 which were all significant in five of the analysed years (Table 5; Fig. 3). Of these, 163.06 contained the greatest number of incidents (64, 14.9% of the total). Of the significant segments from the period prior to the 2016 earthquake (May 2012–November 2016 incl.), 70% (14) were north of Kaikōura. By contrast, following the earthquake (January 2019–April 2022), 63.2% (12) were south of Kaikōura.

The second persistence assessment returned 25 non-unique significant segments. Segment 118.12 (Fig. 3) was the most persistently significant, meeting or surpassing the relevant threshold in six years (2012–2016 (incl.) and 2020) (Table 5). This was followed by 118.11 and 163.02, which were both significant in four of the analysed years, and then by 118.13 and 163.07, which were both significant in three of the analysed years (Table 5). Of the 14 non-unique significant segments prior to the 2016 earthquake, 92.9% (13) were north of Kaikōura. Of the 11 non-unique significant segments post-earthquake, 72.7% (8) were south of Kaikōura.

3.5. Temporal and environmental drivers of NZFS incidents on SH1

Pearson correlation tests found a moderate correlation between average traffic and average daily temperature (Pearson correlation coefficient = 0.655, $p < 0.001$), and a weak significant correlation between wind speed and rainfall (Pearson correlation coefficient = 0.431, $p < 0.01$). ANOVAs suggested temperature ($F = 58.540$, $p < 0.001$) and traffic volume ($F = 9.024$, $p < 0.001$) were significantly correlated with season.

Durbin-Watson tests for autocorrelation suggested that the model without the season variable showed evidence of autocorrelation. However, the addition of the season variable addressed this concern, with the autocorrelation plot and the Durbin-Watson test outputs within the desired thresholds.

None of the variables subjected to VIF tests showed concerning multicollinearity.

While the overdispersion test showed that the residual deviance (2.033) was more than two times greater than the degrees of freedom, this result was not statistically significant ($p = 0.06$). As $p = 0.06$ is close to the predetermined alpha, the impact of overdispersion has been evaluated. Fewer variables were significant in the Quasi-Poisson model compared to the standard Poisson model, meaning the dispersion parameter does influence the variables' standard errors. In the standard Poisson model, temperature, rainfall, wind speed, traffic and the season variables were significant, whereas in the Quasi-Poisson model only season variables were significant. While the dispersion test suggests that the standard Poisson model should be retained, those variables not significant in the Quasi-Poisson model should be interpreted with caution.

Overall, the diagnostic plots suggested only minor, non-concerning deviance from linearity.

The final log-linked Poisson model included all the original explanatory variables. Average temperature, rainfall, wind speed, traffic and season were all significantly associated with NZFS incidents. A one degree increase in average temperature was associated with a decrease in the number of NZFS incidents by a factor of 0.79 (21.4%). A one mm increase in average rain was associated with a decrease in the number of NZFS incidents by a factor of 0.82 (18.3%). A one unit increase in average wind speed was associated with an increase in the number of NZFS incidents by a factor of 1.15 (14.7%). A one unit increase in average traffic was associated with an increase in the number of NZFS incidents by a factor of 1 (0.04%). When the season is spring, summer or

