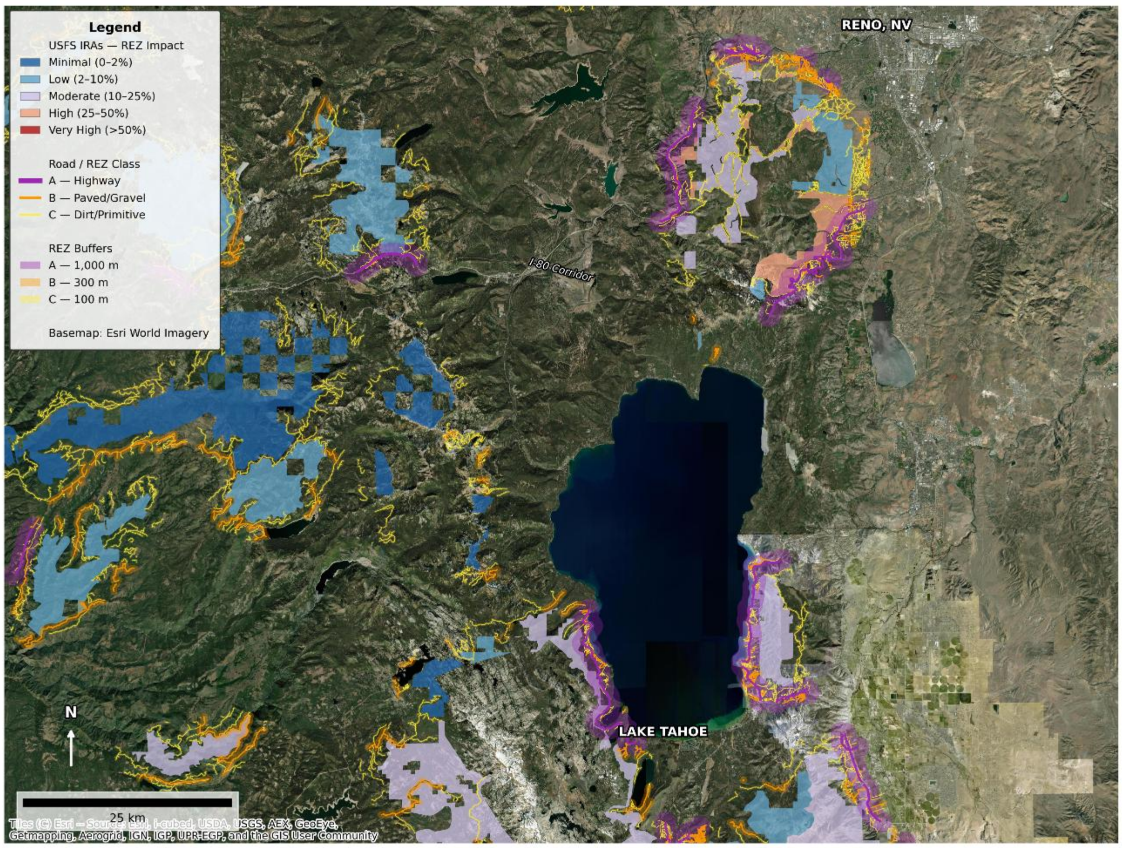
Road Effect Zones and Ecological Values of Inventoried Roadless Areas: A Geospatial Analysis

Road Effect Zone impact on Inventoried Roadless Areas:
an example from the Lake Tahoe region



Zack Wurtzebach, Marc Mayes, and Guillermo Escobar

May 2026

Spatial Informatics Group
Natural Assets Laboratory

A Technical Report Commissioned by The Pew Charitable Trusts

Executive Summary

Inventoried Roadless Areas (IRAs) designated under the 2001 Roadless Area Conservation Rule (Roadless Rule), excluding IRAs in Colorado and Idaho designated under subsequent state-specific rules, encompass 44.7 million acres of National Forest System lands across 2,296 individual areas in 37 states. Despite their “roadless” designation, some IRAs contain roads that were built between the time they were inventoried and before the Rule’s effective date. The 2001 Record of Decision estimated approximately 2.8 million acres of “roaded roadless” areas—areas impacted by roads—but neither the methods for determining “impact” nor the geographic location of that acreage were documented in the project record. This report provides a possible approach to a spatially explicit, science-based framework for quantifying where roads and their Road Effect Zones (REZs)—the area over which the ecological effects of roads and traffic extend into the adjacent landscape—may be affecting roadless area values; specifically, wildlife habitat, water resources, and wildfire ignition patterns. As a national-scale exploratory desktop analysis, our findings represent an approximation of road ecological effects derived from available geospatial data; field-based evaluation would be needed to confirm actual ecological effects in specific locations.

We used OpenStreetMap to assemble 204,343 road segments (totaling 107,032 miles) within one mile of IRA boundaries and classified each into a three-tier REZ framework: Class A (highways, 1,000 m buffer), Class B (paved/gravel, 300 m), and Class C (dirt/primitive/closed, 100 m), calibrated to the road ecology literature and validated across all nine Forest Service regions.

The analysis yields the following principal findings.

1. Existing roads and their REZs may be affecting 5.4% of total IRA area. Based on an analysis of Open Street Maps data, IRAs contain an estimated 11,300 miles of mapped roads. Their ecological Road Effect Zones cover 2.4 million acres—5.4% of total IRA area. Fifty percent of the REZ area (1,214,975 acres) comes from roads within IRA boundaries. The other 50% (1,214,438 acres) of the total REZ area originates from roads outside IRA boundaries, primarily from higher-volume highways and roads. High-volume roads create disturbance zones significantly larger than those from primitive dirt tracks, making road-type differentiation essential to any acreage accounting. The total REZ estimate is similar to, but distinct from, the 2.8 million acres of roaded and roadless areas that the Forest Service identified when promulgating the 2001 Roadless Rule.

2. REZs overlap high-value wildlife habitat and critical drinking water sources. Ranges of 377 federally listed species overlap Roadless Rule IRAs. A case study of the Grizzly Bear identifies

340,641 acres of additional species-specific REZ not captured by our generalized framework. A NatureServe Map of Biodiversity Importance (MoBI) analysis shows that of the 2,144 CONUS IRAs (excluding Alaska), 611 contain species richness or range-size rarity hotspots, and 10.2% of imperiled species richness hotspot areas and 12.8% of range-size rarity hotspot areas within those IRAs fall within Road Effect Zones. Of 307 watersheds of high importance for drinking water, 264 (86%) serving 1.1 million people have non-IRA road density exceeding the 1 mi/mi² threshold associated with risk for sensitive aquatic species (Carnefix and Frissell 2009) and stress on municipal water supplies. Despite road-related stressors, these areas continue to provide habitat for at-risk biodiversity and important watershed services—values that stand to be compromised by additional road development.

3. Wildfire ignition density is significantly higher near roads within IRAs. Analysis of 12,837 wildfire ignitions on National Forest lands (2001–2024) shows that human-caused ignitions near roads are 10 times higher than in unroaded areas of IRAs (19.4 vs. 1.9 per million acres per year). IRAs near population centers and areas of high visitation have significantly more anthropogenic ignitions—a critical consideration for potential road development in IRAs.

I. Introduction

The 2001 Roadless Area Conservation Rule (36 C.F.R. § 294, 2001) prohibits road construction and reconstruction and limits timber harvest on 44.7 million acres of inventoried roadless areas (IRAs) within the National Forest System, encompassing 2,296 individual areas across 37 states (excluding Colorado and Idaho, which had IRAs designated under subsequent rules), subject to specified exceptions. A central goal of the rule is to maintain the roadless area values and characteristics within IRAs, including: “sources of public drinking water”, “diversity of plant and animal communities”; and “habitat for threatened, endangered, proposed, candidate, and sensitive species and for those species dependent on large, undisturbed areas of land” (36 C.F.R. § 294, 2001). While the process to identify IRAs was conducted in the 1970s, the Rule's limitations on road building did not take effect until 2001. During the intervening years, roads were constructed in portions of some IRAs pursuant to agency regulations and forest plans then in effect. As a result, the 2001 Record of Decision estimated that roads had been constructed in approximately 2.8 million acres of IRAs. However, neither the methods used to calculate this acreage nor its geographic extent appear in the project record or subsequent USFS documentation. This gap presents a significant analytical challenge in the context of the Forest Service’s ongoing proposal to rescind the rule.

In this report, we analyze the effects of existing roads on ecological values and drinking water in IRAs using the concept of the Road Effect Zone (REZ) and road density analyses (Forman and Alexander, 1998). Road networks are a primary driver of ecological fragmentation, wildlife disturbance, wildfire ignitions, and watershed impairment (Coffin 2007; Van Der Ree et al. 2015; Aplet et al 2025; Carnefix and Frissel 2009). However, the effect of roads on the surrounding landscape is highly contextual. Variables such as traffic, road surface, topography, and vegetation all mediate the impact of roads on ecological attributes and conditions (Forman and Alexander 1998; Van der Ree et al 2015). As a result, a “one size fits all” REZ buffer is inappropriate for addressing the effects of both high-volume highways and remote, unimproved dirt roads (van Strien and Grêt-Regamey, 2025).

This analysis explores methodological approaches for capturing the effects of diverse road types on select roadless area values and characteristics, thereby establishing a framework for characterizing “roaded roadless areas”. Analyses are framed by the following research questions:

1. Within National Forest System lands, what are the locations and spatial extents of existing roads and their estimated REZ within and adjacent to IRAs?

2. Based on the analyses in Question 1, where within IRAs do REZs stand to impact the ecologically-related roadless area values and characteristics—specifically, high-value wildlife habitat, and catchments and erosion-vulnerable drainage areas associated with critical water resources?
3. What are the differences in wildfire ignition patterns (density, cause, and frequency) between IRA regions with roads and those without?

It should be noted that this report is exploratory in scope. Rather than producing a definitive estimate of all road impacts, the analysis is intended to identify promising methods, characterize key data limitations, and provide a science-based foundation to inform future work, including on-the-ground confirmation of any estimated effects.

2. Road effects on Inventoried Roadless Area values and characteristics

The ecological influence of a road extends beyond its physical footprint. Forman and Deblinger (2000) formalized this concept as the road-effect zone (REZ): the area over which roads and road traffic impact ecological conditions in the adjacent landscape. This concept is particularly relevant to inventoried roadless areas (IRAs), where the presence of a road may diminish the roadless characteristics and ecological values the Rule was intended to protect (36 C.F.R. § 294, 2001). Within a REZ, roads produce multiple stressors, including noise, chemical contamination, altered hydrology, windblown dust, and increased human access (Forman & Alexander 1998; Trombulak & Frissell 2000; Van der Ree et al. 2015; Coffin 2021). Each of these stressors has a different diffusion distance. Chemical contamination, particulates, and soil disturbance from roads typically dissipate within 30-100 m of the road surface (Trombulak & Frissell 2000; Forman et al. 2003; Ament et al. 2014), while noise may travel up to 1000m away (Barber et al. 2010). The spatial extent of these effects is not fixed. It varies with traffic volume, road surface, adjacent topography and vegetation, and species-specific behavior and sensitivity (Eigenbrod et al. 2009; Van der Ree et al. 2015; Coffin et al. 2021; De Jonge et al. 2022). Indeed, road effects scale nonlinearly with traffic volume and speed (Jacobson et al. 2016; Jaeger et al. 2005; Van der Ree 2015). Noise, a primary and far-traveling disturbance mechanism for wildlife, contracts substantially at low traffic volumes, and is often less impactful when intermittent rather than chronic (Jaeger et al. 2005; Francis and Barber 2013; Shannon et al. 2016). Vegetation and topography also mediate road effect distances. Mountainous and forested landscapes reduce REZs for wildlife because they limit visibility and attenuate noise more than open landscapes (Reijnen and Foppen, 1995; Benitez-Lopez et al 2010; De Jonge et al. 2022).

In other words, a “one-size fits all” framework is not appropriate for assessing ecological impacts across busy highways and remote, unimproved dirt roads. These nonlinear, context-dependent dynamics support a tiered buffer framework in which REZ distances are scaled to the characteristics of different road classes rather than applied uniformly across the road network (De Jonge et al. 2022).

For aquatic ecosystems and watershed ecosystem services, such as drinking water provisioning, road density is a more appropriate measure for analyzing road effects. Sedimentation delivery, the primary stressor from rural forest roads, occurs primarily at road-stream crossings and is best assessed at watershed scales, due to hydrological connectivity (Trombulak and Frissell 2000; Wemple et al. 2001; USDA Forest Service 2011). The relationship between road density and the occurrence of sensitive aquatic species exhibits threshold behavior. Bull trout are typically absent from watersheds exceeding 1.7 mi/mi^2 (~1.06 km/km^2) across the Interior Columbia River Basin (Arbelide & Quigley 1997), and meaningful impacts to sensitive aquatic species begin occurring at densities as low as 1 mi/mi^2 (~0.6 km/km^2). Fine sediment delivered through road-stream connections fills spawning gravel beds, reduces dissolved oxygen, and degrades macroinvertebrate communities in sensitive trout habitat across the interior west. The same delivery pathway elevates turbidity at downstream municipal intakes. For these reasons, road density is a key indicator within the U.S. Forest Service's Watershed Condition Framework (USDA Forest Service 2011).

Roads also function as vectors for wildfire ignitions. Across western forest landscapes, proximity to roads is a consistent predictor of wildfire ignition density. At the national scale, Downing et al. (2022) identified road density as the strongest predictor of USFS cross-boundary ignitions. Aplet et al. (2026) analyzed more than 230,000 ignitions on national forest lands from 1992 to 2024 and found that ignition density declined with distance from roads. Lands within 50 m of roads experienced 4.5 times greater ignition density than inventoried roadless areas (7.99 versus 1.97 fires per 1,000 ha). Although road-adjacent fires were smaller on average, the largest 2% of fires—those that were not promptly extinguished—had similar mean sizes regardless of ignition location. The authors therefore concluded that expanding road networks into roadless areas would increase suppression burden without reducing the probability of large fires. These studies indicate that roads serve as major conduits for human-caused ignitions into less accessible forest interiors.

