

ROAD MANAGEMENT REGARDING WILDFIRE VULNERABILITY IN THE REGION OF THESSALY, GREECE

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Abstract

The escalating frequency and severity of wildfire events have revealed fundamental deficiencies in conventional management approaches centered primarily on mitigation efforts. This necessitates a paradigm shift toward proactive strategies grounded in adaptive frameworks that recognize fire as an inherently dynamic ecological phenomenon. Central to this transformation is the reconceptualization of road infrastructure from fixed assets to adaptable systems with the capacity to facilitate both preventive measures and rapid emergency response. Within this shift, road networks assume a complex and essential function. Rather than serving solely as transportation pathways, roads must be understood as integrated, multi-purpose elements within resilient landscape systems. This research consolidates insights from wildfire risk assessment and road network analysis to develop an adaptive management framework for road infrastructure in the Thessaly Region. The approach is grounded in comprehensive wildfire risk evaluation, which enables the classification of road networks into distinct risk zones suitable for tailored management interventions. These interventions must operate as ongoing, responsive processes rather than static, single-occurrence measures, continuously evolving in response to emerging scientific evidence and systematic monitoring. This cyclical approach guarantees that management practices remain both effective and responsive to changing environmental dynamics, thereby strengthening landscape resilience in the face of wildfire threats.

Key words: Road network management, wildfire risk, public policy, GIS, Thessaly Region

1. INTRODUCTION

The Mediterranean Basin is currently navigating a precarious ecological shift often termed a "pyric transition." We are witnessing the rise of "mega-fires" events of such ferocity and speed that they render standard firefighting capabilities obsolete (Moreira et al., 2020). Within this volatile environment, a region's road network plays a complicated, dual role. It is, undeniably, the backbone of civil protection, serving as the primary escape route for civilians

and the entry point for suppression forces (Molina-Terrén et al., 2019). Yet, paradoxically, these same roads fragment habitats and can act as vectors for human-caused ignitions (Leone et al., 2023).

For decades, forest management in Southern Europe viewed roads merely as static assets, maintained strictly for logistical efficiency or biomass exploitation. However, the accelerating climate crisis demands, we rethink this approach. Roads must evolve into dynamic lines of defense integral parts of a "fire-smart" landscape designed to mitigate fire behavior rather than just facilitate travel (Fernandes, 2013). This evolution is particularly pressing in Greece, where the rugged topography creates a logistical nightmare for emergency planners (Xanthopoulos et al., 2022). Previous research has highlighted the importance of optimizing these networks not just for timber transport, but for multi-criteria decision making that includes fire prevention (Liampas, Stamatiou, and Drosos, 2019).

The Region of Thessaly offers the necessary diversity to test this new approach. It presents a landscape of extremes: from the flat agropastoral expanse of the central plain to the steep, inaccessible slopes of the Pindos mountains and the tourist-dense coastlines of Magnesia. While recent Greek legislation (Circular YPEN/DAOKA/42966/1311, 2024) has rightly focused on hardening properties near forests, there is a glaring lack of strategy regarding the resilience of the road network itself.

The aim of this paper is to union the wildfire risk data with detailed network topology, to strengthening landscape resilience in the face of wildfire threats framework. Our goal is to move beyond static maintenance schedules to a system of continuous risk assessment (Chuvienco et al., 2023). The study aims to quantify the "accessibility deficit" in Thessaly, identifying exactly where the need for protection is mostly needed and pinpoint the operational "blind spots" that compromise safety (Palaiologou et al., 2020).

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

The struggle to align road ecology with wildfire defense is not unique to Greece; it is a priority shared across the Mediterranean, with pivotal research emerging from Portugal, Spain, and Italy. Following Portugal's tragic 2017 fire season, the scientific consensus shifted away from pure suppression. Researchers like Moreira et al. (2020) championed the idea of "Fire-Smart Territories." The core argument is that we cannot simply fight fires; we must engineer landscapes that resist them. In this view, road networks should do more than connect point A to point B, they should compartmentalize the land, breaking up continuous fuel loads into manageable blocks (Tedim et al., 2018). Major arteries thus become strategic "anchor points" for counter-fire operations (Castellnou et al., 2019).