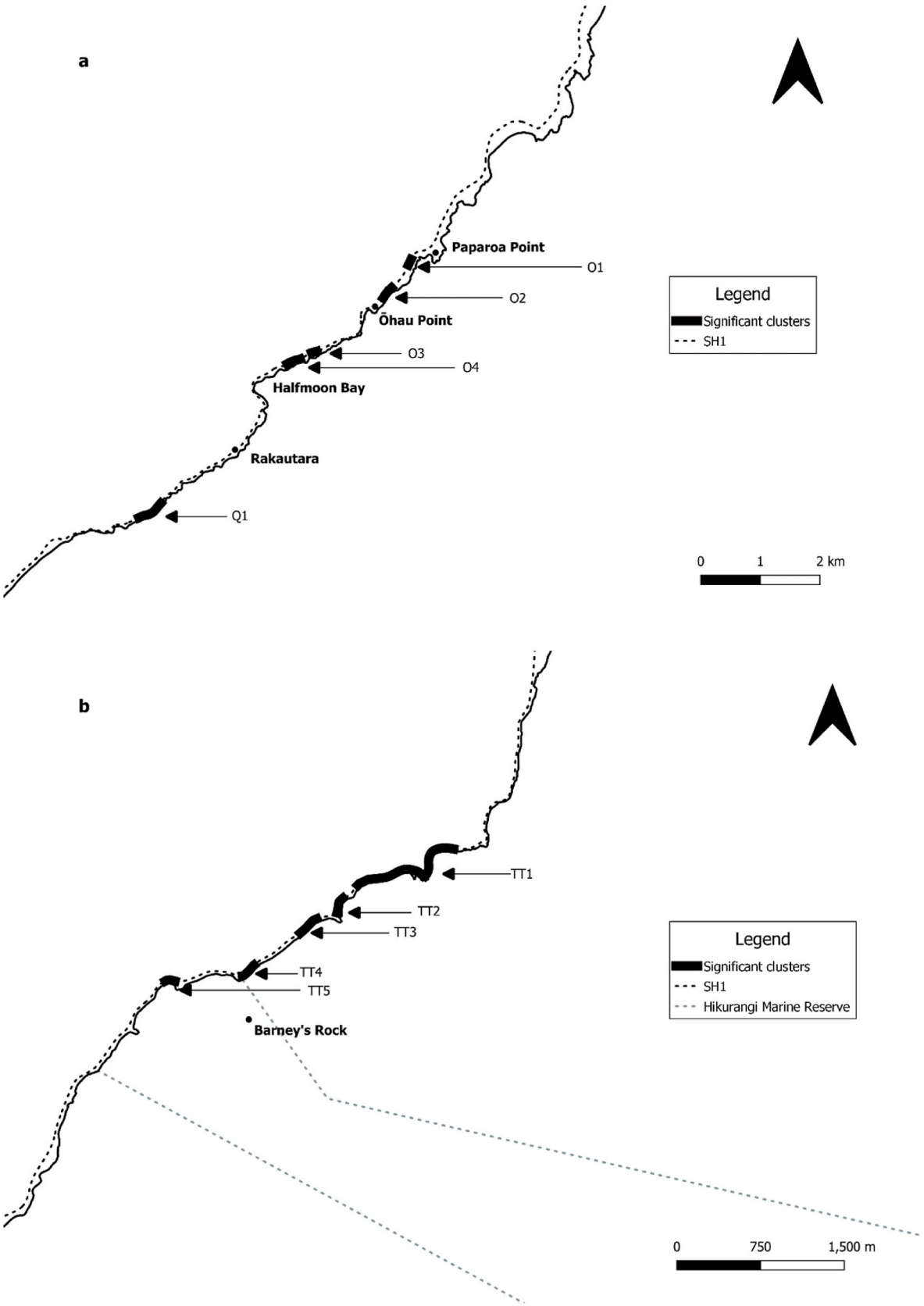

Fig. 2. Locations of significant clusters of New Zealand fur seal road incidents a). North of Kaikōura and b). South of Kaikōura, New Zealand.

Table 5
New Zealand fur seal incidents recorded in different kilometre sections of State Highway 1 through time. * Denotes values that were significant in the respective year in the analysis involving all 86 sections, ** denotes values that were significant in the respective year in the second persistence analysis (involving only the 25 sections with at least one incident).

Section	Year									
	2012	2013	2014	2015	2016	2018	2019	2020	2021	2022
90.07	0	0	0	0	0	0	0	0	1	0
118.06	0	0	0	1	0	0	0	0	0	0
118.07	0	0	0	1	0	0	0	0	0	0
118.08	0	0	0	0	1	0	0	0	0	0
118.09	2	0	0	0	0	0	0	0	0	0
118.10	1	0	0	0	0	0	0	0	0	0
118.11	5**	1	2	14**	11**	0	4*	10**	1	2
118.12	6**	7**	15**	14**	15**	0	4*	11**	4*	2
118.13	2	10**	19**	11**	1	0	1	0	2	0
118.14	2	10**	13**	7*	0	1	0	0	5*	0
118.15	1	0	1	1	0	0	0	0	0	0
118.16	0	1	1	0	0	0	0	0	0	0
118.17	0	0	0	1	0	0	0	1	0	2
118.18	0	1	1	3	2	0	0	1	3	7**
118.19	0	0	0	2	0	0	0	0	0	0
163.05	0	0	0	2	1	1	0	3	0	0
163.06	0	1	0	4*	0	0	10**	17**	18**	14**
163.07	0	3	3	4*	0	0	7**	15**	12**	4*
163.08	2	6**	6*	4*	0	1	9**	3	3	4*
163.09	0	0	0	0	0	0	2	4*	4*	1
163.10	0	0	0	0	0	0	0	0	1	0
163.11	0	0	0	4*	0	0	0	0	1	0
163.12	1	2	1	0	0	1	0	0	0	0
163.13	0	1	0	0	0	0	0	0	0	0
163.15	1	0	2	1	0	0	0	0	0	0

