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Investigating the Resilience of Accessibility to Emergency and Lifesaving Facilities under Natural Hazards

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CSUTC California State University Transportation Consortium

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16. Abstract

Studying accessibility, including the resilience of city transportation networks, is critical to understand how these networks influence individuals' mobility and lives. This study developed an analytical research framework to examine the resilience of accessibility to emergency and lifesaving facilities under the threats of natural hazards such as earthquakes and wildfires. With a cumulative-opportunity approach, the authors measured accessibility by counting emergency and lifesaving facilities (including parks, schools, hospitals, roads, and fire stations) that can be reached by driving at the census tract level in San Fernando Valley, CA. With the calculated accessibility, the authors run simulations to collect data showing what would happen if an area were affected a selected disaster. They then used statistical analysis to identify those areas where accessibility is significantly reduced compared to the original status. A normalized difference accessibility index (NDAI) was further created to suggest plans and strategies to help those vulnerable areas through adding facilities/services or improving transportation infrastructure.

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Executive Summary

The threats of climate change and associated natural hazard events have been motivating many researchers to work on a variety of topics concerning urban resilience. In planning, accessibility plays a key role in addressing urban resilience issues because it is a dimension that connects land-use allocation and the transportation network, which together determine people's quality of life. Therefore, the main purpose of this study is to develop an analytical research framework to examine the resilience of the accessibility to emergency and lifesaving facilities under natural hazards, which are important in the response phase of the natural hazard management circle.

Using the San Fernando Valley in California as a case study, this framework is constructed with four parts. First, using the cumulative-opportunity approach, we calculate accessibility to parks, schools, hospitals, fire stations, and roads respectively within 5 minutes by driving at the census tract level for the case of pre-disaster. Second, by identifying possible natural hazards, we recalculate accessibility to these facilities recalculated after taking out a part of the transportation network falling in a defined hazard zone for 30 simulations. Third, statistical comparisons are conducted to identify the most affected areas in terms of significant drop in accessibility. Lastly, we create a normalized difference accessibility index (NDAI) to indicate whether facility allocation or the transportation network should be used to improve the resilience of accessibility in these hotspots.

Our main contribution is the simulated hazard impact analysis on the accessibility of a variety of emergency and lifesaving facilities based on natural hazard identification. Moreover, inspired by a widely used index, the Normalized Difference Vegetation Index in remote sensing for detecting healthy vegetation, the NDAI we create in this framework provides decision-makers a solid index to guide more efficient location-based plans and strategies in improving accessibility resilience. With this research framework, we determine the accessibility damage hotspots and their associated statistical significance levels. The NDAI results for the five types of facilities suggest that the outskirt areas and relatively less developed areas in the study region would need more transportation investments such as road networks to improve the accessibility resilience in the face of seismic or wildfire hazards.

1. Introduction

Given the long-term impacts of climate change, extreme natural events have been more frequent and severe across the world, such as wildfire, droughts, hurricanes, and sea-level rising. In addition to these climate-change-induced hazards, some other natural hazards, such as earthquakes and landslides, are also threatening human life and property. For example, California is prone to frequent earthquakes, such as the 1994 Northridge Earthquake (Mw 6.7) and the 1971 San Fernando Earthquake (CEA, 2019), and there have been several record-breaking wildfires in recent years (Cal Fire, 2022; Petersen, 1996).

The concern over these threats mentioned above has been increasingly attracting attention to the field of resilience. This concept is generally defined in three ways: (1) as an outcome related to (or being the flip side of) vulnerability (Kasperson & Kasperson, 2013), (2) as the capability for resisting hazards' impact to retain essential functions (ISDR, 2004), and (3) as the ability to recover the original status and to adapt to natural disasters (Carpenter et al., 2001). The understanding of resilience supports the role of urban planning and transportation planning as useful mechanisms for disaster mitigation due to their proactive nature that distinguishes them from the immediate and reactive activities taken during disaster response, recovery, and preparedness in the natural hazard management circle (Godschalk, 2003). Particularly, the role of emergency and lifesaving (E&L) facilities is crucial for the response phase of the natural hazard management circle. For instance, the open space in parks and schools can be used as shelters in a disaster . Therefore, it is important to understand how easily a resident can access an E&L facility subject to travel constrains (e.g., fleeing for refuge and relocating victims). For example, Qiang and Xu (2020) assessed the road network resilience by calculating the reduction of accumulated accessibility over the Winter Storm Harper in Cleveland, OH, in 2019, using crowd-sourced traffic data from Google Maps.