There is a counter-intuitive thread in the literature regarding road density. Conventional wisdom suggests that more roads equal faster response times, which is crucial for stopping a fire early (Plucinski, 2019). However, Leone et al. (2023), working in the Apulia region of Italy, uncovered a complication: higher road density often leads to higher ignition frequency simply because it brings more people into the forest. This "accessibility paradox" suggests that paving more roads into the wilderness is not a silver bullet (Ricotta et al., 2018). The solution lies not in quantity, but in the defensibility of the existing corridors (Dunn et al., 2020).

Effective management requires sophisticated decision support systems. Palaiologou, Papageorgiou et al. (2021) demonstrated that spatial optimization frameworks are essential for balancing competing forest management priorities, such as timber production versus fire resilience. Their work in Macedonia, Greece, highlighted that trade-offs are inevitable, and that optimal infrastructure planning must account for these conflicting goals. Similarly, Liampas, Stamatiou, and Drosos (2019) utilized Least Cost Path Analysis (LCPA) to prove

that road network planning must integrate biomass exploitation with fire prevention logic to be economically and ecologically viable.

The Vulnerability of the Wildland-Urban Interface (WUI) is the critical zone where human settlements meet combustible vegetation. In Greece, unmanaged WUI expansion has been identified as a primary driver of risk (Mitsopoulos et al., 2020). Studies by Badia et al. (2019) in Spain confirm that roads in these zones often fail during mass evacuations due to smoke occlusion and panic. In this study, the analysis of Thessaly's road network specifically targets these interface zones, applying the lessons from the catastrophic Mati fire of 2018 (Lekkas et al., 2018).

3. METHODOLOGY

To rigorously evaluate the interplay between infrastructure and fire risk, we adopted a geospatial analysis approach covering the entirety of the Region of Thessaly. The Study Area of Thessaly acts as a crucial ecological crossroad in Greece. Administratively split into four units of Karditsa, Larissa, Magnesia (including the Sporades), and Trikala, the region is defined by a massive central plain ringed by mountains (Olympus, Ossa, Pelion, Pindos). This semispherical shape creates diverse microclimates, transitioning from lowland scrub to high-altitude coniferous forests, each presenting distinct fire behaviors (Koutsias et al., 2016).

The methodology to calculate the wildfire risk is based in the National Wildfire Risk Assessment Framework (Gitas et al., 2021). This standard evaluates risk through 14 parameters across six groups: morphology, climate, slope, vegetation, infrastructure, and incident history. For this study we tweaked the model and make a Wildfire Risk Map using only five of the six groups, deliberately excluding the "infrastructure" parameter. We did this to avoid circular logic; we wanted to assess the inherent danger of the landscape before overlaying the road network to see how well the infrastructure serves the terrain (Salavati et al., 2022).