3. Road Locations and Road Effect Zones

3.1 Road Classification

Three publicly available road datasets were evaluated for spatial coverage, attribute completeness, and suitability for ecological impact classification within Inventoried Roadless Areas: OpenStreetMap (OSM), the USFS Infrastructure (INFRA) Road Core national dataset, and Motor Vehicle Use Maps (MVUM). A three-way spatial comparison was conducted for Colorado (369 IRAs) using a 50-meter buffer matching threshold[1]. OSM contained 22,061 km of roads within IRA buffer zones compared to 12,336 km in INFRA and 9,527 km in MVUM. MVUM was nearly a complete subset of INFRA (99.8% overlap). Of INFRA's 12,336 km, 854 km (6.9%) lacked a corresponding OSM segment within 50 m; only 63 km of that gap was open roads (ML2–ML3), the remainder being closed or restricted routes. In the other direction, 5,277 km of OSM roads within National Forest administrative boundaries had no match in INFRA — including 1,729 km of informal or non-system tracks, 1,553 km of residential streets in inholdings, and 490 km of county and state highways. Informal or non-system types of roads include legacy logging and access roads, and user-created roads. Furthermore, while INFRA provides maintenance-level and surface-type classifications for over 98% of segments, the accuracy of these classifications varies widely across forests (J. Hogland pers. Comm., 2026). OSM surface data tags were available for only 47% of segments, though highway type tags were present for all features. A hybrid OSM+INFRA approach was considered, but there are significant challenges to integrating geometry and attributes. These include non-coincident line features that produce duplicate segments, orphaned endpoints where the two schemas fail to connect, and incompatible classification systems– all of which would have required manual reconciliation. Cleaning the integrated dataset and addressing these issues would have been infeasible within the scope and constraints of this project (J. Hogland, pers. comm., 2026).

For each of the 38 states containing IRAs, we extracted OSM roads within a one-mile (1,609 m) buffer of all IRA boundaries—a distance that conservatively captures the extent to which road effects extend into adjacent roadless areas (Forman and Alexander, 1998; Trombulak & Frissell 2000; Benitez-Lopez et al., 2010). The extraction used a two-pass osmium parsing approach: the first pass identified all ways tagged with a `highway` key and collected referenced node IDs; the second pass resolved node coordinates and constructed LineString geometries. Non-motorized trails (`path`, `footway`, `cycleway`, `bridleway`, `steps`, `pedestrian`) were excluded.

[1] While Colorado was not part of the study area, it was selected because it was the state SIG-NAL analysts were most familiar with, which promoted initial visual validation and classification refinement.

The final integrated road network for 2001 Rule IRAs contains 199,846 road segments totaling 103,522 miles (166,602 km) across 37 states (excluding Idaho and Colorado). Of these, 11,300 miles (18,186 km) lie inside IRA boundaries.

3.2 Road Effect Zone Classification

Each OSM road segment was classified into one of three Road Effect Zones (REZs) based on expected ecological impact intensity. While vehicular traffic is the leading indicator of impacts (Van der Ree et al. 2025; van Strien and Grêt-Regamey, 2025), the absence of Annual Average Daily Traffic estimates for low-traffic infrastructure outside of the federal-aid highway network precluded an AADT-based classification approach. As a result, we developed a three-class system based on road surface and function. We assumed that primitive and unmaintained forest roads, for instance, receive far less traffic than paved forest roads. The three-class system was developed from the road ecology literature and validated through visual accuracy assessment (Section 4.3).

- **Class A (1,000 m):** Class A roads are major paved roads. A conservative 1 km REZ buffer is frequently used for these types of roads in road ecology and roadless area research because it encompasses most of the significant ecological degradation associated with primary roads (Hoffman et al. 2024; Ibisch et al. 2016; Eigenbrod et al. 2009; Benitez-Lopez et al. 2010).

- **Class B (300 m):** Class B (moderate impact, 300 m buffer) includes roads with paved or gravel surfaces, grade 1–2 tracks, and tertiary or residential roads with surface evidence. While these roads are often the primary access points to National Forest areas, they receive far less traffic than major motorways. An REZ of 300 m captures most of the ecological impacts from moderate-traffic roads (de Jonge et al. 2022; van Strien and Grêt-Regamey 2025). It also approximates the distance at which moderate traffic noise attenuates to ambient levels in forested landscapes (Reijen and Foppen. 1995; Polak et al. 2013; Shannon et al. 2016; Wilk et al 2025).

- **Class C (100 m):** Class C (low impact, 100 m buffer) encompasses all remaining roads (dirt, unpaved, and primitive tracks). Because the majority of these roads are unimproved and often very remote, we assume they experience limited traffic, limiting potential impacts from noise, light, and pollution. A 100m buffer was selected for these roads because it is commonly identified in the literature as a minimum REZ buffer (Forman and Alexaner 1998; Raymond et al. 2026) and aligns with a 100m REZ for paved and unpaved roads on federal land (Ament et al. 2014). A 100m buffer also acknowledges that the recreational use of these roads may generate ecologically significant noise even at low traffic volumes (Zeller et al. 2024; Ware et al. 2015). Furthermore, it captures the primary sediment delivery, soil disturbance, and edge-effect zone for unpaved roads (Luce et al. 2001; Gucinski et al. 2001). Closed roads are included in this class because they retain persistent hydrological effects regardless of traffic status (Luce and Black 1999; Switalski et al. 2004), and our data make it difficult to differentiate between closed, decommissioned, and open roads with sufficient accuracy.

Classification was applied hierarchically: Class A criteria override Class B, which in turn overrides Class C. Each segment was assigned a confidence rating: "high" when surface type and highway class were both available and consistent, "medium" when one attribute was available, and "low" when classification relied on default assumptions. Non-overlapping unified REZ zones were created by dissolving all buffered road geometries by class and applying a priority hierarchy (A > B > C), so that any location within multiple overlapping buffers is assigned to the highest-impact class.

Table 1. Road Effect Zone classification system and road network summary.

Class	Impact Level	Buffer Distance	OSM Criteria	Segments	% of Total	Length (km)	Length (mi)
A	High	1,000 m	Highway type: motorway, trunk, primary, secondary (+ links)	6,927	3.4%	9,218	5,728
B	Moderate	300 m	Paved or gravel surface; grade 1--2 tracks; tertiary/residential with surface evidence	24,764	12.1%	27,634	17,171
C	Low	100 m	All others: dirt/unpaved, grade 3--5, primitive roads, closed/decommissioned	172,652	84.5%	135,400	84,134
Total				**204,343**	**100%**	**172,251**	**107,032**

Classification accuracy was assessed using a stratified random sample of 450 road segments verified through visual inspection in Google Earth across all nine Forest Service regions. Each sampled segment was assigned a reference class (A, B, or C) based on visible road characteristics (surface type, lane count, and surrounding infrastructure) and compared to the predicted class. The classification achieved 86% overall accuracy with a Kappa statistic of 0.60 (Moderate agreement). Class A assignments are perfectly reliable (100% user's and producer's accuracy), Class B user's accuracy is high (90.7%), and the primary error pattern is conservative—misclassifying higher-impact B roads into the lower-impact C class rather than the reverse, meaning REZ area estimates are more likely to underestimate than overestimate potential ecological road impacts. At the same time, our buffers are somewhat conservative in that they likely overestimate the spatial extent of road effects, particularly for class A. A full description of OSM accuracy tables by region and the error matrix is provided in Appendix C.

3.3 Spatial Extent of Road Effect Zones

When buffered at their class-specific distances (Class A: 1,000 m; Class B: 300 m; Class C: 100 m), **roads within our analysis area produce a unified, non-overlapping REZ covering 2.4 million acres (9,650 km²) of 2001 IRAs—5.4% of total IRA area**. Notably, **50% of all mapped REZ acreage within IRA boundaries originates from 11,300 miles of roads located *inside* IRA boundaries, while the other 50% comes from roads outside IRA boundaries.** Class A highways, with their 1,000 m buffer, generate the largest share of external REZ (77.4% from outside), because a highway running parallel to an IRA boundary projects its entire buffer zone into the IRA interior. Class B roads show an even split (53.8% from outside), while Class C roads, with their narrow 100 m buffer, contribute REZ primarily from segments inside IRAs.[2]

Table 3. Road Effect Zone area by class and road location (non-overlapping, priority-ordered, clipped to 2001 Rule IRAs).

REZ Class	Area (acres)	% of REZ Total	From Roads Inside IRAs (acres)	% from Inside	From Roads Outside IRAs (acres)	% from Outside
A (1,000 m buffer)	956,651	39.4%	215,817	22.6%	740,834	77.4%
B (300 m buffer)	542,729	22.3%	250,906	46.2%	291,823	53.8%
C (100 m buffer)	930,032	38.3%	748,251	80.5%	181,781	19.5%
Total REZ	**2,429,412**	**100%**	**1,214,975**	**50.0%**	**1,214,438**	**50.0%**

Each IRA was classified into five impact tiers based on the percentage of its area falling within a Road Effect Zone (Figure 1). These tiers are descriptive and intuitive categories chosen to characterize the distribution of REZ coverage across the IRA system. The breakpoints (2%, 10%, 25%, 50%) are “rounded” divisions that correspond to natural inflection points in the distribution of REZ coverage across IRAs (approximate quartile boundaries at P25=2.4%, P75=15.0%, P90=28.7%) and visible density transitions in the histogram. The Minimal and Low tiers, IRAs

[2] See Appendix G for the results of a buffer-width sensitivity analysis.

with less than 10% REZ coverage, encompass 1,451 IRAs (63%) and 37.5 million acres (84% of total IRA area). Conversely, the 69 Very High IRAs (>50% REZ coverage) are almost exclusively small fragments totaling only 78,000 acres. The High and Very High tiers together account for 282 IRAs (12%) but only 1.2 million acres (3%). **Together, the analysis shows that the most road-affected IRAs are few in number and ecologically small, while the large, landscape-scale roadless areas that anchor wildlife habitat and watershed integrity remain predominantly outside Road Effect Zones (Figure 1).**

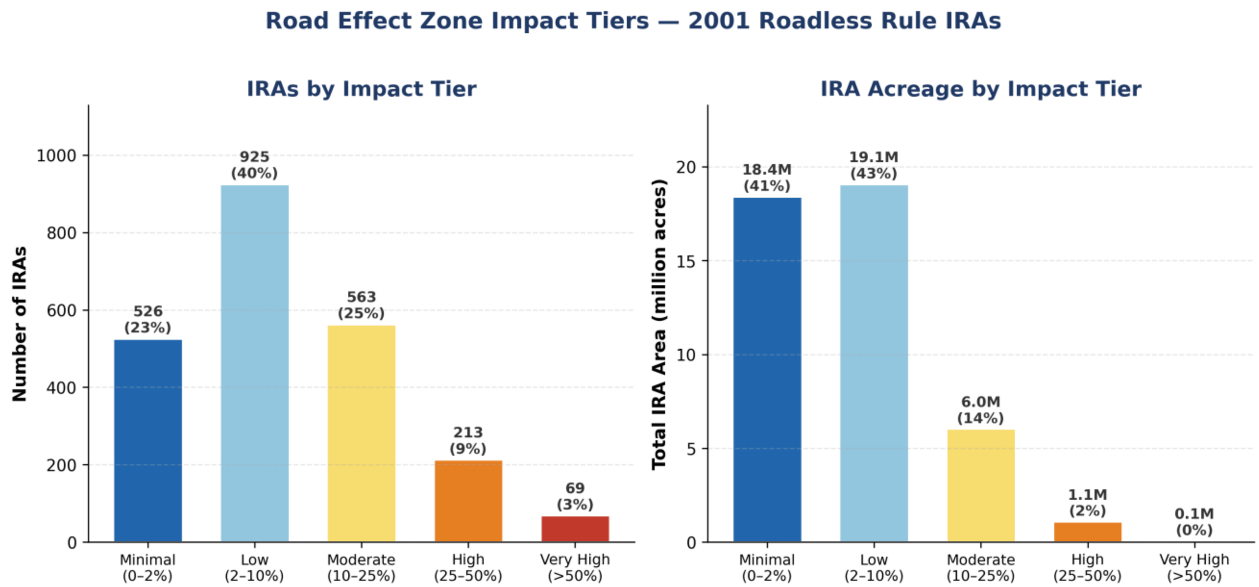


Figure 1. Distribution of 2,296 IRAs by Road Effect Zone impact tier. Tiers reflect the percentage of each IRA's area within a REZ. Left: number of IRAs per tier. Right: total IRA acreage per tier.

The spatial distribution of REZ impact tiers across all 2,296 IRAs is shown in Appendix E (maps E1-E3). The large, intact Minimal and Low tier IRAs dominate the northern Rockies and Pacific Northwest, while the Moderate, High, and Very High tier IRAs are concentrated along California's Sierra Nevada, Utah's Wasatch Range, and the southern Appalachians. Indeed, REZ coverage varies substantially by USFS region (Figure 2). The Southern (R08) and Eastern (R09) regions have the highest median REZ coverage (14.6% and 15.6%, respectively), while the western regions (R01–R06) cluster around 4–8% median coverage but exhibit long tails of heavily roaded outliers. Alaska (R10) is nearly untouched, with a median of 0% and only a handful of IRAs with measurable REZ (though it also includes a few notable outliers). Quite predictably, eastern and southern IRAs face a greater share of road influence than their western counterparts, due to their smaller size and proximity to major population centers.

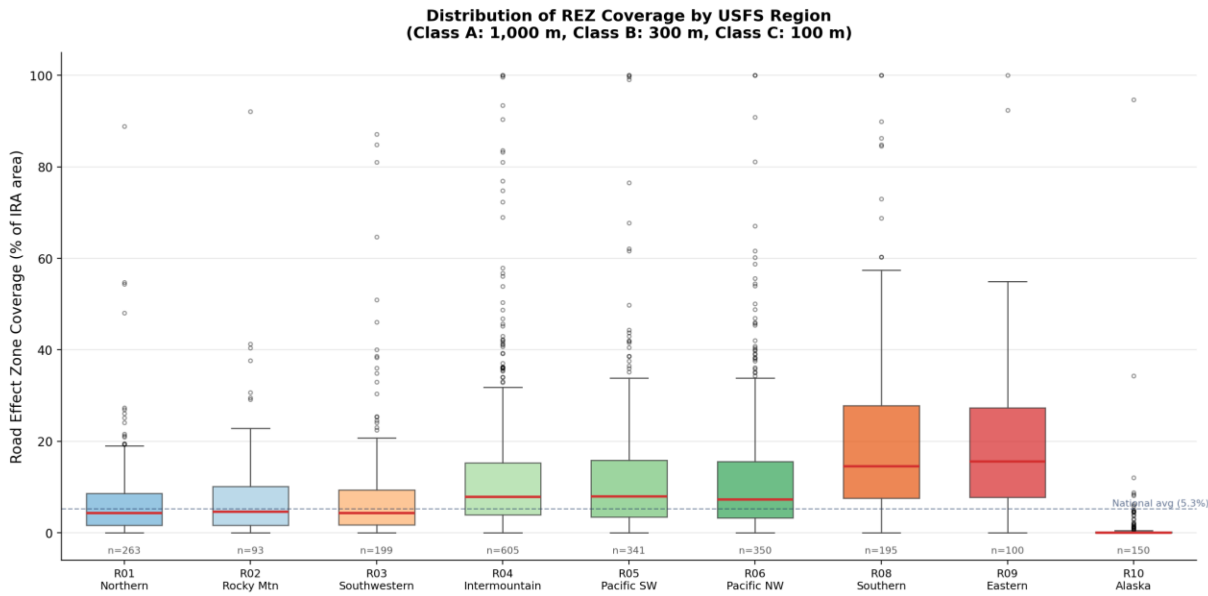


Figure 2. Distribution of REZ coverage (% of IRA area) by USFS Region. Box shows interquartile range; red line is median; whiskers extend to 1.5x IQR; circles are outliers. Buffer distances: Class A = 1,000 m, Class B = 300 m, Class C = 100 m.