winter compared to autumn, there was an expected decrease in NZFS incident by 0.02 (98.1%), 0.068 (93.2%) and 0.034 (96.6%).

4. Discussion

Our results show that roads can threaten pinnipeds, despite their reduced terrestrial dispersion relative to species typically studied in road ecology.

Between 2012 and 2022, annual average NZFS incidents (59 ± 16.9) were almost five times greater than between 1996 and 2005 (12) Boren et al., (2008); Importantly, 2012–2022 incident numbers would likely have been higher still without the effects of the 2016 earthquake and New Zealand's COVID-19 lockdowns. Post-earthquake, it took ca. 17 months for SH1 to reopen in both directions for travel at all hours (Blake et al., 2019), with additional reductions to vehicle flow stemming from traffic slowing measures implemented during the rebuild. Similarly, the longest COVID-19 lockdown affecting the study area saw average daily traffic counts fall by 78.9% between March–April 2020. As tourism recovers post-pandemic, threats to both the NZFS population and motorists will likely increase and need regular assessment. Further, there are economic and societal considerations to this phenomenon, as Kaikōura's economy is heavily reliant on marine mammal tourism (Curtin, 2003), creating additional impetus for implementing effective mitigation.

The best explanation for the observed increase in NZFS incidents on SH1 is growth of the local NZFS colonies. Between 2005 and 2015, estimated pup production at Ōhau Point increased from ~600 (Boren et al., 2006) to 2471 (Gooday 2016). A 2023 assessment suggests that current pup production is similar to that calculated by Gooday (2016), albeit within a different distribution (Hall et al. *unpublished data*). Also, NZFS now breed in additional locations both north and south of the colonies described by Boren et al. (2008) (Fig. 1) (Hall et al. *unpublished data*). Increased average daily traffic volumes, from 2300 (Boren et al., 2008), to 2500 (Aghababaei et al., 2020) have likely also contributed, however this increase is small in comparison to the growth in NZFS pup production. Increased road mortality, or, in this case, incidents, due to increased population density has been shown in several species (Frangini et al., 2022; Kazemi et al., 2016; Rolandsen et al., 2011), and the combination of pups' predominance in road incidents, together with the importance of breeding sites in predicting incident locations, supports this explanation. In places where pinniped populations are expanding in proximity to anthropogenic centres and infrastructure, such as South America (Sepúlveda et al., 2021), managers need to be particularly aware of the risks posed by roads, and how these risks can change as the population changes. In New Zealand, the New Zealand sea lion (NZSL; *Phocarctos hookeri*), an endangered pinniped species also recolonising the country's mainland, may be at particular risk from roads. NZSL can venture up to 1.5 km in land during breeding (Augé et al., 2012), and an adult female and juvenile have already been killed on roads in recent years (Chilvers, pers. comm.). If that species' mainland population continues growing, their interactions with roads should also be closely monitored.

Pups' representation in road mortality increased from the average of 61% recorded between 1996 and 2005 (Boren et al., 2008) to 89.5% for complete years between 2012 and 2022. Notably, Boren et al. (2008) observed that pups' representation in road mortality increased annually through their study, mirroring growth at the Ōhau Point colony, and reaching 83% in 2005. While we did not find a steady increase in pup road mortality, the average is reduced by an anomalously low value in 2015 (58.6%), and, in the final three complete years (2019–2021), pups comprised 95.7% of overall road mortality. The age breakdown of animals involved in WVCs is likely species or population specific (Borda-de-Água et al., 2014; Garrah et al., 2015; Lodé, 2000), however, over-representation of younger age cohorts has been previously observed in a range of species (Borda-de-Água et al., 2014; Drews, 1995; Vyas and Vasava, 2019). Potential explanations for this include these individuals' reduced understanding of the dangers of roads (Seiler, 2003) and possession of only partially developed sensory and motor functions for judging vehicle speeds and avoiding collisions (Baker et al., 2007). For NZFS, pups largely remain on land between birth and weaning (ca. nine months, Berkson and DeMaster 1985), and are mostly provisioned by their mothers (Harcourt et al., 2002). In road-adjacent colonies, therefore, pups spend more time proximate to roading when compared with weaned individuals, who forage at sea (Costa and Trillmich, 1988). This factor, combined with pups' predisposition to