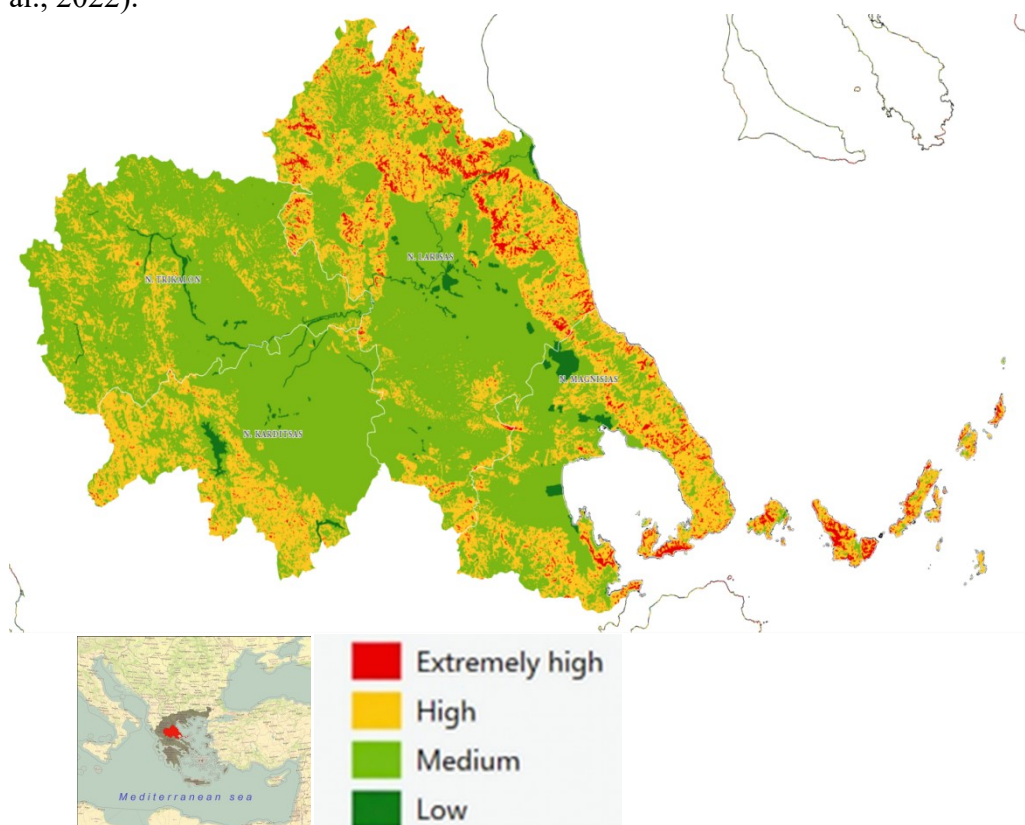


Figure 1. Wildfire risk mapping of Thessaly

The Geospatial Analysis workflow was implemented through a four-stage process. In the initial stage, road network data were acquired from open-source repositories within the OpenStreetMap (OSM) framework, and a comprehensive vector dataset was compiled specifically for the Thessaly Region. This compilation yielded a total road network extent of 41,798 km of infrastructure (note that road length measurements throughout this study represent horizontal plane projections). The second step is to overlay the road network to the wildfire risk map using GIS. This allowed us to tag every single kilometer of road with the risk level of the land it crosses (Low, Medium, High, Extremely High). The third step is the extraction, where we analyze the numbers, calculating road lengths per risk category at the Regional, Prefecture, and Municipal levels. The last step is the Indicator Development. To make sense of the raw data, we developed the "Accessibility-Risk Mismatch" indicator. This metric compares the percentage of land requiring protection against the percentage of infrastructure available to provide it.