Figure 3 illustrates the REZ framework at landscape scale in the Tahoe National Forest/Lake Tahoe region. The satellite basemap shows how Class A highway corridors (notably I-80) produce wide REZ swaths that bisect otherwise intact IRAs, while the dense network of Class C primitive roads creates a fine-grained mosaic of disturbance within lower-tier IRAs. The map demonstrates why road classification matters. Class A roads, though only 3.5% of segments, produce 40% of the total REZ because their 1,000 m buffer extends far into surrounding landscapes. Class C roads constitute 84.1% of segments but produce only 37% of total REZ area because of their narrow 100 m buffer. Class B roads contribute 23% of REZ area from 12.4% of segments.

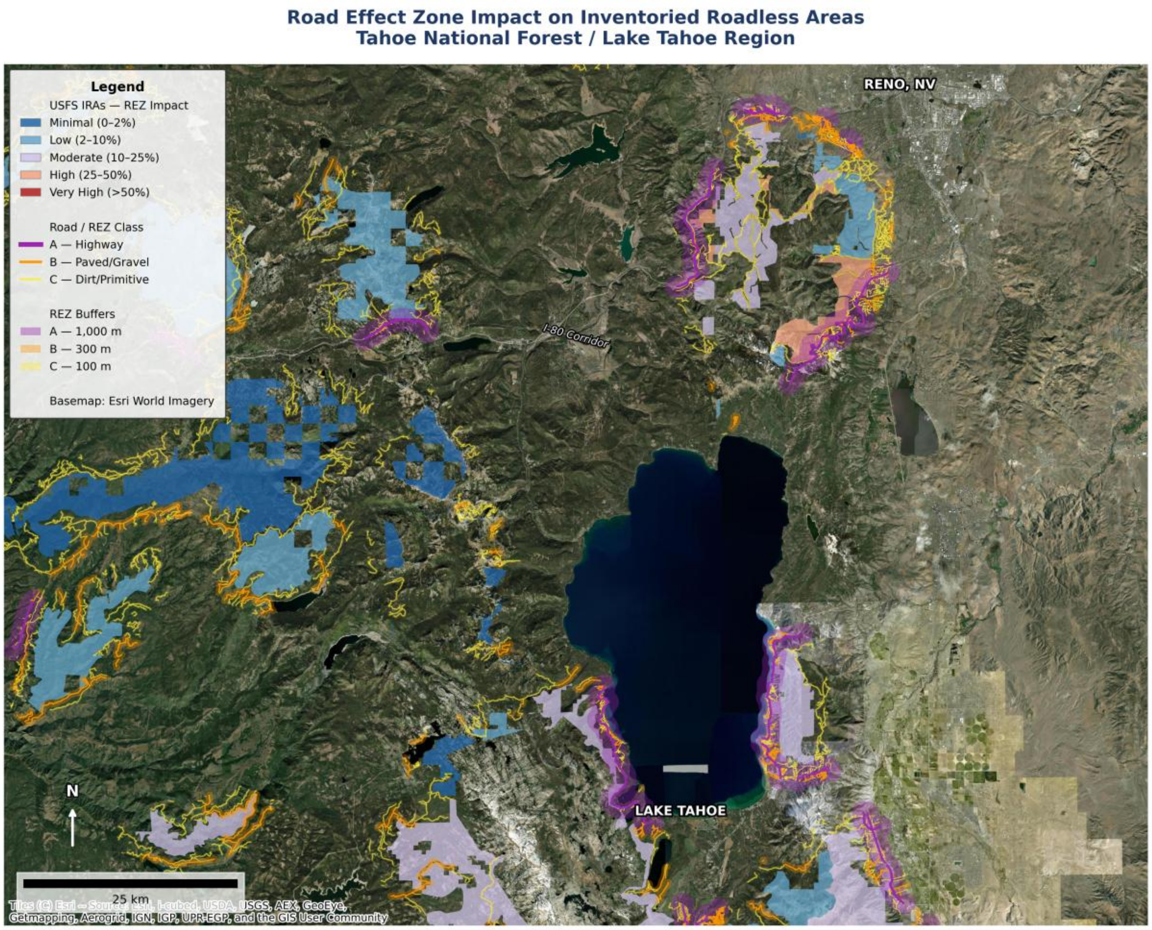


Figure 3. Road Effect Zone framework at landscape scale: Tahoe National Forest / Lake Tahoe region. Satellite basemap shows IRAs classified by REZ impact tier, with classified roads and REZ buffers overlaid. Class A highway corridors (I-80) produce wide REZ swaths bisecting otherwise intact IRAs.

The REZ framework has direct implications for any analysis considering recission of the Roadless Rule. By classifying road effects into three tiers based on road characteristics rather than treating all roads as equivalent, this analysis reveals that the ecological footprint of roads within and adjacent to IRAs varies significantly based on road type and assumptions of traffic volume and use. This distinction is critical for identifying which IRAs currently experience the greatest degradation of roadless area values and where those values remain most intact. An undifferentiated approach would overstate the impact of the thousands of primitive road segments that produce minimal ecological disturbance while understating the outsized influence of a smaller number of high-standard roads whose effect zones penetrate deep into otherwise intact IRA cores.

4. Ecological Values at Risk

4.1 Species-specific road effect zones

The rescission of the roadless rule could affect hundreds of vulnerable wildlife species, including those whose ranges are poorly represented in existing protected-area networks (Dietz et al., 2021). Because wildlife species respond heterogeneously to road effects (Benitez-Lopez et al., 2010; de Jonge et al., 2022), it is important to consider species-specific road-effect zones for at-risk, wide-ranging species that depend on IRAs for intact habitat. To do so, we first downloaded the USFWS Complete Species Current Range dataset (2,294 range records, 1,818 unique species) from ecos.fws.gov. Each species' range polygon was intersected with the 2001 Rule IRA union geometry. For species with multiple Distinct Population Segment (DPS) records, all polygons were unioned before intersection. The overlap area was computed in acres and as a percentage of the total species range, then filtered to formally listed (Endangered and Threatened) species.

The ranges of **377 federally listed species** (Endangered or Threatened under the Endangered Species Act) overlap with 2001 Rule Inventoried Roadless Areas. The species with the largest IRA overlap include the North American wolverine (14.6 million acres, 11.1% of total range), Yellow-billed cuckoo (14.4 million acres), Canada lynx (11.1 million acres, 7.3% of range), and Whitebark pine (9.8 million acres, 19.5% of range). **For many of these federally listed species, IRAs provide the largest remaining blocks of unfragmented habitat on federal lands.**

To demonstrate the importance of a species-specific approach, we analyzed road-effect distance for the Grizzly bear (*Ursus arctos horribilis*), a wide-ranging species listed as Threatened under the ESA. Grizzly bears are highly sensitive to roadway impacts; proximity to roads is associated with habitat displacement, reduced habitat security, and increased human-caused mortality (Lamb et al., 2018; Proctor et al., 2019). Current scientific and regulatory guidance defines secure habitat as more than 500m from an open motorized access route (Interagency Grizzly Bear Committee, 2024). This species-specific distance exceeds the generalized 3-class buffer on Class B roads (300 m) and Class C roads (100 m), making it a useful case study for evaluating how the generalized framework may underestimate road impacts for sensitive species.

A 500 m buffer was applied to all Class A, B, and C roads within the intersection of the grizzly bear's USFWS range and 2001 Rule IRA boundaries (4.5 million acres). Closed and decommissioned roads (tagged `motorvehicle=no` or `vehicle=no` in OSM) were excluded from this analysis because they do not generate the traffic-related disturbance that drives grizzly bear avoidance behavior (Waller & Servheen, 2005; Interagency Grizzly Bear Committee, 2024). An excess REZ shapefile was created by buffering only the exceeding road classes at the species-specific distance and subtracting the generalized REZ to isolate the additional area beyond what the 3-class system captures (Table 2).

Table 2. Grizzly bear species-specific REZ analysis.

Metric	Value
ESA Status	Threatened
Road Classes Analyzed	A, B, C (excluding closed roads)
Species-Specific REZ Distance	500 m
Range in 2001 Rule IRAs	4,457,768 acres
Full Species-Specific REZ	487,874 acres
Excess REZ (beyond generalized framework)	340,641 acres
Exceeding Road Classes	B (500 m vs. 300 m), C (500 m vs. 100 m)

The full species-specific REZ encompasses 487,874 acres of grizzly bear habitat within IRAs. **The area where the 500 m grizzly-specific buffer extends beyond the generalized framework is 340,641 acres.** This excess originates primarily from Class C roads, where the species-specific buffer (500 m) extends 400 m beyond the generalized Class C buffer (100 m), and from Class B roads, where the species-specific buffer extends 200 m beyond the generalized Class B buffer (300 m).

As this example shows, any analysis that relies solely on generalized REZ buffer distances would fail to account for species-specific responses to road effects—a particularly important consideration for at-risk species that depend on intact habitat. While there is no established road-effect buffer for Wolverine, for instance, they exhibit high sensitivity to low traffic roads (0–30 vehicles/12 h) (Scrafford et al. 2018). Additional species-based road-effect analyses are therefore essential to provide a “fine-filter” complement to a generalized “coarse-filter” REZ framework—an approach aligned with the aims of the USFS 2012 planning rule (36 CFR Part 219, 2012).

4.2 Biodiversity Hotspots and Road Effect Zones

To evaluate whether road-affected areas within IRAs coincide with areas of high biodiversity value, REZ zones were intersected with the NatureServe Map of Biodiversity Importance (MoBI) 2024 dataset. MoBI provides 330 m resolution rasters of imperiled species richness and range-size rarity across the contiguous United States, derived from habitat suitability models for all species tracked by NatureServe as imperiled (G1–G3 global conservation status) (Hamilton et al. 2021). Two MoBI metrics were analyzed: species richness (count of imperiled species with modeled habitat at each pixel) and range-size rarity (sum of inverse range sizes for imperiled species present, giving higher weight to species with smaller ranges). MoBI raster tiles were downloaded from the NatureServe ArcGIS tiled image service and decoded from LERC format at 330 m resolution in EPSG:5070. Biodiversity hotspots were defined as pixels in the top 20% of values among all species-bearing pixels within IRAs. A top-quintile threshold was used because it is an established practice in spatial conservation prioritization (Myers et al. 2000; Margules and Pressey 2000) and is consistent with NatureServe's own hotspot identification methods for MoBI data (Hamilton et al. 2021). A rank-based (percentile) threshold was used rather than a fixed value cutoff to account for the discrete (integer) nature of species richness values, which would produce uneven class sizes under a fixed-value approach.

Across all 2,14 Continental U.S. (CONUS) IRAs under the 2001 Rule, 2.3 million acres (7.7%) of IRA area falls within the modeled REZs. **For imperiled species richness, 1,416,000 acres of IRA area qualify as a hotspot (top 20% of values). Of this, 144,500 acres (10.2%) falls within the REZ. For range-size rarity, which upweights species with small ranges and thus greatest vulnerability to habitat loss, 1,420,000 acres qualifies as hotspot, of which 181,600 acres (12.8%) falls within the REZ**.

Table 3. MoBI biodiversity hotspot area within Road Effect Zones by USFS Region.

Region	IRAs	SR Hotspot (acres)	SR in REZ (acres)	SR % in REZ	RSR Hotspot (acres)	RSR in REZ (acres)	RSR % in REZ
R01 Northern	263	19,274	3,608	18.7	142,088	7,958	5.6
R02 Rocky Mountain	93	18,091	3,160	17.5	26,887	3,259	12.1
R03 Southwestern	199	985,052	64,942	6.6	214,228	17,584	8.2
R04 Intermountain	605	132,445	17,776	13.4	500,586	56,634	11.3
R05 Pacific Southwest	341	506,755	76,819	15.2	678,992	92,744	13.7
R06 Pacific Northwest	350	85,422	10,932	12.8	143,275	24,685	17.2
R08 Southern	195	16,720	4,383	26.2	48,147	10,895	22.6
R09 Eastern	100	4,241	1,451	34.2	32,305	9,041	28.0
CONUS Total	**2,144**	**1,768,000**	**183,071**	**10.2**	**1,786,508**	**222,800**	**12.8**

Note: SR = Species Richness (all imperiled); RSR = Range-Size Rarity (all imperiled). Hotspot defined as top 20% of MoBI pixel values within IRAs. Alaska and Puerto Rico excluded (no MoBI coverage). Source: NatureServe Map of Biodiversity Importance (MoBI) 2024, 330 m resolution.

The spatial distribution of hotspot-REZ overlap is shown in Appendix E, maps E4-E6. **Of 2,144 CONUS IRAs, 897 contain biodiversity hotspots, and 611 contain biodiversity hotspot areas that overlap with Road Effect Zones.** To distinguish levels of road exposure among IRAs containing biodiversity hotspots, hotspot-REZ overlap was classified into high and moderate tiers using a threshold of 5 km² (~1,236 acres) of combined species richness and range-size rarity hotspot area falling within a Road Effect Zone. The 5 km² threshold is not an ecologically derived breakpoint but a distributional one that isolates the upper tail of the overlap distribution; it corresponds to the 90th percentile of overlap values among IRAs with any hotspot-REZ intersection. Based on this threshold, there are 69 IRAs in which road effects threaten the most biodiverse portions of the IRAs CONUS-wide. These high-overlap IRAs are concentrated in southern California, the Pacific Northwest, and the Appalachian region. The 542 IRAs with hotspot-REZ overlap below this threshold were classified as moderate, and 286 IRAs had biodiversity hotspots that fell outside of the REZ.