Most existing transportation resilience studies either examine whether the transportation system would remain functional during a disaster or assess how difficult it would be to recover the function after the event. They basically neglect the fact that accessibility (either facility access or service delivery) is also a result of facility allocation. With the widely used method, the cumulative-opportunity approach, accessibility can be measured as the total number of urban opportunities that a resident can reach through a specific transportation mode within a certain travel distance or travel time (Castiglione et al., 2006). This measurement has been broadly applied in accessibility studies for addressing social inequality issues by considering that the transportation network and land-use pattern in a city can influence individuals' physical activity space and therefore their socioeconomic outcomes (Chen & Wang, 2020; Delmelle & Casas, 2012).

Based on the understanding of natural disaster risk as a function of hazard, vulnerability, and exposure (Randolph, 2012), avoidance theory and mitigation theory are typically applied to develop traditional natural hazard mitigation measures (Godschalk, 2003). The former would propose to allocate activities away from natural hazard areas to reduce exposure, while the latter would suggest structure engineering measures to reduce the vulnerability on site (Randolph, 2012; Schoennagel et al., 2017). The logic of these two theories responds to the role of urban planning in natural hazard management mentioned above. However, urban planning is also playing a role in natural hazard management in terms of the preparedness for emergency response as “soft mitigation” (Lichterman, 2000). For example, "soft mitigation" in urban planning could be reflected as efficient allocation of emergency response facilities. This role seems to be neglected in planning literature.

Therefore, this study aims to develop a research framework to examine the resilience of the accessibility to emergency and lifesaving facilities under natural hazards. California’s San Fernando Valley is selected as the study region, considering two natural hazards, earthquakes and wildfires. Using the cumulative-opportunity approach, we firstly calculated accessibility to parks, schools, hospitals, roads, and fire stations respectively during normal conditions. Then, considering the spatial distribution of two natural hazards, accessibility to such facilities was repeatedly recalculated by removing a part of the transportation network within the hazard zone until achieving a large number (30 times in this study) for statistical analysis. The accessibility results before and after the consideration of the two natural hazards were statistically compared to identify where accessibility would drop most significantly. For those hotspots, at last, we create a normalized difference accessibility index (NDAI) to indicate whether efforts for the improvement of accessibility resilience should focus on facility allocation or the transportation network itself. Such a research framework can be utilized by urban planners to find out the most vulnerable locations and the necessary hazard mitigation resources in terms of facility allocation and transportation investments.