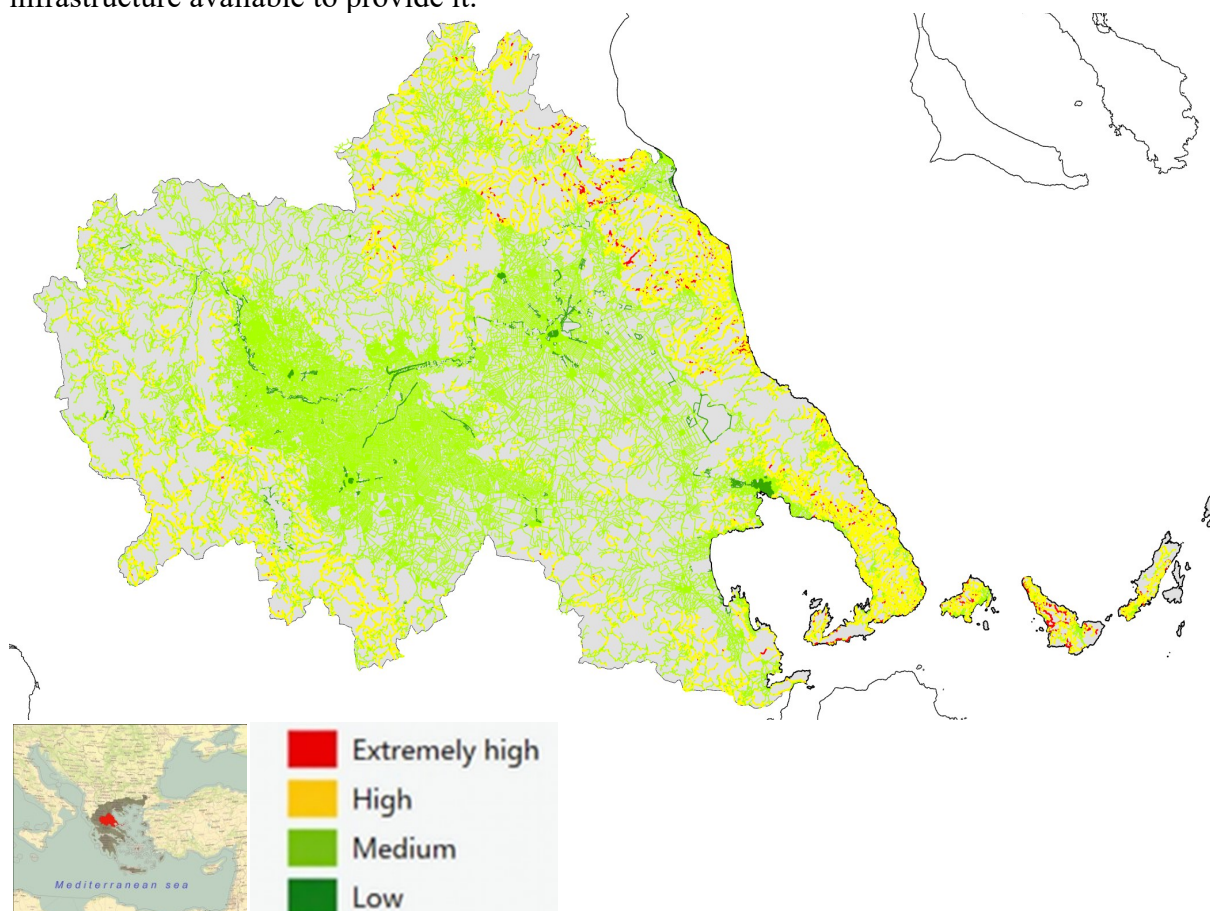


Figure 2. Wildfire risk mapping of the road network

4. STATISTICAL DATA & RESULTS

Analyzing nearly 42,000 km of roads against the fire risk landscape exposed deep inequalities in Thessaly's resilience profile.

The Regional Risk Distribution, the data reveals a stark imbalance. Most of the region's roads pass through relatively safe areas, while the most dangerous zones are under-served.

Table 1. Comparison of Land Area vs. Road Network Length per Risk Category

Wildfire Risk	Area (km²)	Area (km²) Percentage	Road network (km)	Road network (km) Percentage
Extremely High	1215.61	8.7%	583.42	1.4%
High	3953.23	28.1%	8058.98	19.3%
Medium	8449.29	60.1%	31893.98	76.3%
Low	430.65	3.1%	1262.56	3.0%
Total	14048.78	100.0%	41798.93	100.0%

- Low Risk: This covers 3.1% of the land and contains a proportional 3.0% (1,262 km) of the roads.
- Medium Risk: This category dominates, covering 60.1% of the land and holding the vast majority—76.3% (31,894 km)—of the network. This makes sense, as this includes the agricultural plains where road density is naturally high.
- High Risk: Here, the gap widens. High-risk land accounts for 28.1% of the region, yet it contains only 19.3% (8,059 km) of the roads.
- Extremely High Risk: This is the crucial finding. The most dangerous 8.7% of the land (1,215 km²) is served by a meager 1.4% (583 km) of the road network.