Regional patterns reveal that the highest proportional hotspot exposure occurs in the Eastern (R09) and Southern (R08) regions, where 27–34% of species richness hotspot area falls within REZ. These regions contain smaller, more roaded IRAs that contain the highest species diversity in the United States. The Pacific Southwest (R05) combines large absolute hotspot area (379,753 acres for species richness, 506,585 acres for range-size rarity) with moderately high REZ exposure (~15%), making it the region with the greatest total area of road-affected biodiversity hotspots. The Southwestern region (R03) dominates species richness hotspot area (882,560 acres—62% of the CONUS total) but has relatively low REZ exposure (6.8%), reflecting the large, remote character of New Mexico and Arizona IRAs.

These findings underscore that road impacts on imperiled species' habitat are not uniformly distributed but are concentrated in specific regions and individual IRAs—some of which represent the last remaining intact habitat for endemic and range-limited species. In the 286 IRAs with hotspots outside an REZ, additional road development could compromise these critical areas for conservation. Likewise, in the 611 IRAs with existing hotspot-REZ overlap, decommissioning roads may be a more prudent option, particularly in biodiversity hotspots such as the Appalachian region. Because road-edge effects extend hundreds of meters beyond the road surface, removing even a single road segment from a hotspot can improve habitat quality across a zone far larger than the road's physical footprint.

4.3 Drinking Water Watersheds and IRAs

National Forest System lands are the single largest source of surface drinking water in the United States, and IRAs provide a significant proportion of this critical ecosystem service to millions of downstream users (Talty et al 2020). The USDA Forest Service's Forests-to-Faucets 2.0 (F2F2) assessment identifies and ranks the importance of forested watersheds to downstream surface drinking water supplies (Mack et al. 2022). This national watershed framework was intersected with IRAs to quantify the drinking water resources that roadless area protections help conserve.

To ensure complete road coverage, OpenStreetMap road data was extracted for the full geographic extent of all HUC-12 watersheds where IRAs constitute at least 20% of the watershed area. For each of the 2,281 qualifying HUC-12 watersheds (excluding Idaho and Colorado): (1) the watershed polygon was split into IRA and non-IRA portions using intersection/difference with the IRA union geometry; (2) OSM roads were extracted from state-level PBF files using two-pass osmium parsing, clipped to watershed boundaries; (3) road length was computed separately for IRA and non-IRA portions; (4) road density (km/km^2) was calculated for total watershed, IRA portion, and non-IRA portion; and (5) F2F2 surface drinking water importance was classified into four analyst-defined tiers based on the IMP_R (importance) percentile score. The IMP_R metric estimates a watershed's importance to surface drinking water by multiplying its average annual water yield by the weighted downstream population served by surface-water intakes, with nearer downstream users weighted more heavily than farther ones. It is measured as a continuous percentile rank (0–99). The four-tier classification used here (Critical, High, Moderate, Lower) was developed for this analysis to facilitate interpretation and is not part of the F2F2 dataset itself. Priority watersheds were defined as those with an IMP_R score greater than 75%. Non-IRA road density was evaluated against the empirical threshold of 1 mi/mi² (0.6 km/km²), at which significant ecological impacts are already apparent (Carnefix and Frissell 2009). While this threshold derives from aquatic species research, it represents a commonly used empirical benchmark for road density effects on watershed ecological function in the absence of a drinking-water-specific threshold.

A total of **2,281 HUC-12 watersheds** with at least 20% IRA coverage were analyzed across 28 states.

Table 4. Watershed importance tiers (analyst-defined, based on F2F2 IMP_R percentile score).

Importance Tier	IMP_R Score	Watersheds	People Served
Critical	> 90	107	1,046,996
High	75--90	200	190,887
Moderate	50--75	520	256,367
Lower	< 50	1,465	28,347
Total		**2,281**	**1,517,095**

Note: This table includes only the 2,281 watersheds where IRAs constitute at least 20% of the watershed area, ensuring a meaningful IRA contribution to catchment hydrology. The 307 highest-priority watersheds (Critical + High importance, IMP_R >= 75) represent the municipal water supplies most vulnerable to land management changes upstream.

When analyzing differences between IRA portions and non-IRA portions of the same watersheds, we found a striking difference: **the median road density was 17.2 times higher outside IRA boundaries than inside IRA boundaries (0.11 mi/mi² inside vs 1.91 mi/mi² outside).**

When total watershed road density (combining IRA and non-IRA portions) is considered, 218 of 307 priority drinking water watersheds (71%) exceed 1 mi/mi² for total watershed density. These watersheds are concentrated along Utah's Wasatch Front, southern California, and the Pacific Northwest—wildland-urban interface landscapes where dense development outside the IRA drives total watershed road density well above the impact threshold.

In these priority watersheds, the low-density IRA portion is the only component holding total watershed condition from further deterioration (Maps E7-E8). For instance, if IRA portions of priority watersheds acquired the same road density as non-IRA portions, the road network within watersheds would expand by 10,578 miles. Median total watershed density would rise from 1.40 to 2.43 mi/mi² (the latter more than two times the Carnefix and Frissell (2009) impact threshold). While this counterfactual is extreme, the fact remains that any additional road development would further stress existing conditions for aquatic ecosystems and municipal drinking water supplies.

5. Wildfire Ignition and Road Proximity

5.1 Wildfire Ignitions

To evaluate the relationship between road proximity and wildfire ignition patterns within IRAs, we analyzed the USFS Electronic Data Warehouse (EDW) Fire Occurrence dataset (FIRESTAT) (USDA Forest Service 2024). This dataset contains point locations of all wildfire ignitions on National Forest System lands, attributed with ignition cause (human, lightning, or unknown), date, and size.

All ignitions within 2001 Rule IRA boundaries from 2001 through 2024 (the last year for which data was available) were extracted, yielding 12,837 fire events across 24 fire seasons. Prescribed fires were excluded based on the PRESCRIBED field. Each ignition point within IRAs was spatially classified into two categories: 1) within an REZ buffer and 2) outside an REZ buffer.

Ignition density was calculated as fires per million acres per year for each zone and cause category. This metric normalizes for differences in zone area and observation period, enabling direct comparison of ignition rates between road-proximate and unroaded portions of IRAs.

Two statistical tests were applied. First, a chi-square goodness-of-fit test evaluated whether fires are distributed proportionally to zone area (null hypothesis: ignition density is uniform across zones). Second, Poisson rate ratios with 95% confidence intervals (log-normal approximation) were computed for buffered-versus-unroaded density comparisons, overall and stratified by cause. These tests were applied to the overall buffered/unroaded comparison, the four-zone comparison (Class A, B, C, and unroaded), and the human-caused fire subset separately.

To characterize geographic variation in fire-road relationships, ignitions were summarized by USFS administrative region and by state. For each unit, we computed total fire count, ignition density (fires per million IRA acres per year), the proportion of human-caused versus lightning-caused ignitions, and the human ignition rate. Fire cause was classified from the STATISTICA field: "Lightning" causes were coded as natural, and all other cause codes (campfire, arson, equipment use, smoking, debris burning, children, railroad, and miscellaneous) were classified as human-caused.

5.2 Ignition Density by Road Proximity

The relationship between roads and wildfire is frequently invoked in debates over roadless area management, with proponents of road construction arguing that increased access reduces fire risk. Our analysis of 12,837 wildfire ignitions within 2001 Rule IRAs from 2001–2025 aligns with other findings that contradict this premise (Aplet et al. 2026).

Table 5. Wildfire ignition density by zone and cause (2001-2024).

Zone	Fires	Area (acres)	Fires/M acres/yr
Road-buffered (all REZ)	2,010	2,384,503	33.72
Unroaded (outside REZ)	10,827	42,316,241	10.23
Road-buffered -- Lightning	898	2,384,503	15.06
Road-buffered -- Human	1,112	2,384,503	18.65
Unroaded -- Lightning	8,859	42,316,241	8.37
Unroaded -- Human	1,968	42,316,241	1.86

Ignition density in road-buffered zones of IRAs is **3.3 times** higher than in unroaded zones (35.1 vs. 10.6 fires per million acres per year; Poisson rate ratio 3.29, 95% CI: 3.14–3.45). **This differential is driven primarily by human-caused ignitions near roads, which is 10.1 times higher than in unroaded areas** (19.4 vs. 1.9 per million acres per year; rate ratio 10.08, 95% CI: 9.37-10.84). Increased ignition density was also higher for more traveled roads. Among road classes, Class B roads showed an ignition density of (40.5 fires/M acres/yr), followed by Class A highways (39.9) and Class C (26.9). We hypothesize that Class A and B roads are similar because most ignitions happen close to roads, and because Class A roads are “through-ways”, which preclude people from stopping or camping. Lightning ignition rates are also elevated near roads (15.7 vs. 8.7; rate ratio 1.80, 95% CI: 1.68–1.92), likely reflecting the correlation between roads and lower-elevation, drier vegetation types.

Chi-square goodness-of-fit tests confirm that fires are not distributed proportionally to zone area. For the four-zone comparison (Class A, B, C, and unroaded), chi-square = 2,937.4 (df = 3, p < 0.001). For human-caused fires specifically, chi-square = 5,843.5 (df = 1, p < 0.001).

5.3 Regional and Cause-Code Patterns

Looking more broadly across 28,630 ignitions in IRAs (full FIRESTAT record), 73.5% were lightning-caused, and 26.5% were human-caused. Among human-caused fires, campfires were the leading cause (3,476 fires, 45.9% of human ignitions), followed by miscellaneous (1,843, 24.3%) and arson (741, 9.8%). Smoking, equipment use, and debris burning collectively accounted for the remainder.

Table 6. Wildfire ignition density by USFS Region (full FIRESTAT record).

Region	IRAs	IRA Acres (M)	Fires	Lightning	Human	% Human	Rate*	Human Rate*
R05 Pacific SW	381	4.42	6,727	4,371	2,356	35.0%	60.9	21.3
R06 Northwest	351	3.98	5,757	4,508	1,249	21.7%	57.9	12.6
R01 Northern	257	6.66	4,791	3,952	839	17.5%	28.8	5.0
R04 Intermountain	538	7.20	4,691	3,659	1,032	22.0%	26.1	5.7
R03 Southwest	199	2.72	3,477	2,926	551	15.8%	51.1	8.1
R02 Rocky Mountain	124	3.32	2,077	1,421	656	31.6%	25.0	7.9
R08 Southern	190	0.93	643	183	460	71.5%	27.5	19.7
R09 Eastern	105	0.68	240	17	223	92.9%	14.0	13.0
R10 Alaska	150	14.78	227	18	209	92.1%	0.6	0.6

*Fires per million IRA acres per year.

The regional pattern reveals stark geographic differences in ignition sources. The more densely populated Southern, Eastern, and Pacific Southwest Regions have significantly higher rates of human ignitions than the more sparsely populated regions of the Mountain West (Appendix E, maps E9-E12). This indicates that the ignition rate and associated wildfire risk increase with proximity to population centers and visitor access, a consideration with implications for decisions related to new road development. **Constructing new roads in currently unroaded IRA cores would extend ignition risk into landscapes that currently experience the lowest fire-start**

densities in the National Forest System—particularly in IRAs near major population centers or areas with high visitor use.

6. Key Findings

The analyses presented in Sections IV–VII provide an exploratory picture of how roads interact with the ecological values and characteristics associated with IRAs.

Roads and their ecological effects are present within IRAs, but the vast majority of IRA area remains intact.
The integrated road network identifies 11,300 miles of roads inside 2001 Rule IRA boundaries, and the three-class REZ framework shows that 2.4 million acres (5.4%) of total IRA area falls within a road-influenced zone. The remaining 42.3 million acres (94.6%) represents ecologically intact core areas outside any REZ. Importantly, 50% of all mapped REZ acreage (within IRA boundaries originates from 11,300 roads located *inside* IRA boundaries, while the other 50% comes from roads outside IRA boundaries.

Road impacts are heterogeneous and require differentiated analysis.
In our framework, Class A highways produce ecological effects ten times wider than Class C primitive roads, reflecting well-documented and non-linear dynamics (Van der Zee et al. 2015). Treating all roads as equivalent would misrepresent both the extent and intensity of road effects within IRAs.

REZs overlap high-value wildlife habitat and drinking water sources.
Species respond heterogeneously to the effects of roads—an especially important consideration for the 377 ESA-listed species whose ranges overlap 2001 Rule IRAs. A case study of the Grizzly Bear identifies 340,641 acres of additional species-specific REZ not captured by our generalized framework. This example highlights the importance of a complementary "fine-filter" analysis for road-sensitive species, many of which are dependent on intact habitat that IRAs provide. There are 611 CONUS IRAs contain MOBI biodiversity hotspots, and 542 of those contain hotspots that overlap with REZs. Road impacts on imperiled species' habitat are not uniformly distributed but are concentrated in specific regions and individual IRAs—some of which represent the last remaining intact habitat for endemic and range-limited species. Avoiding additional road development and road decommissioning should be a priority in these critical areas for conservation. Full-watershed road extraction across 2,281 HUC-12 watersheds with at least 20% IRA coverage shows road density in IRA portions is 17.2 times lower than in non-IRA portions (median 0.069 vs. 1.184 km/km²). Of 307 priority drinking water watersheds (IMP_R >= 75), 218 (71%) have non-IRA road density exceeding 1 mi/mi² (0.6

km/km²), the threshold at which significant ecological impacts are already apparent (Carnefix and Frissell 2009). In these watersheds, any additional road development will exacerbate existing stressors for both aquatic ecosystems and drinking water systems.

Wildfire ignition density is significantly higher near roads. Road-buffered zones within IRAs experience 3.3 times higher ignition density than unroaded zones, driven primarily by a 10.0-fold increase in human-caused ignitions. This pattern is consistent across road classes, with higher-class roads showing higher ignition density. Our analyses also highlight significant spatial variation in human-caused ignitions. IRAs near population centers and areas of high visitation have significantly more anthropogenic ignitions—a critical consideration for potential road development in IRAs.

The analysis provides a replicable framework and baseline dataset. The road classification system, REZ buffer distances, species-specific thresholds, and watershed density data provide a spatially explicit framework for evaluating the ecological consequences of changes to road management policy in roadless areas.