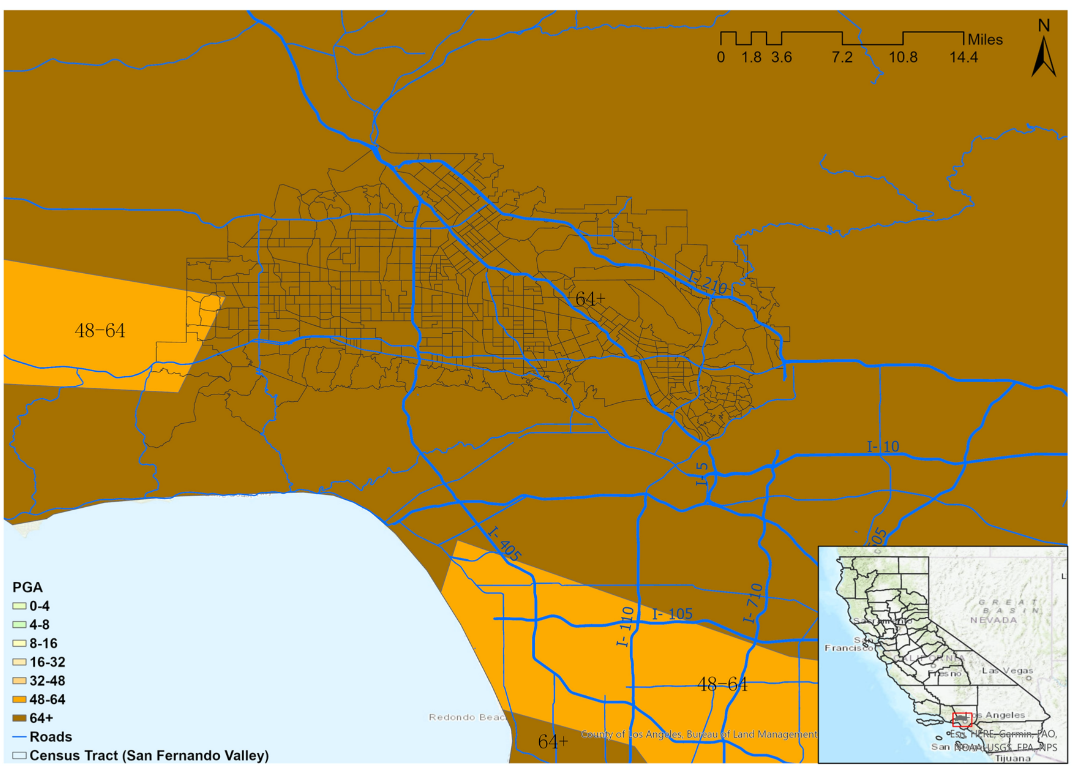
2. Methodology & Data

The analytical framework elaborated above includes the following four parts.

2.1 Natural Hazard Identification

Seismic and wildfire events are the two natural hazards considered for this analysis in the San Fernando Valley. This study refers the concept of "hazard level" as the potential magnitude of a natural hazard with fixed frequency. Therefore, for seismic hazards in the future, we assume that they will follow the historical pattern observed from the past earthquake events. Using the seismic hazard map from the National Geospatial-Intelligence Agency (HSIP Team, 2012; updated in 2017), two seismic hazard levels are identified (see Figure 1): moderate (0.48–0.64*g*) and high (>0.64*g*) as multiples of the acceleration due to gravity (*g*). With the census tract as the unit of analysis in this study, a census tract with a 0.64*g* seismic hazard is most likely to experience an earthquake with a 0.64*g* peak ground acceleration (i.e., ground shaking) every 50 years. Figure 1 shows that the whole Valley is mostly located in a severe seismic hazard area (>0.64*g*).

Figure 1. Distribution of Seismic Hazards



The identification of wildfire hazard is based on the predicted wildfire data by Westerling (2018) for California under the Representative Concentration Pathway (RCP) 8.5 scenario from 1953 to 2099. This predicted wildfire dataset includes 100 simulations for a year for each cell (6 km by 6 km) across the state of California, in terms of a burned-out percentage of each cell in a simulation.

The concept of a burned-out area means the hectares that a cell is projected to be burned out with one scenario based on a single GCM (downscaled by LOCA), a single RCP, and the set of 10 Land-Use/Land-Cover simulations associated with a single (low, central, high) population trajectory. With this dataset, we identify wildfire hazard in the study region using the following three steps:

1) Define three levels of wildfire hazards: a severe case if more than 75% of the area of a cell is burned out in a simulation, a moderate case if more than 50% is burned out, and a mild case if more than 25% is burned out;

2) Set up two time periods, 2020–2060 and 2060–2099, with 100 (simulations) × 40 (years) cases for each cell;

3) Identify a cell as a wildfire hazard zone during a time period if more than 5% of the 4,000 cases are identified as burned-out cases at any hazard level identified in the first step.

The results of applying these three steps are displayed in Figure 2 and Figure 3, showing that for wildfire hazards, the most hazardous areas in the valley concentrate in the outskirts of the north.

Figure 2. Distribution of Wildfire Hazards (2020–2060)