Table 2. Data of Land Area vs. Road Network Length Data per Risk Category per Regional Unit & Municipality and Municipality Population

Regional unit	Municipality	Population	Extremely High	High	Medium	Low	Total
Karditsa	Argitheia	3498	5.84	367.39	250.91	0.42	624.57
	Karditsa	55979	4.07	362.38	2211.74	87.58	2665.77
	Lake Plastiras	5234	4.02	169.28	345.75	21.98	541.02
	Mouzaki	11246	3.25	196.67	1233.41	8.34	1441.67
	Palamas	13427		11.05	2017.81	58.81	2087.67
	Sofades	16927	3.94	238.27	2138.25	2.54	2383.01
	Total Karditsa	106311	21.12	1345.04	8197.87	179.68	9743.72
Larissa	Agia	10710	113.41	1027.17	760.14	22.96	1923.67
	Elassona	25459	82.63	1254.75	1997.48		3334.86
	Kileler	18070	0.44	86.31	2721.81	89.79	2898.35
	Larissa	164093		26.78	1568.61	164.23	1759.63
	Tempi	12005	105.67	595.58	1082.78	51.70	1835.73
	Tyrnavos	22283	16.43	240.11	1125.10	55.00	1436.64
	Farsala	16342	2.57	148.71	1609.30	14.90	1775.48
	Total Larissa	268962	321.15	3379.41	10865.22	398.59	14964.37
Magnesia & Sporades	Almyros	16073	10.55	440.42	1442.85	13.90	1907.72
	Alonnisos	3138	15.61	109.34	33.03		157.97
	Volos	139672	19.90	414.60	1124.96	318.25	1877.71
	Zagora-Mouresi	4562	13.74	263.39	221.61		498.73
	South Pelion	8276	90.56	1011.62	218.03		1320.20
	Rigas Feraios	8869	1.20	109.76	803.04	73.38	987.37
	Skiathos	5804	21.79	112.46	75.05	0.99	210.29

	Skopelos	4520	66.95	166.34	54.62		287.91
	Total Magnesia & Sporades	190914	240.30	2627.93	3973.17	406.52	7247.92
Trikala	Meteora	19276	0.60	402.61	2909.69	56.22	3369.12
	Pyli	12851	0.25	227.76	1782.53	30.67	2041.21
	Trikala	78608		51.61	2754.53	111.57	2917.70
	Farkadona	11350		24.62	1410.97	79.32	1514.90
	Total Trikala	122085	0.84	706.60	8857.72	277.77	9842.93
Total Thessalia	688272	583.42	8058.98	31893.97	1262.56	41798.93	

In the analysis by Regional Unit, it is perceived that the risk is not shared equally among the prefectures.

Regional Unit Risk Distribution



Figure 3. Comparison of Regional Units vs Percentage of Road Network Length per Risk Category

- Larissa: This unit faces the highest absolute exposure, with 321 km of roads in "Particularly High" risk zones and over 3,300 km in "High" risk zones.
- Magnesia & Sporades: While smaller in area, this unit faces the most acute relative threat. A staggering 36% of its road network sits in "High" risk zones, with another 3% in "Particularly High" zones.
- Trikala & Karditsa: These units are comparatively sheltered. Trikala has less than 1 km of road in the highest risk category, and Karditsa has only about 21 km. The overwhelming majority of their networks (90% and 84%, respectively) sit in "Medium" risk territory.

In the analysis by altitude, it is perceived that the vertical distribution of risk challenges follows the assumption that the highest peaks are the most dangerous.

Altitude Zones

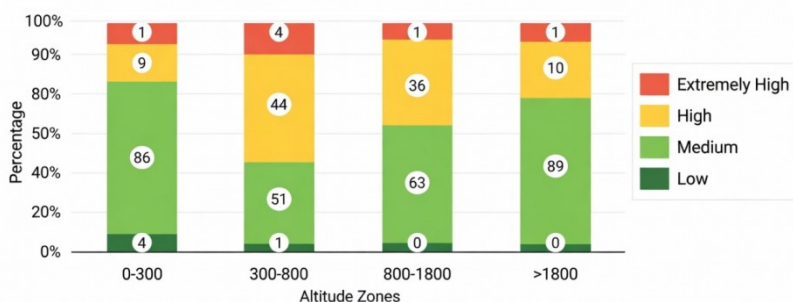


Figure 4. Distribution of High-Risk Road Networks by Altitude Zone.