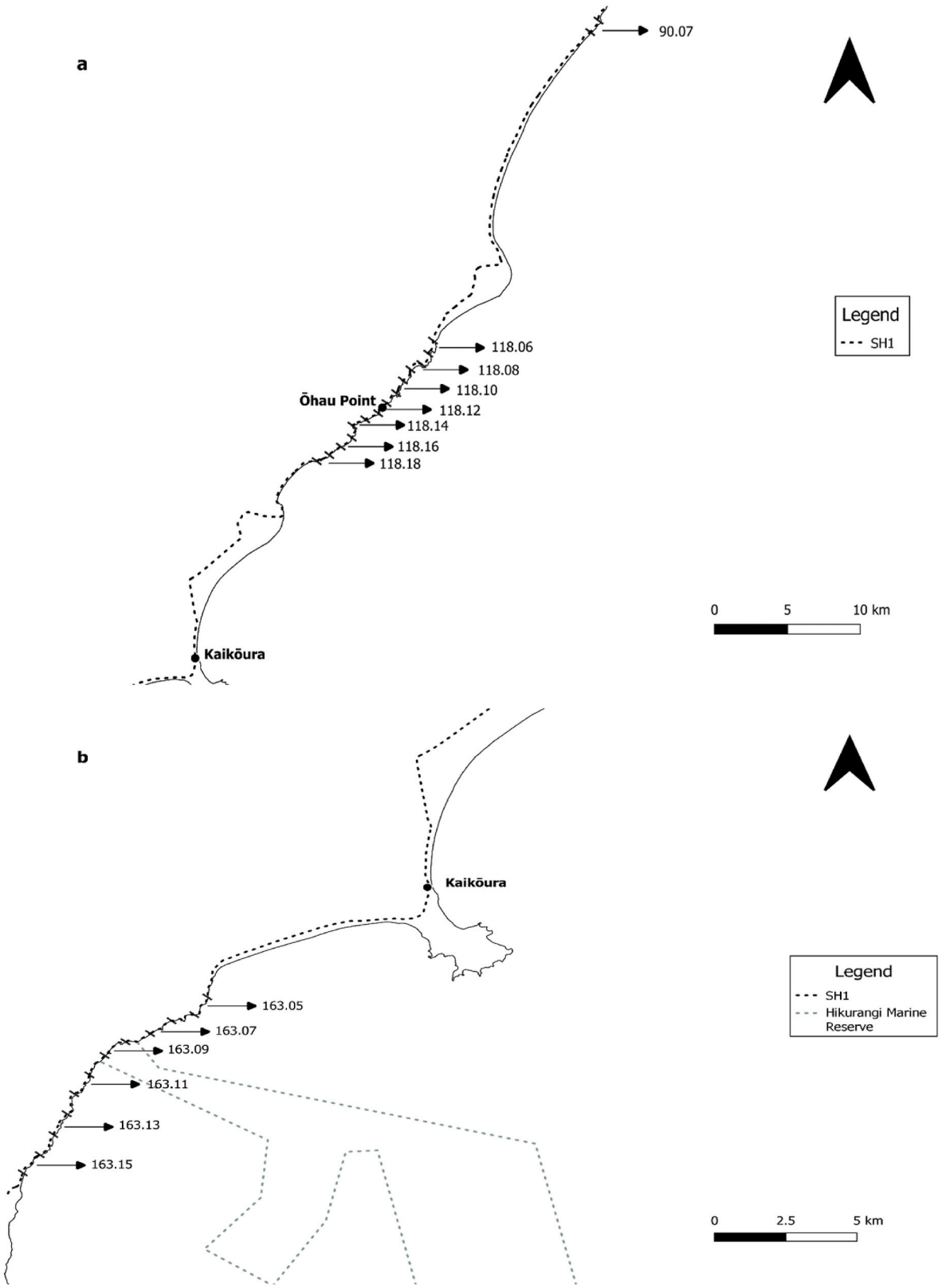

Fig. 3. Kilometre segments containing at least one New Zealand fur seal incident, a). North of Kaikōura and b). South of Kaikōura, New Zealand. For contiguous sections, every other section is labelled.