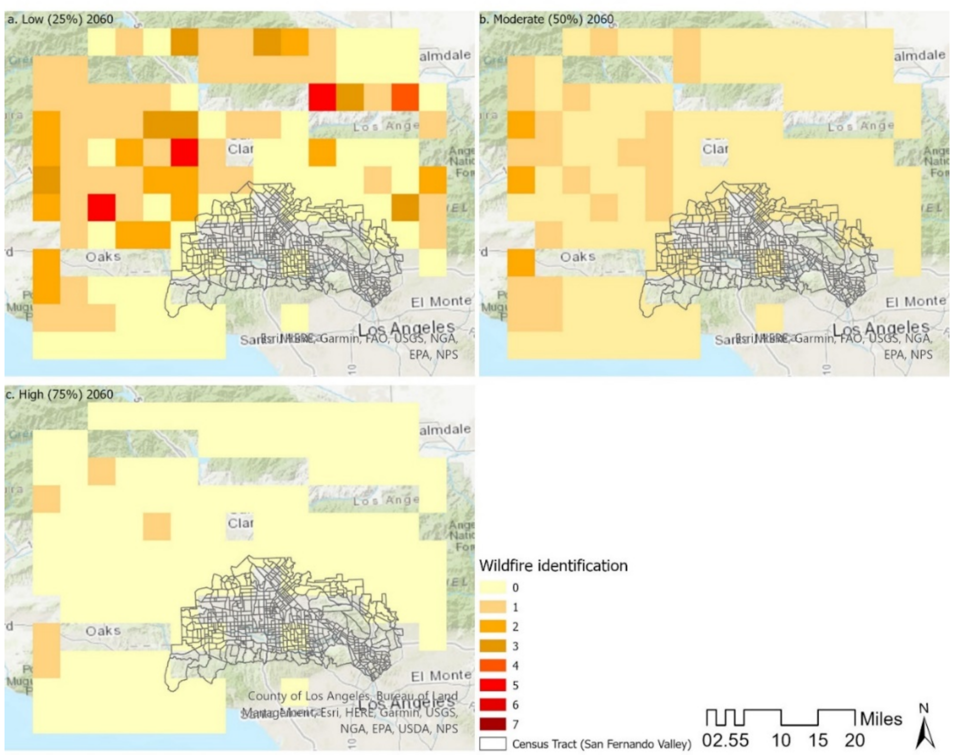
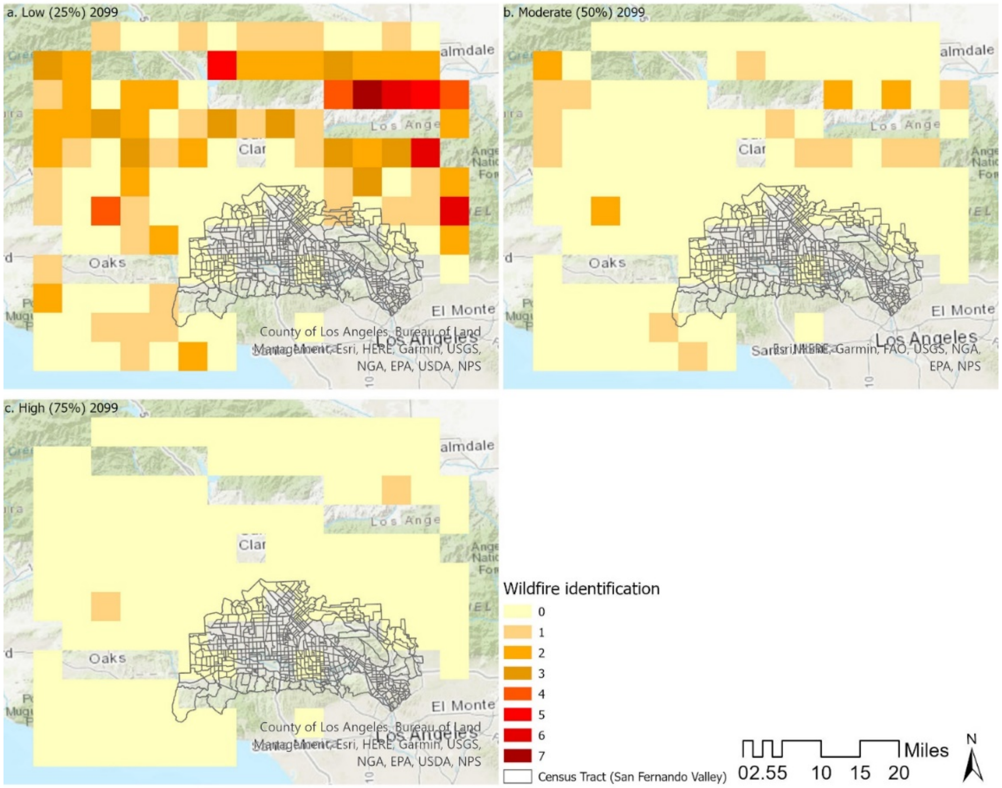


Figure 3. Distribution of Wildfire Hazards (2060–2099)



2.2 Pre-Disaster Accessibility Assessment

As mentioned in the introduction, we use the cumulative-opportunity approach to measure accessibility for its advantages in straightforward construction and interpretation. This approach has been used in the previous three FSTI accessibility projects. After evaluating the overall distribution of road network and emergency and lifesaving (E&L) facilities and considering the needs during a potential natural hazard, this study selects census tract as the unit of analysis and calculates accessibility to parks, schools, hospitals, roads, and fire stations within 5 minutes by driving from a census tract centroid. For point facilities such as schools, hospitals, and fire stations, the accessibility is calculated as:

$$ACC_i^f = \sum_{j=1}^{n} D_j, \tag{1}$$

where

- ACC_i^f: the number of point facilities accessible by driving for a census tract i;
- D_j: a binary value, 1 if the facility j falls within the service area and 0 otherwise.