- 0 – 300 m: The lowlands are mostly safe, containing 86% of the Medium-risk network.
- 300 – 800 m: This is the "Danger Zone." This mid-altitude belt contains 44% of the region's total "High" risk roads. This elevation typically marks the WUI, where human activity impinges on forest land (Radeloff et al., 2018).
- 800 – 1800 m: While this zone holds 36% of the "High" risk network, the "Particularly High" risk drops to just 1%.

A further analysis has been conducted for the 502 local communities of the 25 Municipalities. After thorough investigation into the municipal level of community, specific "Red Areas" emerge that are disproportionately exposed to wildfire risk. The road length of each community is recorded in the Figure 5 below, indicating the high or extremely high risk zones.

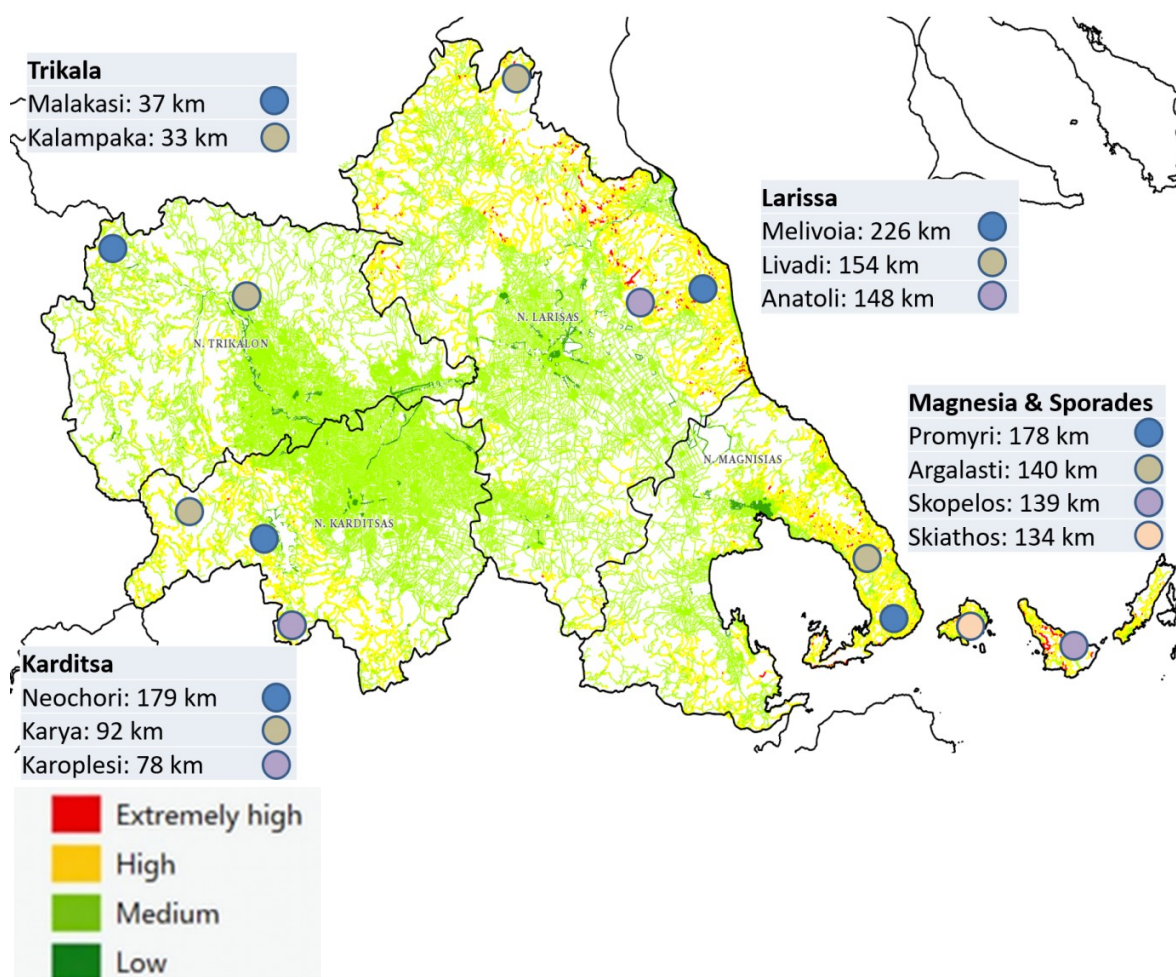


Figure 5. Municipal Communities - Absolute Length of High-Risk Road Network (km)