8. Limitations

Several limitations should be considered when interpreting these results:

- **Road data.** There are significant gaps and limitations in all road-related datasets that we explored. During our visual classification, we noticed numerous roads not captured by OSM or INFRA adjacent to and within IRAs. While OSM was the most complete overall, OSM highway tags and surface attributes vary significantly in completeness across regions. Visual validation in Google Earth across all nine Forest Service regions yielded 85% overall accuracy (Kappa = 0.58), but the error matrix shows an asymmetric pattern: the classification under classifies higher-impact roads more often than it overclassifies lower-impact roads (Class A producer's accuracy 35%, Class C producer's accuracy 99%). This conservative bias means REZ area estimates are more likely to be underestimates. We also tried to estimate AADT for roads, but this is infeasible outside of Class A roads, due to limited sampling on Class B and C roads.
- **IRA shapefiles.** Many roads found within IRAs are an artifact of poorly drawn IRA shapefiles. We found several instances of roads running within IRAs, parallel to their boundary, because the polygon extended over a road.
- **REZ buffer distances.** While buffer distances are drawn from the empirical literature, they represent general assumptions rather than site-specific conditions. REZs are asymmetric, highly variable, and dynamic across spatial and temporal scales (Forman and Alexander

1998; Van der Ree et al. 2015). Actual ecological effects vary with topography, traffic, vegetation, season, and species-specific responses. Site-specific analyses are therefore needed to determine where impacts are actually occurring.

- **Species range data.** USFWS range polygons represent the broad geographic range of each species, not fine-scale occupancy. Overlap with IRAs indicates potential habitat, not confirmed presence. This was an exploratory approach to show the importance of species-specific considerations.
- **Wildfire ignition analysis.** The comparison of roaded and unroaded zones does not control for all confounding variables (elevation, aspect, fuel type, accessibility for detection). However, the large sample size (12,837 ignitions over 25 years) and the consistency of the pattern across road classes support the finding.

9. Future Research and Analysis

Future research and analysis could leverage additional modeling to estimate traffic on low-volume, non-Federal-aid roads, thereby allowing for the identification of more context-dependent REZs. Model covariates could combine Forest Service road-network attributes with spatial predictors such as distance to communities, recreation sites, timber or management activity, road surface and maintenance class, topography, road density, and proximity to higher-order roads—factors that significantly influence local-road AADT. Potential approaches include geographically weighted regression, kriging/interpolation, and machine-learning and probe-data approaches (Mathew and Pulugurtha, 2021; Pulugurtha and Mathew, 2021; FHWA, 2021). Because rural forest roads are highly seasonal and often recreation-driven, modeled AADT products should report prediction intervals and identify segments where field verification is needed before use in roadless-area screening or ecological-impact assessment.

Another avenue is to evaluate where road-effect zones (REZs) overlap with landscape features likely to be important for species persistence and movement under climate change, including climate refugia and ecological corridors. Although this report identifies where roads are likely affecting species within IRAs at present, overlaying REZs with mapped climate refugia would help identify places where road impacts may undermine areas expected to remain climatically suitable as conditions change. Similarly, combining REZs with connectivity or corridor models would flag road segments that bisect key wildlife movement pathways, where decommissioning could reduce barrier effects and improve landscape permeability.

The Pew Charitable Trusts provided funding for this project, but Pew is not responsible for errors in this white paper and does not necessarily endorse its findings or conclusions.

References

Ament, R., Clevenger, A. P., Yu, O., & Hardy, A. (2008). An assessment of road impacts on wildlife populations in U.S. National Parks. *Environmental Management, 42*(3), 480–496.

Ament, R., Powell, S., Stoy, P., & Begley, J. (2014). Roadside vegetation and soils on federal lands – Evaluation of the potential for increasing carbon capture and storage and decreasing carbon emissions (Final Report). Western Transportation Institute, Montana State University; prepared for the Federal Highway Administration, Office of Federal Land.

Aplet, G. H., Hartger, P., & Dietz, M. S. (2026). Three-decade record of contiguous-U.S. national forest wildfires indicates increased density of ignitions near roads. *Fire Ecology, 22*, 8.

Barber, J. R., Crooks, K. R., & Fristrup, K. M. (2010). The costs of chronic noise exposure for terrestrial organisms. *Trends in ecology & evolution*, *25*(3), 180-189.

Benítez-López, A., Alkemade, R., & Verweij, P. A. (2010). The impacts of roads and other infrastructure on mammal and bird populations: A meta-analysis. *Biological Conservation, 143*(6), 1307–1316.

Carnefix, G., & Frissell, C. A. (2009). *Aquatic and other environmental impacts of roads: The case for road density as indicator of human disturbance and road-density reduction as restoration target* (Pacific Rivers Council Science Publication 09-001). Pacific Rivers Council.

Coffin, A. W. (2007). From roadkill to road ecology: A review of the ecological effects of roads. *Journal of Transport Geography, 15*, 396–406.

Coffin, A. W., Ouren, D. S., Bettez, N. D., Borda-de-Água, L., Daniels, A. E., Grilo, C., & Rauschert, E. S. J. (2021). The ecology of rural roads: Effects, management, and research. *Issues in Ecology, 23*, 1–35.

de Jonge, M. M. J., Gallego-Zamorano, J., Huijbregts, M. A. J., Schipper, A. M., & Benítez-López, A. (2022). The impacts of linear infrastructure on terrestrial vertebrate populations: A trait-based approach. *Global Change Biology, 28*(24), 7217–7233.

Dietz, M. S., Barnett, K., Belote, R. T., & Aplet, G. H. (2021). The importance of US national forest roadless areas for vulnerable wildlife species. *Global Ecology and Conservation*, *32*, e01943.

Downing, W. M., Dunn, C. J., Thompson, M. P., Caggiano, M. D., & Short, K. C. (2022). Human ignitions on private lands drive USFS cross-boundary wildfire transmission and community impacts in the western US. *Scientific Reports, 12*, 2624.

Eigenbrod, F., Hecnar, S. J., & Fahrig, L. (2009). Quantifying the road-effect zone: Threshold effects of a motorway on anuran populations in Ontario, Canada. *Ecology and Society, 14*(1).

Federal Highway Administration. (2021). *Non-traditional methods to obtain annual average daily traffic (AADT)* (Report No. FHWA-PL-21-030).

T. T., & Alexander, L. E. (1998). Roads and their major ecological effects. *Annual Review of Ecology and Systematics, 29*, 207–231.

Forman, R. T. T., & Deblinger, R. D. (2000). The ecological road-effect zone of a Massachusetts (U.S.A.) suburban highway. *Conservation Biology, 14*(1), 36–46.

Forman, R. T. T., Sperling, D., Bissonette, J. A., Clevenger, A. P., Cutshall, C. D., Dale, V. H., Fahrig, L., France, R. L., Goldman, C. R., Heanue, K., Jones, J. A., Swanson, F. J., Turrentine, T., & Winter, T. C. (2003). *Road ecology: Science and solutions.* Island Press.

Francis, C. D., & Barber, J. R. (2013). A framework for understanding noise impacts on wildlife: An urgent conservation priority. *Frontiers in Ecology and the Environment, 11*(6), 305–313.

Gucinski, H., Furniss, M. J., Ziemer, R. R., & Brookes, M. H. (2001). *Forest roads: A synthesis of scientific information* (General Technical Report PNW-GTR-509). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Hamilton, H., Smyth, R. L., Young, B. E., Howard, T. G., Tracey, C., Breyer, S., Cameron, D. R., Chazal, A., Conley, A. K., Frye, C., & Schloss, C. (2022). Increasing taxonomic diversity and spatial resolution clarifies opportunities for protecting US imperiled species. *Ecological Applications, 32*(3), e2534.

Hoffmann, M. T., Ostapowicz, K., Bartoń, K., Ibisch, P. L., & Selva, N. (2024). Mapping roadless areas in regions with contrasting human footprint. *Scientific Reports, 14*, 4722.

Ibisch, P. L., Hoffmann, M. T., Kreft, S., Pe'er, G., Kati, V., Biber-Freudenberger, L., DellaSala, D. A., Vale, M. M., Hobson, P. R., & Selva, N. (2016). A global map of roadless areas and their conservation status. *Science, 354*(6318), 1423–1427.

Jacobson, S. L., Bliss-Ketchum, L. L., de Rivera, C. E., & Smith, W. P. (2016). A behavior-based framework for assessing barrier effects to wildlife from vehicle traffic volume. *Ecosphere, 7*(4), e01345.

Jaeger, J. A. G., Bowman, J., Brennan, J., Fahrig, L., Bert, D., Bouchard, J., Charbonneau, N., Frank, K., Gruber, B., & von Toschanowitz, K. T. (2005). Predicting when animal populations are at risk from roads: An interactive model of road avoidance behavior. *Ecological Modelling, 185*(3–4), 329–348.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics, 33*(1), 159–174.

Luce, C. H., & Black, T. A. (1999). Sediment production from forest roads in western Oregon. *Water Resources Research, 35*(8), 2561–2570.

Luce, C. H., Rieman, B. E., Dunham, J. B., Clayton, J. L., King, J. G., & Black, T. A. (2001). *Incorporating aquatic ecology into decisions on prioritization of road decommissioning* (Water Resources and Environment Technical Note 3). U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Mack, E., Lilja, R., Claggett, S., Sun, G., & Caldwell, P. (2022). *Forests to Faucets 2.0: Connecting forests, water, and communities* (General Technical Report WO-99). U.S. Department of Agriculture, Forest Service.

Madadi, H., Moradi, H., Soffianian, A., Salmanmahiny, A., Senn, J., & Geneletti, D. (2017). Degradation of natural habitats by roads: Comparing land-take and noise effect zone. *Environmental Impact Assessment Review, 65*, 147–155.

Margules, C. R., & Pressey, R. L. (2000). Systematic conservation planning. *Nature*, *405*(6783), 243-253.

Mathew, S., & Pulugurtha, S. S. (2021). Comparative assessment of geospatial and statistical methods to estimate local road annual average daily traffic. *Journal of Transportation Engineering, Part A: Systems, 147*(7), 04021035.

OpenStreetMap contributors. (2024). *OpenStreetMap*. https://www.openstreetmap.org

Polak, M., Wiącek, J., Kucharczyk, M., & Orzechowski, R. (2013). The effect of road traffic on a breeding community of woodland birds. *European Journal of Forest Research*, *132*(5), 931-941.

Pulugurtha, S. S., & Mathew, S. (2021). Modeling AADT on local functionally classified roads using land use, road density, and nearest nonlocal road data. *Journal of Transport Geography, 93*, 103071.

Quigley, T. M., & Arbelbide, S. J. (Eds.). (1997). *An assessment of ecosystem components in the Interior Columbia Basin and portions of the Klamath and Great Basins* (General Technical Report PNW-GTR-405). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Raymond, S., Chadwick, E. A., & Perkins, S. E. (2026). Quantifying roadless areas and fragmentation in the context of wildlife-vehicle collision risk in Great Britain. *Scientific Reports*, 16, 3890.

Reijnen, R., Foppen, R., Braak, C. T., & Thissen, J. (1995). The effects of car traffic on breeding bird populations in woodland. III. Reduction of density in relation to the proximity of main roads. *Journal of Applied Ecology, 32*, 187–202.

Shannon, G., McKenna, M. F., Angeloni, L. M., Crooks, K. R., Fristrup, K. M., Brown, E., Warner, K. A., Nelson, M. D., White, C., Briggs, J., McFarland, S., & Wittemyer, G. (2016). A synthesis of two decades of research documenting the effects of noise on wildlife. *Biological Reviews, 91*, 982–1005.

Sosa-Pérez, G., & MacDonald, L. H. (2017). Reductions in road sediment production and road-stream connectivity from two decommissioning treatments. *Forest Ecology and Management, 398*, 116–129.

Switalski, T. A., Bissonette, J. A., DeLuca, T. H., Luce, C. H., & Madej, M. A. (2004). Benefits and impacts of road removal. *Frontiers in Ecology and the Environment, 2*(1), 21–28.

Talty, M. J., Mott Lacroix, K., Aplet, G. H., & Belote, R. T. (2020). Conservation value of national forest roadless areas. *Conservation Science and Practice*, *2*(11), e288.

Trombulak, S. C., & Frissell, C. A. (2000). Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology, 14*(1), 18–30.

U.S. Department of Agriculture, Forest Service. (2000). *Forest Service roadless area conservation: Final environmental impact statement* (Vols. 1–4). U.S. Department of Agriculture.

U.S. Department of Agriculture, Forest Service. (2011). *Watershed condition framework* (FS-977). https://www.fs.usda.gov/sites/default/files/Watershed_Condition_Framework.pdf

U.S. Department of Agriculture, Forest Service. (2024). FIRESTAT fire occurrence – Yearly update [Data set]. USDA Forest Service Enterprise Data Warehouse. https://data-usfs.hub.arcgis.com/datasets/810d6a45daf441e9bdb5838ef080366b_0

van der Ree, R., Smith, D. J., & Grilo, C. (2015). The ecological effects of linear infrastructure and traffic: Challenges and opportunities of rapid global growth. In R. van der Ree, D. J. Smith, & C. Grilo (Eds.), *Handbook of Road Ecology* (pp. 1–9). John Wiley & Sons, Ltd.

van Strien, M.J., Grêt-Regamey, A. Global expansion of the ecological impact of extra-urban road traffic. *Nat Sustain* **8**, 1294–1303 (2025). https://doi.org/10.1038/s41893-025-01637-2

Ware, H. E., McClure, C. J. W., Carlisle, J. D., & Barber, J. R. (2015). A phantom road experiment reveals traffic noise is an invisible source of habitat degradation. *Proceedings of the National Academy of Sciences, 112*(39), 12105–12109.

Wemple, B. C., Swanson, F. J., & Jones, J. A. (2001). Forest roads and geomorphic process interactions, Cascade Range, Oregon. *Earth Surface Processes and Landforms, 26*(2), 191–204.

Wilk, J., Szyszlak-Bargłowicz, J., Słowik, T., Stachyra, P., & Zając, G. (2025). Evaluation of the acoustic impact of the public road network on a nature conservation area: A case study. *Applied Sciences, 15*(12), 6511.

Zeller, K. A., Ditmer, M. A., Squires, J. R., Rice, W. L., Wilder, J., DeLong, D., Egan, A., Pennington, N., Wang, C. A., Plucinski, J., & Barber, J. R. (2024). Experimental recreationist noise alters behavior and space use of wildlife. *Current Biology, 34*(13), 2997–3004.e3.

Appendix A: Data Sources and Access

Dataset	Source	URL/Path
IRA boundaries	USFS Geodata Clearinghouse	data.fs.usda.gov
OSM roads	Geofabrik GmbH	download.geofabrik.de
INFRA roads	USFS Geodata Clearinghouse	data.fs.usda.gov
MVUM roads	USFS Geodata Clearinghouse	data.fs.usda.gov
Species range	USFWS ECOS	ecos.fws.gov
F2F2 watersheds	USFS	usfs.maps.arcgis.com
Measure of Biodiversity Importance	NatureServe	https://www.natureserve.org/map-biodiversity-importance
FIRESTAT ignitions	USFS EDW	apps.fs.usda.gov

Appendix B: Summary Statistics

Table B-1. 2001 Rule IRA system overview.