The school (including public elementary, middle, and high schools) and hospital data are collected from LA County GIS Data Portal. The dataset for fire stations is compiled from OpenStreetMap (OSM) and LA Fire Department (LAFD) GIS Unit.

For parks, the equation is specified as follows:

$$ACC_i^p = \sum_{j=1}^{n} A_j, \tag{2}$$

where

- ACC_i^p: the total land area (square miles) of parks accessible by driving for a census tract i;
- A_j: the area of park j falling inside the 5-min service area by driving.

Similarly, the accessibility to roads is calculated as the total length (miles) of road segments falling inside the 5-min service area by driving. Note that the 5-min driving is using the maximum street speed and can be converted into units, such as travel distance or travel time by walking. The data for parks are assembled from OSM and road data with all links gathered from the most recent US Census Bureau TIGER/Line Shapefiles.

2.3 Post-Disaster Accessibility Simulations and Statistical Analysis

Using the same approach for calculating accessibility as Section 2.1, the post-disaster accessibility calculation is conducted for a pseudo-extreme natural event (a seismic or wildfire event scenario based on both hazard identification and urban pattern) by removing a road segment falling in the corresponding identified hazard zone. For both hazards, thirty locations are randomly selected for each type of threat scenario (see Figure 4 and Figure 5) based on the spatial distribution of hazard zones and population density to obtain a large sample for further statistical analysis, using the adaptive sampling approach, which is particularly appropriate when the sampled characteristic is rare and spatially clustered (Bolstad, 2016). For each selected location, it is assumed that the roads within a quarter mile will not be working during a pseudo-event and therefore corresponding facilities within that buffer will not be reachable either. Under this circumstance, accessibility to each type of facility is recalculated for every location. In the end, 30 accessibility simulations for each hazard are generated for statistical analysis. For wildfire hazards, the method of accessibility simulations is the same for the two time periods: note that the identified wildfire hazard cases in each of the two periods only marginally appear in the north of the study region.

Figure 4. Distribution of Selected Impacted Locations (Earthquake)