- The “Red” leaders: The Municipal community of Melivoia (Larissa) tops the regional list with 226 km of its roads in “Particularly High” risk zones. It is followed by Neochori (Karditsa) with 179 km and Promyri (Magnesia) with 178 km.
- The Island vulnerability: The situation on the island of Skopelos is alarming. With 66.95 km of roads in "Particularly High" risk and 166.34 km in "High" risk, over 80% of the island’s entire infrastructure is in dangerous territory (Stefanidis et al., 2020). South Pelion faces a similar challenge with 90.56 km in the highest bracket.

An analysis of risk concentration reveals an extremely unequal distribution of risk.

- The Top 10%: The top 10% of municipalities/communities (just 43 Local Government Units) accounts for 54.7% of the region's total high-risk road network.
- Affected Population: Approximately 54,347 people reside in these 43 areas. This is the population located on the "front line" of risk.
- Based on road length (km):
 - Melivoia (Larissa): 226 km
 - Neochori (Karditsa): 179 km
 - Promyri (Magnesia): 178 km
 - Livadi (Larissa): 154 km
 - Anatoli (Larissa): 148 km
- Based on Risk Per Capita (km/resident): These areas have few residents to manage a massive network.
 - Kokkinopilos (Larissa): 1.19 km per resident.
 - Elafos (Larissa): 0.83 km/resident.
 - Sklithro (Larissa): 0.82 km/resident.
 - Anatoli (Larissa): 0.72 km/resident.

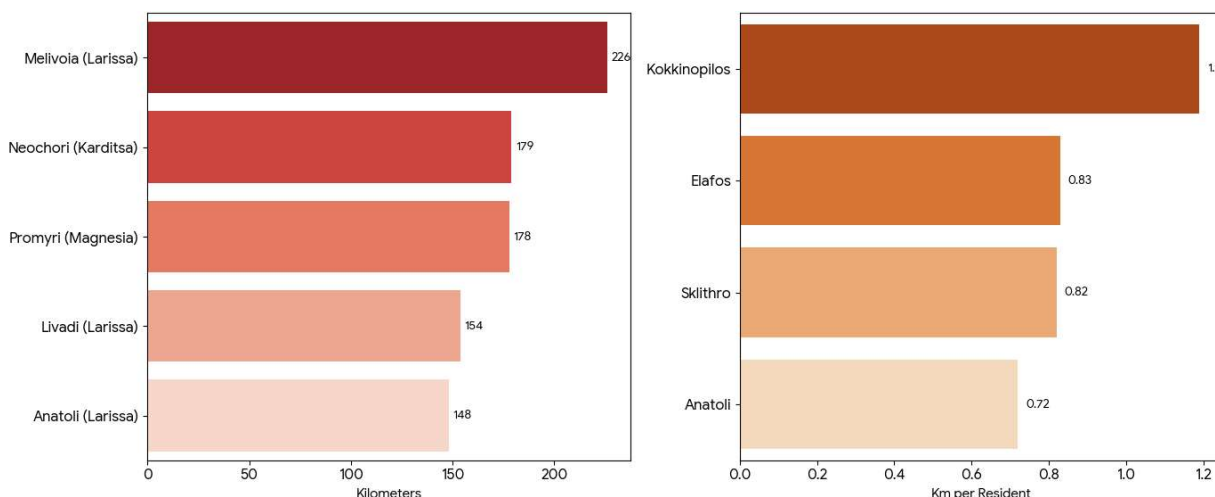


Figure 4. Municipal Communities - Absolute Length of High-Risk Road Network (km)

The interaction of road network wildfire risk with Protected Areas (Natura 2000). The analysis uncovered a troubling overlap between conservation and fire risk. In areas designated as both SCI (Sites of Community Importance) and SPA (Special Protection Areas), 53% of the road network falls into the "High" risk category, with another 11% in "Extremely High." By comparison, non-protected areas have only 17% of their roads in the "High" risk bracket (Grillakis et al., 2017).