exploring novel environments (Gooday 2016), their slower movement (pers. obs.) and the relative novelty of vehicles, may make them more likely to enter a road and less able to avoid vehicles. Some road barriers may also be less effective at excluding pups (see below).

From 2019 (when spatial recording accuracy improved), it was notable that, of the 40 records in which more than one NZFS was recorded in the same location at the same time by NZTA staff, 39 of these records were of pups, all of which had been killed. The unknown lag

between death and recording means it is uncertain whether these pups were killed at the same time, however, this could indicate that pups access SH1 in the unstable pods they are known to form when their mothers are at sea (Crawley and Wilson 1976).

The overrepresentation of pups in NZFS incidents demonstrates the importance of going beyond quantifying road incidents, as effective mitigation may depend on understandings of biology and behaviour at different ontogenetic stages (Huijser and Begley, 2022). When considering pinnipeds, this result also suggests that proximity to roads may be more problematic for otariids than phocids. Phocids typically have far shorter weaning periods than otariids (Costa and Trillmich, 1988) and, as such, even if born near a road, phocid pups would have less opportunity to access it. That said, WVCs involving northern elephant seals (*Mirounga angustirostris*) (Hatfield and Rathbun, 1999) demonstrate that road-related risks are still germane to phocids.

Several environmental and temporal variables were associated with changes in the numbers of NZFS incidents. Understanding these drivers can enable temporary mitigation measures to be implemented during periods of heightened risk if permanent solutions are precluded. Increased average wind speeds and traffic volumes were associated with increases in NZFS incidents. The relationship with increasing traffic volumes has been demonstrated in similar studies (Jasińska et al., 2019; Rendall et al., 2021), raising the prospect that, without mitigation, the local problem may become worse as tourism recovers post-pandemic. Further, while this study focused on pinniped colonies near an anthropogenic centre, expanding global road networks, combined with pinniped eco-tourism (Granquist and Sigurjonsdottir 2014), could mean geographically isolated colonies come under greater threat.

Relationships between wind speed and WVCs are less well-established, particularly with regards to mammals. Perhaps unsurprisingly, wind speed has been shown to influence WVC mortality rates in birds, driving both increases (Erritzoe et al., 2003) and decreases (Soares and Dias 2020) in mortality rates among different species. Increased wind speeds have been positively associated with the numbers of Australian fur seals (*Arctocephalus pusillus doriferus*) ashore (Garlepp et al., 2014), and NZFS move inland during storms (Mcnab and Crawley, 1975). As such, stronger winds could cause NZFS near SH1 to access the road to escape deteriorating oceanic and coastal conditions. Conversely, increased average temperature and rainfall were associated with declining NZFS incidents numbers. Road-related responses to temperature and rainfall are likely species specific (D'Amico et al., 2015; Nelli et al., 2018; Raymond et al., 2021), and in NZFS, these relationships are likely based on finding shelter. Young pups are particularly vulnerable to extreme heat (De Villiers and Roux, 1992), and lack water repellent fur (Erdsack et al., 2013), and so would likely avoid exposed road surfaces during periods of high temperatures or heavy/prolonged rain.

Of the environmental and temporal variables, season had the greatest effect on incidents, and was the sole significant variable returned by the Quasi-Poisson model. Autumn (March–May) had significantly more NZFS incidents than any other season, and, given pups' predominance in NZFS incidents, the most likely explanation for this is pup ontogeny. During summer, once born, pups are initially relatively immobile (Crawley and Wilson, 1976), however, by the start of autumn, they are three to four months old and more mobile and inquisitive (Gooday 2016). They are also left onshore by their mothers for more extended periods, therefore suckling less frequently (5–7 days, Crawley and Wilson 1976). Combined, these factors are the likely reasons why autumn is particularly dangerous for pups born in road-adjacent colonies. By winter, pups are preparing for weaning (Baylis et al., 2005), and thus spend more time learning to hunt at sea for themselves, and by spring they are weaned and no longer at the colony (Stirling 1971). While our strongest mitigation recommendations involve constructing permanent barriers on SH1, these results indicate that temporary barriers at hotspots in autumn, or during high winds or times of increased traffic volumes, could represent effective alternatives. Given that many coastal and some marine species (such as sea turtles) exhibit high seasonal variation in when they are ashore (Higham 1998; Schunk et al., 2022; Sella et al., 2023), seasonal analyses should be prioritised for understanding the risks posed by roads to these species.