Metric	Value
Total IRAs (2001 Rule)	2,296
Total IRA area	44,700,743 acres (44.7 million)
States represented	37
Road segments within 1 mile (excl. ID/CO)	204,343
Total road length in IRA and buffer	172,251 km (107,032 miles)
Roads inside IRAs	18,186 km (11,300 miles)
REZ area (3-class, non-overlapping)	9,797 km^2 (2.4 million acres)
REZ as % of IRA area	5.4%
ESA-listed species in IRAs	377
HUC12 watersheds (>=20% IRA coverage)	2,281
Priority watersheds with non-IRA density > 1 mi/mi^2	264 of 307 (86%)
Priority watersheds with total density > 1 mi/mi^2	218 of 307 (71%)
People served by threshold-exceeding watersheds	1,100,758
IRA vs. non-IRA road density ratio	17.0x
Wildfire ignitions in IRAs (2001--2024)	12,837

Metric	Value
Ignition density ratio (buffered/unroaded)	3.3x
Human ignition density ratio (roaded vs unroaded)	10.1x

Appendix C: OSM attributes and classification accuracy

This appendix documents the OpenStreetMap (OSM) attributes used to classify roads, how those tags were translated into 3-class Road Effect Zones, the completeness of the input attributes, the per-segment confidence of the classifier, and independent validation of the resulting classification. Definitions are summarized from the OSM Wiki (https://wiki.openstreetmap.org). Only the values that appear in our 2001 Rule road dataset are listed.

C.1 Highway – Functional Road Class

The `highway` tag is OSM's primary classifier for any feature drivable, walkable, or rideable. It indicates the road's role in the network rather than its physical condition.

Value	OSM definition (paraphrased)	Typical real-world example
motorway	Restricted-access, divided highway with grade-separated interchanges. The highest road class in OSM.	Interstate freeway (I-90, I-25).
trunk	Important through route, often divided, that does not meet motorway standards.	US-2, US-20 in undivided sections.
primary	Major road connecting larger towns; the most important road below trunk.	Numbered US or state highway, two lanes, paved.
secondary	Secondary through road linking smaller towns or feeding primary roads.	County highway, paved, two lanes.
tertiary	Local road connecting villages or distributing traffic to residential areas.	Paved or graded county road.
unclassified	Minor public road, not a residential street. Despite the name, *unclassified* is itself a class --- a	Paved or gravel rural connector with no route number.

	public road below tertiary that connects places.	
residential	Road providing access to housing, in or near a settlement.	Subdivision street.
track	Road used primarily for agricultural, forestry, or other rough/limited use; usually unpaved. Most Forest Service system roads are tagged `track`. Paired with `tracktype=grade1...5` to indicate condition.	Forest road, ranch two-track, logging spur.
*_link (motorway_link, trunk_link, primary_link, secondary_link, tertiary_link)	Slip road / on-ramp / off-ramp connecting a road of class X to another road. Inherits the impact characteristics of its parent class.	Interchange ramp, turn-off lane.

C.2 Surface – Running Surface Material

The `surface` tag describes the physical material the vehicle drives on. We grouped the values into three families: paved (sealed surfaces), improved unpaved (gravel/compacted aggregate), and unimproved (native soil, sand, or generic unsealed surfaces).

Paved surfaces.

Value	OSM definition (paraphrased)
paved	Generic value indicating a sealed, hard surface where the specific material isn't specified.
asphalt	Bituminous asphalt concrete --- the most common modern paved surface.
concrete	Portland cement concrete slab or pour.
paving_stones	Manufactured pavers or cobble-style stones laid over a prepared base.

Improved unpaved surfaces.

Value	OSM definition (paraphrased)
gravel	Loose, broken stone, typically fist-sized or smaller.
fine_gravel	Smaller, more uniform crushed stone --- closer to a smooth running surface than gravel.
compacted	Mixed material (gravel + sand + fines) compacted into a hard but unsealed surface. Common on well-maintained forest and ranch roads.

Unimproved surfaces.

Value	OSM definition (paraphrased)
unpaved	Generic catch-all when the specific unsealed material isn't specified.
dirt	Native soil, no added material.
earth	Synonym for dirt in older tagging.
ground	Generic natural ground, often used when the surface is a mix or uncertain.
sand	Loose sand.

C.3 Tracktype - Track Grade (only on highway=track)

`tracktype` is a five-step ordinal scale describing the firmness and quality of a track's running surface. It is only meaningful when paired with `highway=track`. The grade does not describe steepness — in OSM, "grade" refers to surface quality, similar to how a road engineer might grade an aggregate road A–F.

Value	OSM definition (paraphrased)	Implied surface	Vehicle suitability
grade1	Solid, sealed or very firmly compacted. Indistinguishable from a paved road in the dry. Visible pavement, asphalt, concrete, or heavily compacted gravel/hardcore.	Paved or compacted gravel	Any passenger vehicle, year-round.

grade2	Mostly solid running surface with a loose top layer (gravel, rolled aggregate, fine stones). Hard packed beneath.	Gravel / compacted	Passenger vehicle, dry conditions.
grade3	Even mix of hard and soft material. Loose surface predominates; ruts may develop.	Mixed gravel/dirt	High-clearance vehicle preferred.
grade4	Predominantly soft surface (soil, grass, sand) with some firm patches. Often two parallel tire tracks with vegetation between.	Mostly dirt/native	High-clearance / 4WD recommended.
grade5	Soft, often barely distinguishable from surrounding terrain. Native soil, sand, or grass throughout. May be impassable when wet.	Native ground	4WD or specialized vehicle.

A `highway=track` segment can range from a freshly graveled forest road that cars drive comfortably (grade1) to a faint two-track that fades into the landscape (grade5). Without `tracktype` we would have to assume one impact level for all of them; with it, well-built tracks can be separated from primitive ones.

C.4 Mapping OSM Tags to REZ Classes

The 3-class Road Effect Zone system combines all three tags hierarchically. Higher-impact rules override lower ones.

REZ Class	Buffer	OSM tags assigning this class
A --- High impact (highway / high volume)	1,000 m	highway in {motorway, trunk, primary, secondary} or any *_link of those four.
B --- Moderate impact (paved / gravel)	300 m	surface in {asphalt, concrete, paved, paving_stones, gravel, fine_gravel, compacted}; or highway=track with tracktype in {grade1, grade2}; or highway in {tertiary, tertiary_link} not

		on a dirt surface; or highway in {residential, unclassified} with paved/gravel surface or grade1/2 evidence.
C --- Low impact (dirt / primitive)	100 m	Everything else, including surface in {dirt, earth, ground, unpaved, sand}, highway=track with tracktype in {grade3, grade4, grade5}, and unclassified/residential roads without surface evidence. Closed roads (motor_vehicle=no or vehicle=no) are also folded into Class C.

Class A always overrides Class B, which always overrides Class C — so a `highway=primary` segment is Class A regardless of its `surface` tag, and a `highway=track` with `surface=asphalt` is Class B regardless of `tracktype`.

C.5 OSM Attribute Completeness

Table C-1. OpenStreetMap attribute completeness for the 2001 Rule road network.

Attribute coverage in the filtered OSM road network (204,343 segments, 107,032 miles). Only attributes used by the classification rules are shown.

Attribute	% of segments	% of road miles
highway	100.0%	100.0%
surface	31.7%	43.7%
tracktype (on highway=track only)	25.7%	30.4%
lanes	6.0%	8.6%
width	0.3%	0.5%
motor_vehicle	4.0%	6.1%
vehicle	0.2%	0.3%

Coverage is highly uneven. The `highway` tag is OSM's primary classifier and is always populated, but surface descriptions are present on less than half the network by length, and physical attributes (lanes, width) are too sparse to drive primary classification rules. `tracktype`—a key signal for distinguishing well-built forest tracks from primitive two-tracks—is recorded for only about a quarter of `highway=track` segments. The classification system therefore relies on the `highway` tag as the backbone and uses `surface`, `tracktype`, and ancillary attributes hierarchically when available.

C.6 Per-Segment Confidence by REZ Class

Table C-2. Per-segment confidence by REZ class.

Each classified segment carries a confidence flag (high / medium / low) reflecting whether the assignment was supported by direct attribute evidence or by a fallback default.

REZ Class	High confidence	Medium	Low (default)	Total segments
A	100.0%	0.0%	0.0%	6,927
B	94.2%	5.8%	0.0%	24,764
C	26.3%	2.6%	71.1%	172,652

High indicates a direct match on `surface`, `tracktype`, or a Class-A `highway` value. *Medium* indicates a fallback to `lanes` or `width` where the primary attributes were missing but an alternate signal supported assignment to a higher class. *Low* indicates default Class C assignment for segments that lacked any positive evidence—typically `highway=track` or `highway=unclassified` segments without surface or tracktype tags.

Class A and B assignments are nearly always anchored in direct evidence (the `highway` tag alone is decisive for A; explicit surface/tracktype evidence supports 94% of B). The majority of Class C assignments, however, are defaults rather than affirmative classifications. This is conservative by design: Class C carries the narrowest 100 m buffer and lowest impact tier, so misclassification of an unmapped segment has minimal area consequence. The independent validation in Table C-4 (Class C user's accuracy 85.1%, producer's accuracy 98.5%) confirms that this fallback strategy nonetheless yields relatively reliable Class C identification.

C.7 Classification Accuracy by Forest Service Region

Table C-3. Classification accuracy by Forest Service region.

Region	Overall Accuracy (%)	Kappa	Agreement Level
Northern	84	0.471	Moderate
Rocky Mountain	92	0.744	Substantial
Southwestern	96	0.485	Moderate
Intermountain	84	0.440	Moderate
Pacific Southwest	84	0.499	Moderate
Pacific Northwest	90	0.611	Substantial
Southern	86	0.655	Substantial
Eastern	86	0.530	Moderate
Alaska	74	0.570	Moderate
All Regions	**86**	**0.600**	**Moderate**

Note: Kappa agreement categories follow Landis and Koch (1977): <0 = Poor; 0.00–0.20 = Slight; 0.21–0.40 = Fair; 0.41–0.60 = Moderate; 0.61–0.80 = Substantial; 0.81–1.00 = Almost Perfect.

C.8 Error Matrix

Table C-4. Error matrix for the combined validation dataset (all regions).

	Actual A	Actual B	Actual C	Pred. Total	Commission Error (%)	User's Acc. (%)
Predicted A	13	0	0	13	0.0	100.0
Predicted B	0	49	5	54	9.3	90.7
Predicted C	0	57	326	383	14.9	85.1
Actual Total	13	106	331			
Omission Error (%)	0.0	53.8	1.5			
Producer's Acc. (%)	100.0	46.2	98.5			

The error matrix reveals that the classification is conservative with respect to road impact: Class A assignments are perfectly reliable (100% user's and producer's accuracy), and Class B user's accuracy is high (90.7%), meaning that when a road is classified as B, it almost always is. However, the model underclassifies many Class B roads into Class C (Class B producer's accuracy 46.2%), meaning that over half of actual B-class roads are assigned to the lower-impact C class. Class C captures nearly all actual low-impact roads (98.5% producer's accuracy) but also absorbs misclassified B segments (85.1% user's accuracy). This asymmetric error pattern means the REZ analysis is more likely to underestimate than overestimate ecological road impacts—misclassified B roads receive the 100 m Class C buffer rather than the 300 m Class B buffer, producing a conservative estimate of total road-affected area.

Appendix D: Buffer-Width Sensitivity Analysis

While our REZ road buffers were drawn from the road ecology literature, we assessed how sensitive the report's headline results are to buffer choice. We compared the full REZ pipeline at four scenarios: the baseline distances; all three distances halved (A=500 / B=150 / C=50); all three distances doubled (A=2,000 / B=600 / C=200); and a single uniform 0.5-mile (805 m) buffer with no class hierarchy. REZ acreage in IRAs increases sharply with buffer width. Doubling the class-tiered buffers triples the REZ extent relative to the baseline analysis, while a single uniform 0.5-mile buffer applied to all roads produces a REZ nearly five times larger than the baseline scenario, and covers more than a quarter of total IRA area.

Table D-1. Buffer parameters and REZ extent across scenarios.

Scenario	A (m)	B (m)	C (m)	REZ km^2	REZ acres	% of IRA
Half	500	150	50	4,025	994,648	2.2%
Baseline	1,000	300	100	9,797	2,420,951	5.4%
Double	2,000	600	200	22,914	5,662,189	12.7%
Uniform 0.5 mi	805	805	805	48,423	11,965,476	26.8%

We found similar effects on REZ impact distribution and REZ acreage in IRA biodiversity hotspots. Under the doubling scenario, the count of "Very High" IRAs grows from 69 to 342, while "Minimal" drops from 509 to 256. The uniform half-mile scenario classifies more than half of the IRAs as High or Very High impact. Biodiversity hotspot exposure also increases drastically, from 4.5–5.9% of MoBI hotspot acres in REZ at the half-buffer scenario, to 40.5–45.0% under the uniform half-mile buffer.

Table D-2. IRA tier distribution and biodiversity hotspot exposure across scenarios.

Scenario	Minimal	Low	Moderate	High	Very High	SR hotspot in REZ	RSR hotspot in REZ
Half	1,037	962	243	36	18	4.5%	5.9%
Baseline	509	927	572	219	69	10.2%	12.8%
Double	256	441	731	526	342	21.3%	26.1%
Uniform 0.5 mi	121	86	255	733	1,101	40.5%	45.0%

Tier columns are counts of IRAs falling in each REZ-coverage tier (Minimal 0–2%, Low 2–10%, Moderate 10–25%, High 25–50%, Very High >50%). MoBI columns show the share of imperiled-species hotspot acreage that falls inside the REZ at each scenario, separately for species richness (SR) and range-size rarity (RSR).

We also ran our scenarios to see how much of the in-IRA REZ is generated by roads that physically lie within IRA boundaries, versus roads that sit outside the boundary.

Table G-3. Inside-IRA road contribution to in-IRA REZ acreage, by class and scenario.