Table 5: Road Network Risk Distribution in Protected Areas.

Natura 2000	Low		Medium		High		Extremely high		Total
	km	%	km	%	km	%	km	%	km
Non-Protected	1059	3%	23988	78%	5290	17%	350	1%	30688.
Natura SCI	56.	1%	3389	64%	1733	33%	143	3%	5322
Natura SCI & SPA	7	2%	141	34%	221	53%	45	11%	414
Natura SPA	139	3%	4375	81%	815	15%	44	1%	5374
Total	1262	3.0%	31893	76.3%	8059	19.3%	583	1.4%	41799

These statistics uncover the challenges that civil protection is facing in Thessaly. The most consequential finding is the quantitative confirmation of an "operational blind spot." The fact that 8.7% of the land requires "Extremely High" protection but effectively has almost no road access (1.4% of the network) created a severe capability gap. In tactical terms, this means that if a fire ignites in these blind spots, ground forces are essentially locked out during the initial attack phase. Without roads, there are no anchor points to establish containment lines and no safe routes for heavy machinery (Thompson et al., 2017). These zones effectively become "no-go" areas for ground crews, forcing a reliance on aerial suppression, which is fickle and dependent on daylight and weather.

The concentration of 44% of the high-risk network in the 300-800m altitude belt pinpoints the primary theater of operations. This isn't deep wilderness; it is the WUI - a patchwork of abandoned fields, shrubland, and homes. The risk here is driven by the continuity of fuels and the high probability of human ignition. Adaptive management must focus attention on this zone. Vegetation clearing and road hardening here act as a shield, buffering the inhabited plains from the mountain forests above (Modugno et al., 2016).

In Thessaly there is the Islands and coastal Constraint. The data for Skopelos and South Pelion highlights a fragility unique to coastal and island environments. On the mainland plains of Trikala, if one road is blocked, there is usually another route. On an island like Skopelos or Skiathos, the network is finite and linear. With 80% of its roads in the danger zone, a single well-placed fire could sever the island's north-south axis, trapping residents and tourists. In this context, road management elevates from a forestry issue to a critical public safety imperative (Sakis et al., 2022).

The intense concentration of risk in Natura 2000 zones (53% High Risk) creates a policy dilemma. These areas need the most aggressive fuel management to prevent catastrophic biodiversity loss, yet they are shielded by environmental laws that often restrict mechanical clearing (Xofis, 2020). This "conservation paradox" demands a nuanced approach, such as "Bio-Diverse Fuel Breaks" where roadside management favors low-flammability native species rather than the "bare earth" clearing.

5. CONCLUSIONS

This study employed granular geospatial analysis to quantify the intersection of wildfire risk and infrastructure in Thessaly, revealing that risk distribution is highly heterogeneous and concentrated within the 300–800 m altitude belt. The findings demonstrate the inadequacy of uniform maintenance protocols, highlighting a critical "accessibility deficit" where the zones of highest flammability possess the lowest road density, effectively creating operational voids for ground suppression forces. Consequently, current resource allocation models predicated on traffic volume are rendered obsolete in the context of resilience; a transition to "Risk Per Capita" metrics is required to rectify the disproportionate exposure of "outlier" communities. Ultimately, effective mitigation requires a paradigm shift from static clearing to dynamic zoning, necessitating the transformation of key arterial routes into "fire-hardened corridors" capable of sustaining safe operational access during extreme fire behavior. Future research should look to integrate real-time traffic data and dynamic meteorological models to further refine the risk categorization of these road segments as the fire season evolves (Papakosta and Straub, 2017).

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