The contemporary hotspot analysis identified significant clusters both north and south of Kaikōura. Notably, there were no significant clusters within the boundaries of the pre-earthquake Ōhau Point colony, which previously contained the region's densest aggregation of NZFS (Boren et al., 2006). From our results, effectively mitigating just 2.75 km of the 90 km of SH1 in this region could prevent almost 90% of NZFS incidents.

The KDE + method, like other kernel density estimation-based methods (Anderson, 2009; Xie and Yan 2008) permits more precise location of clusters than traditional methods involving Poisson or negative binomial approaches (e.g., Malo et al., 2004; Lee et al., 2006) (Bíl et al., 2019). The latter involve aggregating incidents into arbitrarily defined road segments, and thus can only define those segments as significant or not. Additionally, methods involving arbitrary segmentation could inadvertently separate incidents within a cluster. By contrast, the KDE + method uses the locations of incidents to define the starts and ends of significant clusters. Further, the KDE + method's capacity to rank significant clusters by strength enables the prioritisation of the most important sites for mitigation. This is particularly beneficial when assessing large mammal WVCs, as effective mitigation is often costly (Rytwinski et al., 2016). The method's targeting capabilities are taken a step further with the more stringent 'segment test', which is applied to each road segment in its entirety, rather than to every location on the road. This can reduce false alarm rates when identifying the most concerning locations. The four segments identified by the segment test here accounted for only 1.95 km of SH1 and contained 60.4% of the NZFS incidents. While we strongly recommend permanent mitigation measures be implemented at all the significant sites highlighted in Fig. 2, if resources were limited, the sections that met the threshold of the segment test should be the priority.

The presence of an abutting breeding area was by far the most important driver of the spatial variation in NZFS incidents, correctly classifying 74 out of 78 observations. Breeding sites contain the greatest year-round NZFS density, and increased population density has been associated with increased WVC rates in several species (Rolandsen et al., 2011; Kazemi et al., 2016). Additionally, NZFS pups (the predominant age group in road incidents) typically remain in the vicinity of their birth site until they wean (Crawley and Wilson 1976). The importance of breeding sites in predicting incident locations has wider implications when targeting road incident mitigation for fur seals. While substantial numbers of adult and sub-adult males haul out away from rookeries outside the breeding season (Crawley and Wilson 1976), including at road-adjacent sites along the Kaikōura coast (pers obs.), such sites are less problematic than rookeries. However, as adult haul-out sites can develop into breeding areas as part of the fur seal recolonization process (Dix, 1993; Ryan et al., 1997) monitoring of road incidents near haul out areas remains important.

The hotspot persistence analyses demonstrated clear shifts in the epicentre of significant kilometre sections over time, from the north to the south of the study area. The increasing prevalence of incidents south of Kaikōura correlates with population growth in this area. Pre-earthquake, there were no published records of mainland NZFS breeding south of Kaikōura within the study area (Boren et al., 2006), whereas a 2023 assessment identified multiple breeding sites along this coastline (Hall et al., *unpublished data*). However, pup production remains higher in the north coast colonies (Hall et al., *unpublished data*), and, given the links between population density and WVCs (Frangini et al., 2022; Kazemi et al., 2016; Rolandsen et al., 2011), it would be expected that this area would remain the epicentre of local NZFS incidents, in the absence of other factors.