Scenario	Class A	Class B	Class C	All Classes
Half	25.2%	52.2%	89.1%	58.6%
Baseline	22.6%	46.2%	80.4%	50.0%
Double	22.8%	42.3%	77.5%	45.4%
Uniform 0.5 mi	n/a	n/a	n/a	59.9%

Inside-IRA roads contribute only about a quarter (22.6–25.2%) of in-IRA Class A REZ at every class-tiered scenario tested – the remainder is generated by highways outside IRA boundaries whose buffers reach in. Class B sits in an intermediate range (42–52%), and Class C is predominantly internally generated (77–89%). The percentage of inside-IRA REA rises to 59.9% in the .5 mile scenario because the dense low-volume road network within IRAs (22,434 in-IRA road parts) generates a much larger inside-source REZ when buffered at 805 m than at the baseline's 100 m.

The qualitative findings of the report are robust to plausible variation in buffer distance. At every scenario tested, REZ exposure is substantial, IRAs fall along a steep gradient of road exposure, biodiversity hotspots are disproportionately exposed (10–26% of hotspot acres in REZ at baseline-or-wider buffers), and roughly half of in-IRA REZ at the baseline scenario is generated by roads outside the IRA boundary.

Appendix E: Maps

The following maps provide regional detail for the four principal map themes presented in the report. Western US maps show all IRAs in USFS Regions R01–R06 on a single page. Eastern, Southern, and Alaska maps use a six-panel layout covering Appalachia, Northeast, Upper Midwest, Lower Midwest and Gulf, Southeast, and Alaska (R10). A satellite detail map of the West Slope Winds IRA illustrates wildfire ignition patterns at landscape scale.

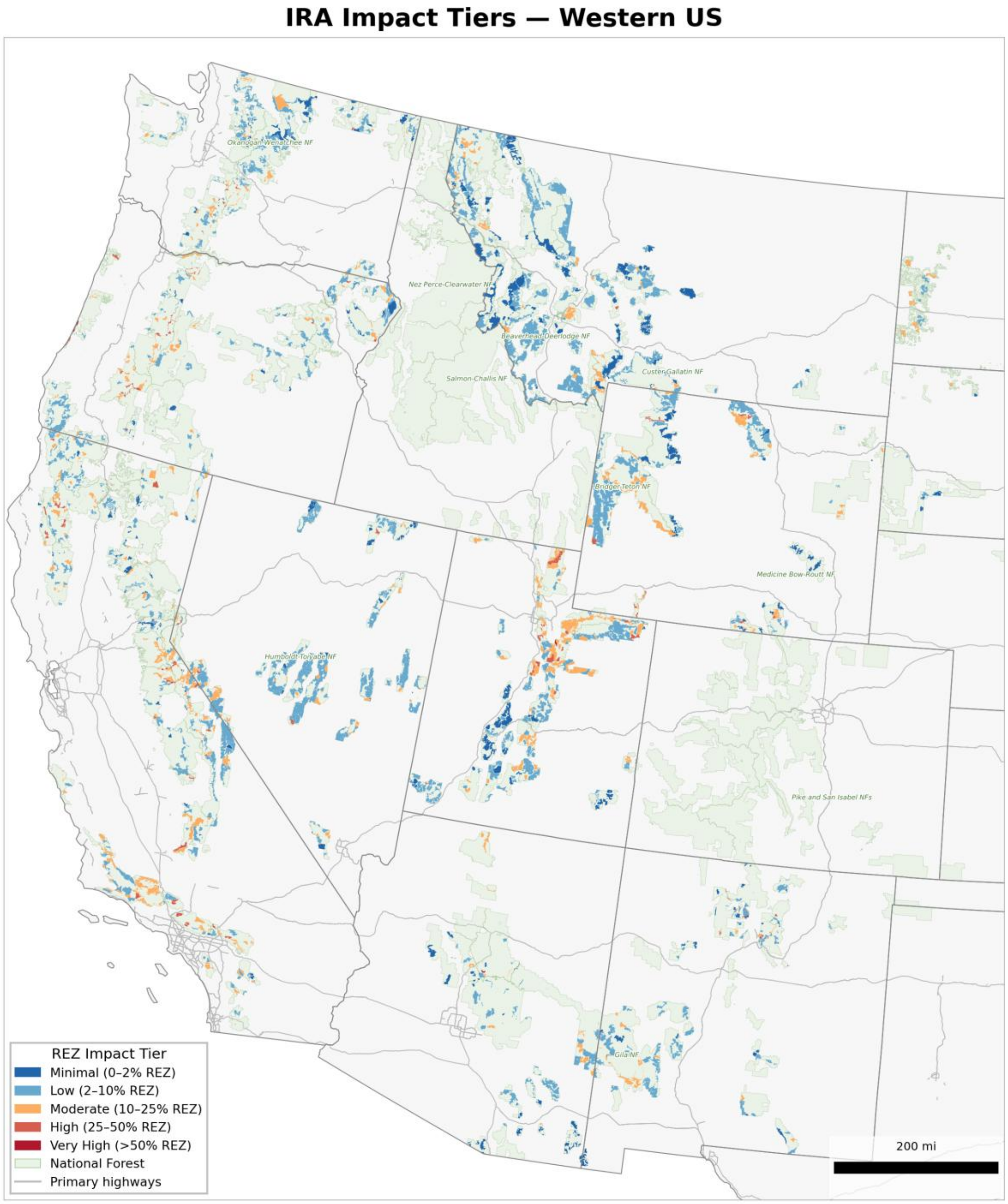


Figure E-1. REZ Impact Tiers — Western United States.

Figure E-2. REZ Impact Tiers — Eastern/Southern United States.

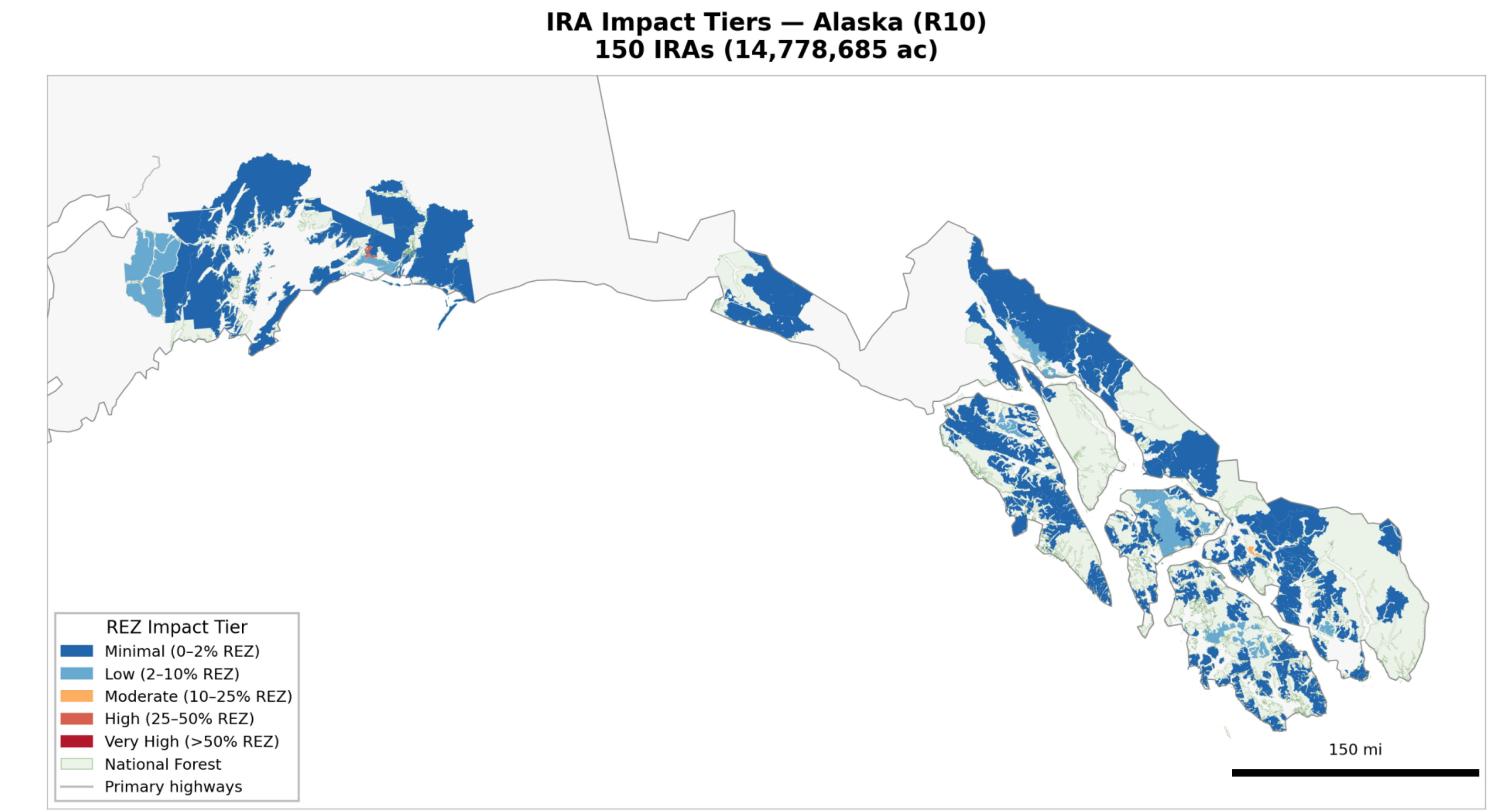


Figure E-3. REZ Impact Tiers — Alaska.

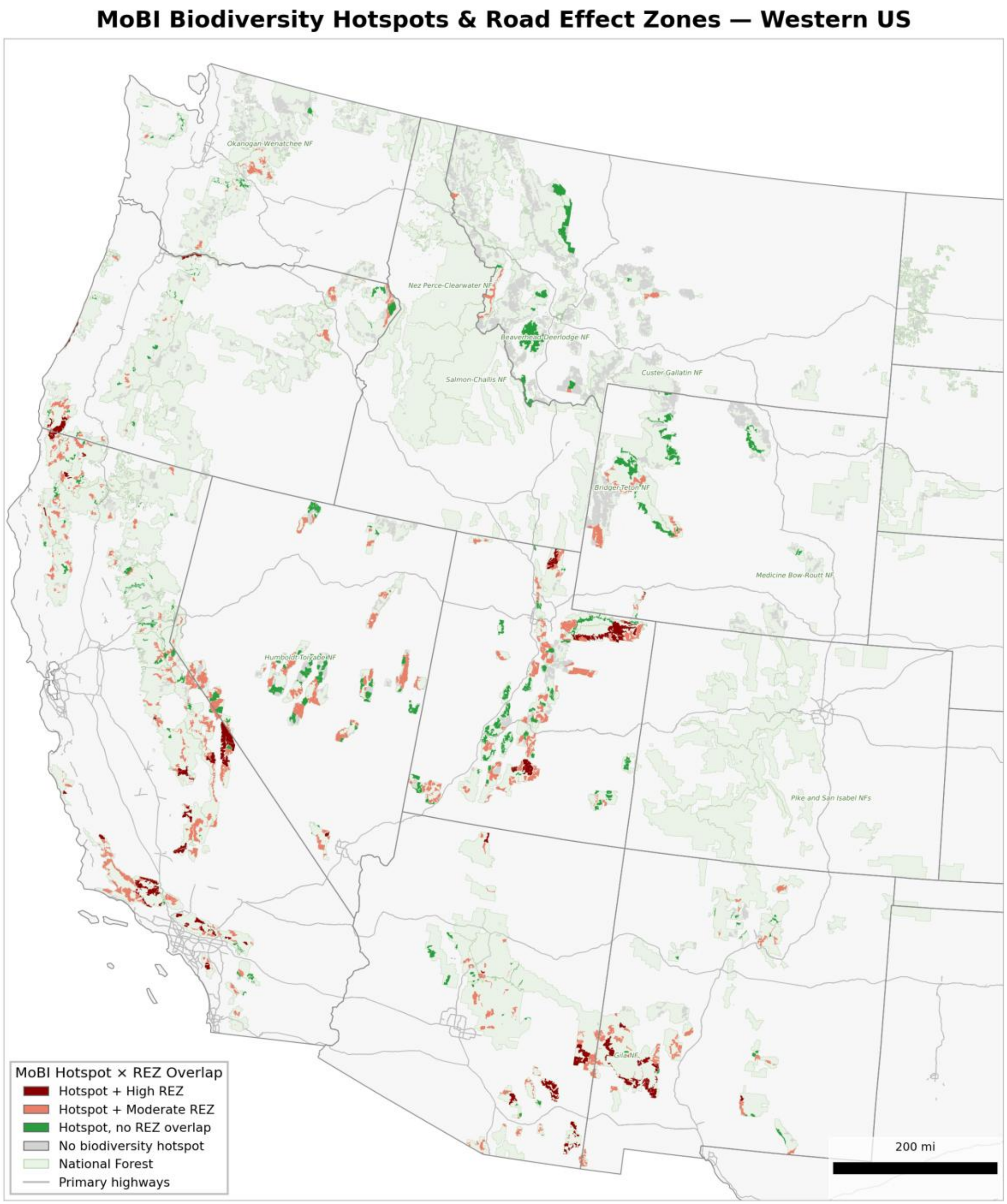


Figure E-4. MoBI Biodiversity Hotspot × REZ Overlap — Western United States.

MoBI Biodiversity Hotspots & Road Effect Zones — Eastern & Southern US

Figure E-5. MoBI Biodiversity Hotspot × REZ Overlap — Eastern/Southern United States.

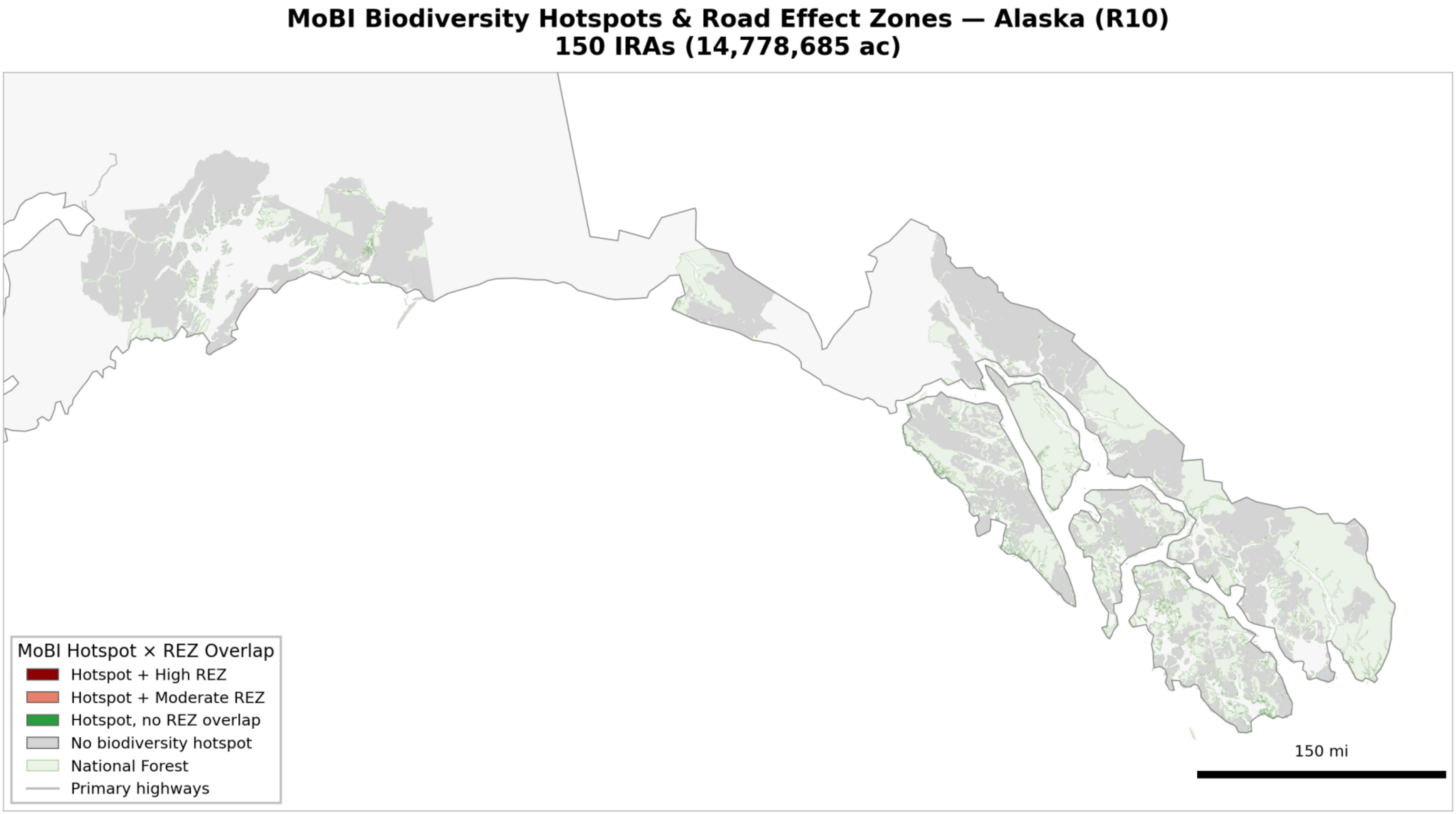


Figure E-6. MoBI Biodiversity Hotspot × REZ Overlap — Alaska.

Figure E-7. Priority Drinking Water Watershed Road Density — Western United States.

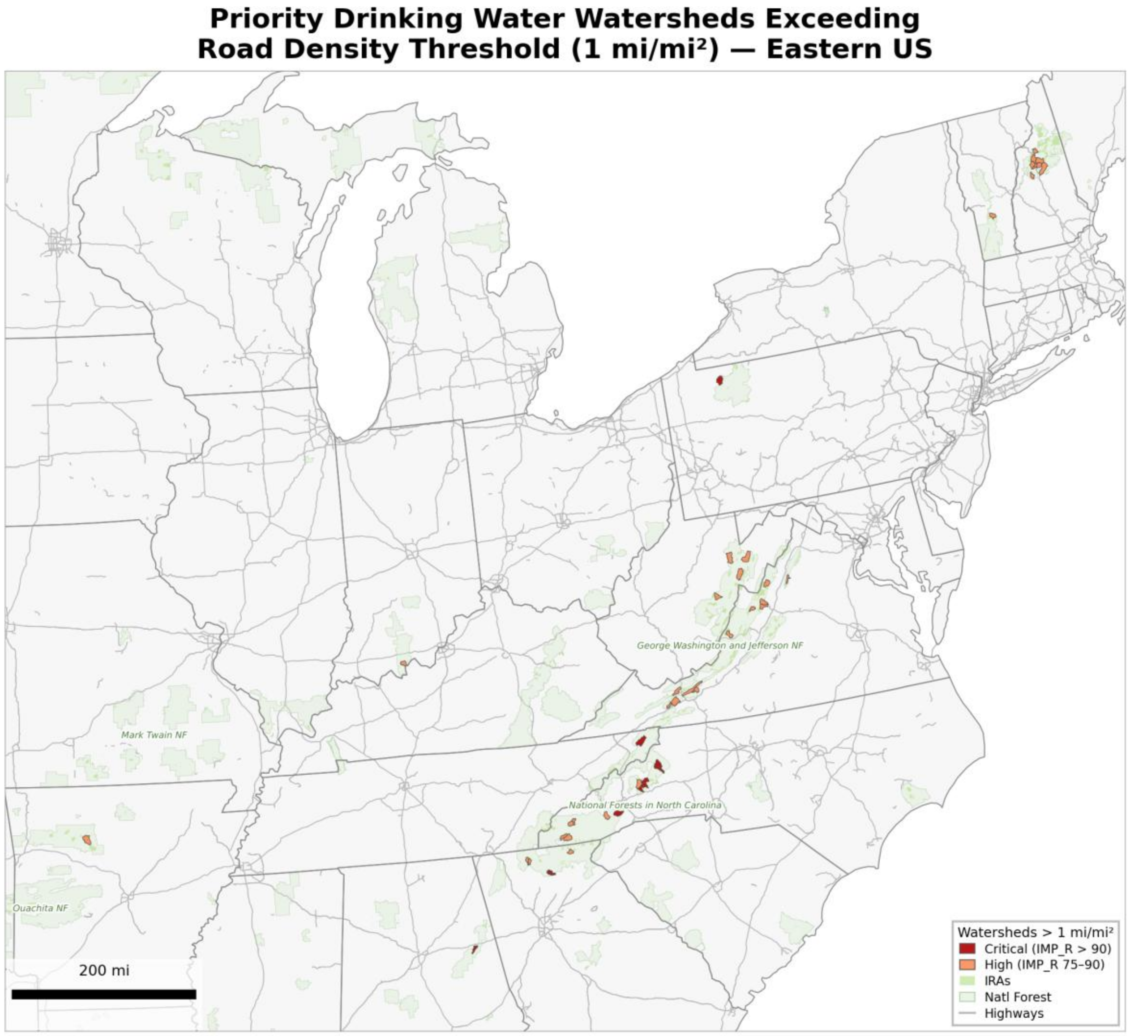


Figure E-8. Priority Drinking Water Watershed Road Density — Eastern United States.

Figure E-9. Human-Caused Wildfire Ignitions (2001–2024) — Western United States.

Figure E-10. Human-Caused Wildfire Ignitions (2001–2024) — Eastern/Southern United States.

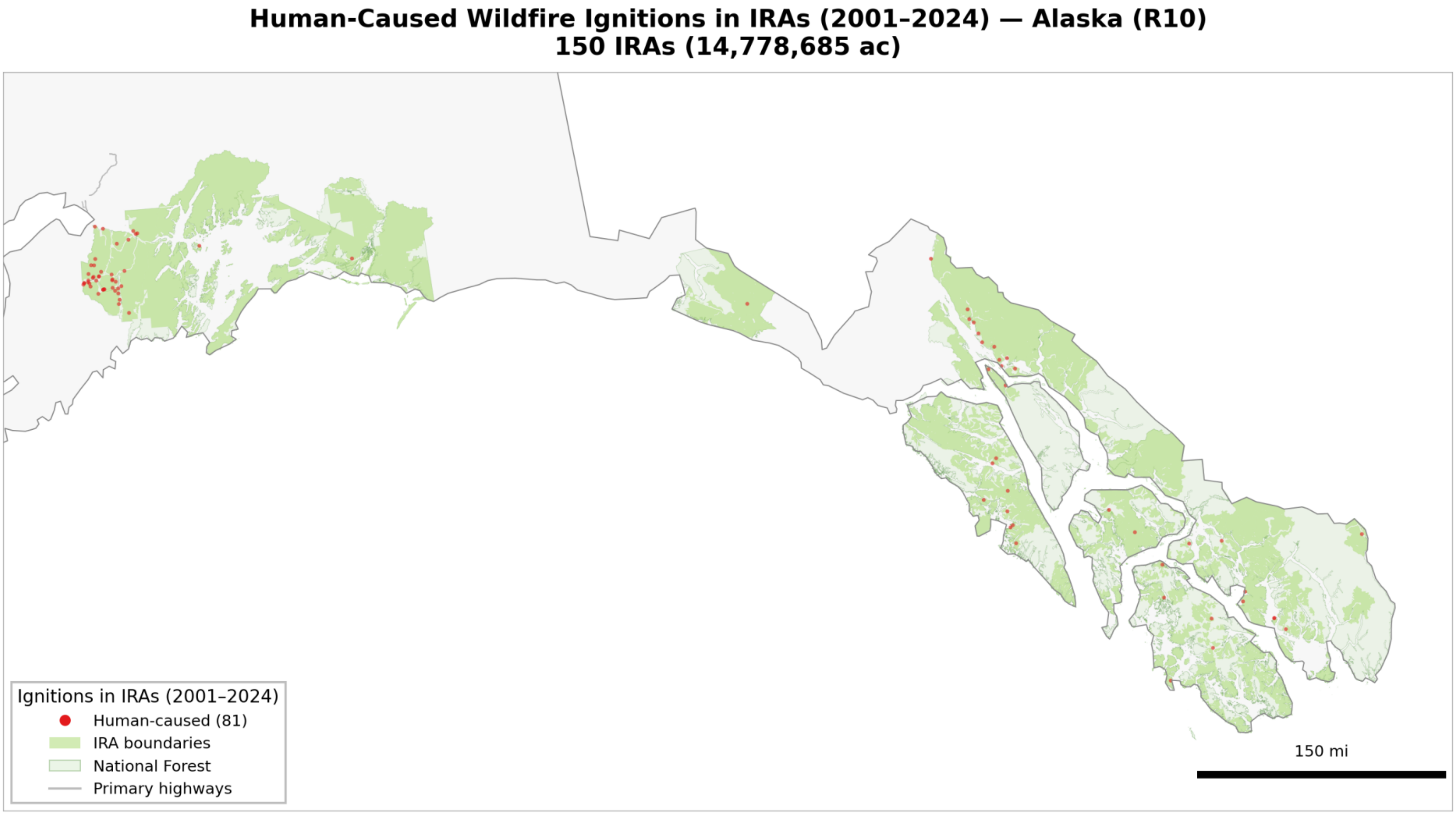


Figure E-11. Human-Caused Wildfire Ignitions (2001–2024) — Alaska.

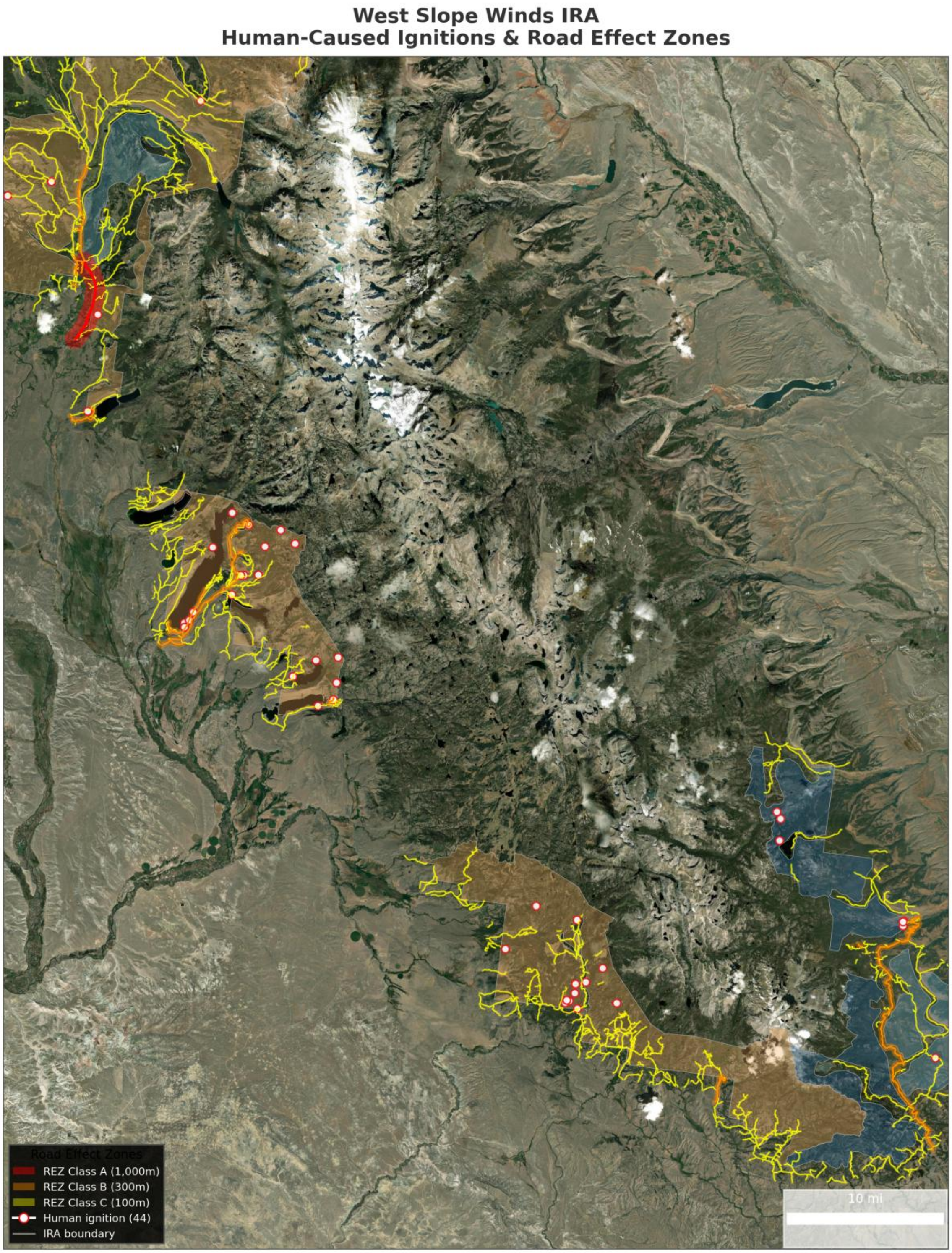


Figure E-12. Satellite Detail: West Slope Winds IRA — wildfire ignitions in IRAs are clustered around roads.