The most significant changes to SH1's infrastructure since the earthquake took place north of Kaikōura. This included adding 2.5 km of non-contiguous sea wall, most of which is around Ōhau Point, the largest

NZFS colony, and stands between 8 and 10 m above sea level. Segments now containing sea wall, such as 118.12 and 118.13, have shown decreases in overall NZFS incident numbers since this barrier's construction in 2018 (Table 5). By using historic RoadRunner videos, it is also possible to approximate the timing of modifications to other road barriers and compare this to trends in NZFS incidents. For example, in segments such as 118.11 (Fig. 3), motorcycle protection rail (MPR – double guard rail) implementation coincided with substantial decreases to NZFS incidents. By contrast, in south coast segments, such as 163.06 (Fig. 3), large increases in NZFS incidents have occurred concomitantly with the erection of single guard rail and plastic mesh safety fence (PMSF), suggesting that these barriers do not effectively exclude NZFS.

Our results, therefore, support evidence that changes to roading infrastructure can modify its impacts on proximate wildlife (Ciocheti et al., 2017; Secco et al., 2022). Such impacts appear to be variable, largely due to differences in species behaviour and habitat preferences (Ciocheti et al., 2017). Generally, post-earthquake modifications to SH1 appear to have reduced NZFS incidents in previous hotspots north of Kaikōura. However, the road is now closer to the coast, which has reduced the depth of some NZFS colonies (pers. obs.), underlining the complex range of effects that must be considered when planning and implementing a wildlife-adjacent infrastructure project.

These results also demonstrate why species' behaviour and biology must be considered when selecting exclusion barriers (Woltz et al., 2008). Given the small size of NZFS pups, which are over-represented in NZFS incidents on SH1, it is unlikely that a barrier like single guard rail, where the lowest edge of the railing stands more than 40 cm above the road surface, would effectively exclude them. The most effective barrier for excluding NZFS pups would, therefore, likely be one that reaches the road surface. Such measures have been effective in preventing road access in other species with short limbs and a limited agility, such as turtles (Woltz et al., 2008). Barriers fitting this description currently exist on the Kaikōura coast and experience varying success. For example, MPR appears to have reduced the number of incidents in parts of 118.11 compared with the previous barrier in place in this section – metal wire fencing that did not reach the road surface. Contrastingly, PMSF in 163.06 and 163.07 appears ineffective, as incident numbers there have increased dramatically despite this barrier being extended. This is likely due to a combination of poor maintenance, (pers. obs.), and fence-end effects (Huijser et al., 2016; Kim et al., 2021). For example, in 163.06, the two PMSF sections do not stretch the entire length of their nearest breeding areas, so it is not surprising that this section experiences high NZFS incident numbers. We recommend that, at a minimum, barriers should span the entire length of the nearest breeding sites. As this study has demonstrated that hotspot locations may shift over time, it will also be necessary to continue the current monitoring approaches, and update mitigation responses as necessary. Other actions that could reduce the occurrence of NZFS incidents include reducing maximum vehicle speeds in high-risk areas and increasing the amount of warning signs regarding the possibility of NZFS on the roads to increase driver awareness.

The issues highlighted here are likely to be replicated elsewhere in New Zealand as NZFS continue to recolonise areas within their pre-exploitation range (Dix, 1993; Bouma et al., 2008; Cowling et al., 2014), and in other countries where pinnipeds are recovering from exploitation (Kirkwood et al., 2010; Milano et al., 2020). The problem is also likely to be exacerbated by the synergistic climate-change induced impacts of sea level rise and increasingly frequent and severe storms, which may force coastal species such as fur seals to retreat inland (McLean et al., 2018).

5. Conclusions

This research demonstrates how roads can impact coastal species, which are typically underrepresented in road ecology studies, and highlights the benefits of identifying WVC hotspots to permit the most efficient allocation of mitigation resources. As such, hotspot analyses could be conducted for any wildlife populations impacted by road mortality, or the threat thereof.

Where wildlife populations are threatened by road mortality, species-specific barriers should be selected based on what will be most effective for reducing WVCs. At locations in which multiple species are threatened, barrier design should account for differences in their behaviour and ontogeny. Additionally, predictive habitat studies are required for wildlife populations that are expanding near roads to allow assessments of probable areas of future habitation, and thus enable proactive decision making regarding future exclusion measures (MacMillan et al., 2016).

Author contributions

Alasdair Hall, Louise Chilvers and Jody Weir contributed to the study conception and design. Material preparation, data collection and analysis were performed by Alasdair Hall, Ashley Vidulich and Jonathan Godfrey. The first draft of the manuscript was written by Alasdair Hall and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106851.

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