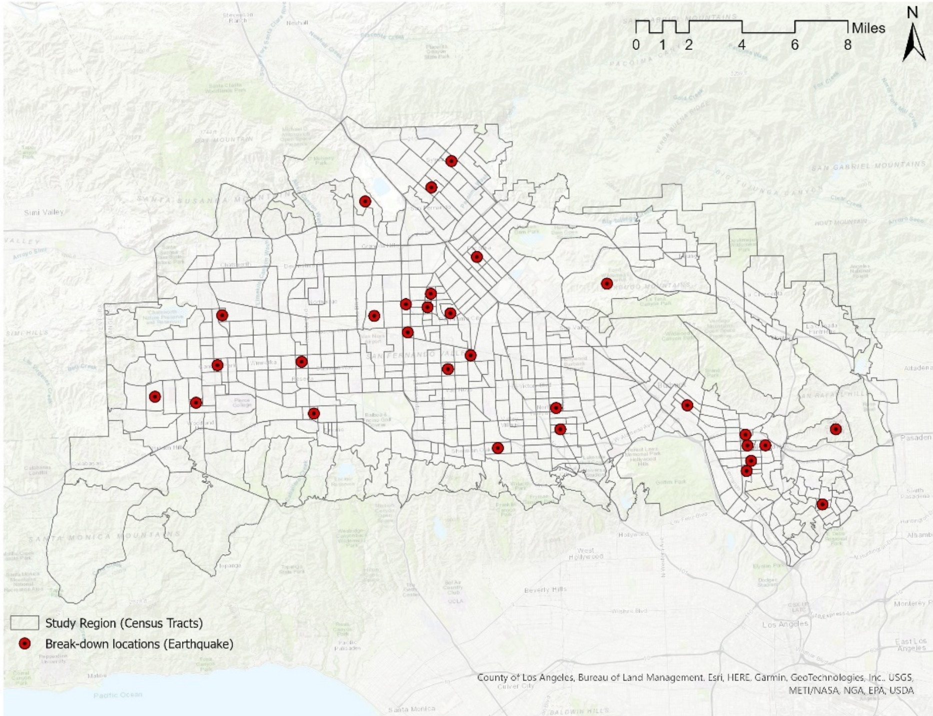
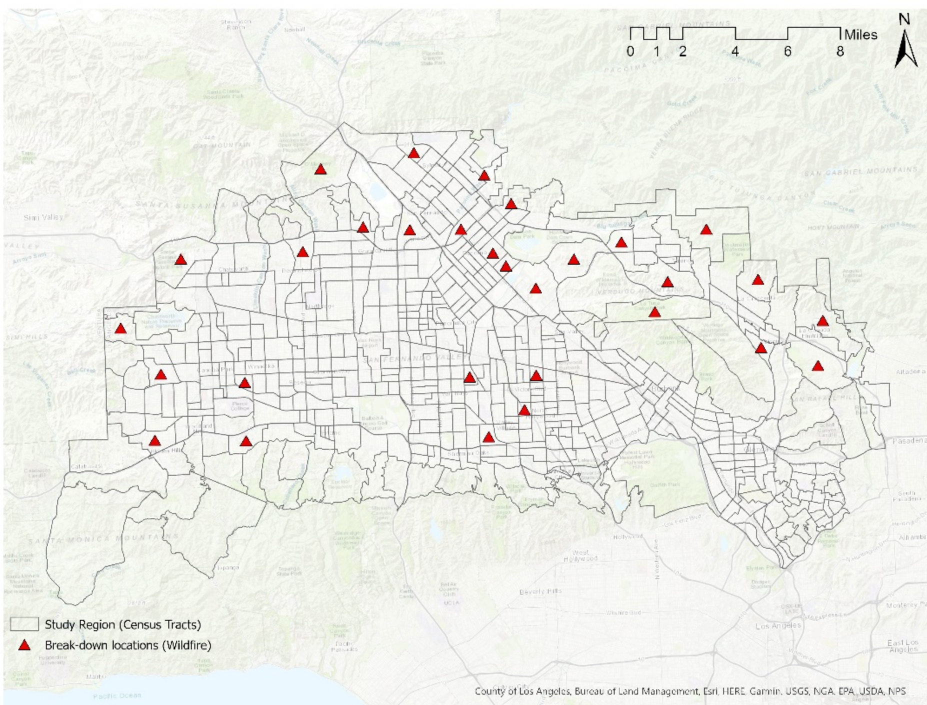


Figure 5. Distribution of Selected Impacted Locations (Wildfire)



The simulated results will produce 30 post-disaster accessibility to a type of facility for each census tract. Then, the change of accessibility in percentage before and after an extreme natural event is calculated for each type of facility. Therefore, hotspots will be identified for those locations with a highly decreased percentage. To reach statistical conclusions on these differences, we conduct a t-test to examine whether the simulated results are different from the original accessibility level using a 5% significance level, by assuming that the 30 simulated values of each census tract are distributed with a normal pattern. With these test results, urban planners would be able to focus on less resilient locations facing a significant accessibility drop.

2.4 Normalized Difference Accessibility Index (NDAI)

Inspired by the widely used index in remote sensing for detecting healthy vegetation from other special features in a satellite image (Bolstad, 2016), we create a new index, the Normalized Difference Accessibility Index (NDAI), to examine whether transportation or facility investment is more needed for less-resilient locations in the adaption to the natural hazards. The equation for calculating this index is specified as:

$$NDAI_{ki} = ACC_{ki} - RA_i, \tag{3}$$

where

- ACC_{ki}: standardized number/length/area of a specific facility k reachable within 5 min by driving from census tract i;

- RA_i: standardized number of census tracts reachable from that census tract i under the same travel constraints.

The values of ACC_{ki} and RA_i are the standardized mean of the 30 simulated accessibility results for each hazard and each facility. Considering that the accessibility to a facility is a result of transportation network and facility allocation, this index is used to identify which of these two factors plays a more important role in an existing accessibility outcome. Therefore, to improve the resilience of accessibility, a positive NDAI would suggest the need of more transportation investments, while a negative NDAI would suggest more facilities investments needed.

As a reference to compare with the NDAI results after the extreme hazard events, the NDAI values of the five types of facilities are presented for the pre-disaster accessibility in Figure 6 and Figure 7. Also, these pre-disaster results can be used by decision-makers to assist in designing and implementing plans and strategies for prioritizing facilities or transportation network investments during normal situations.

Figure 6. Pre-Disaster NDAI (Schools, Hospitals, Fire Stations)

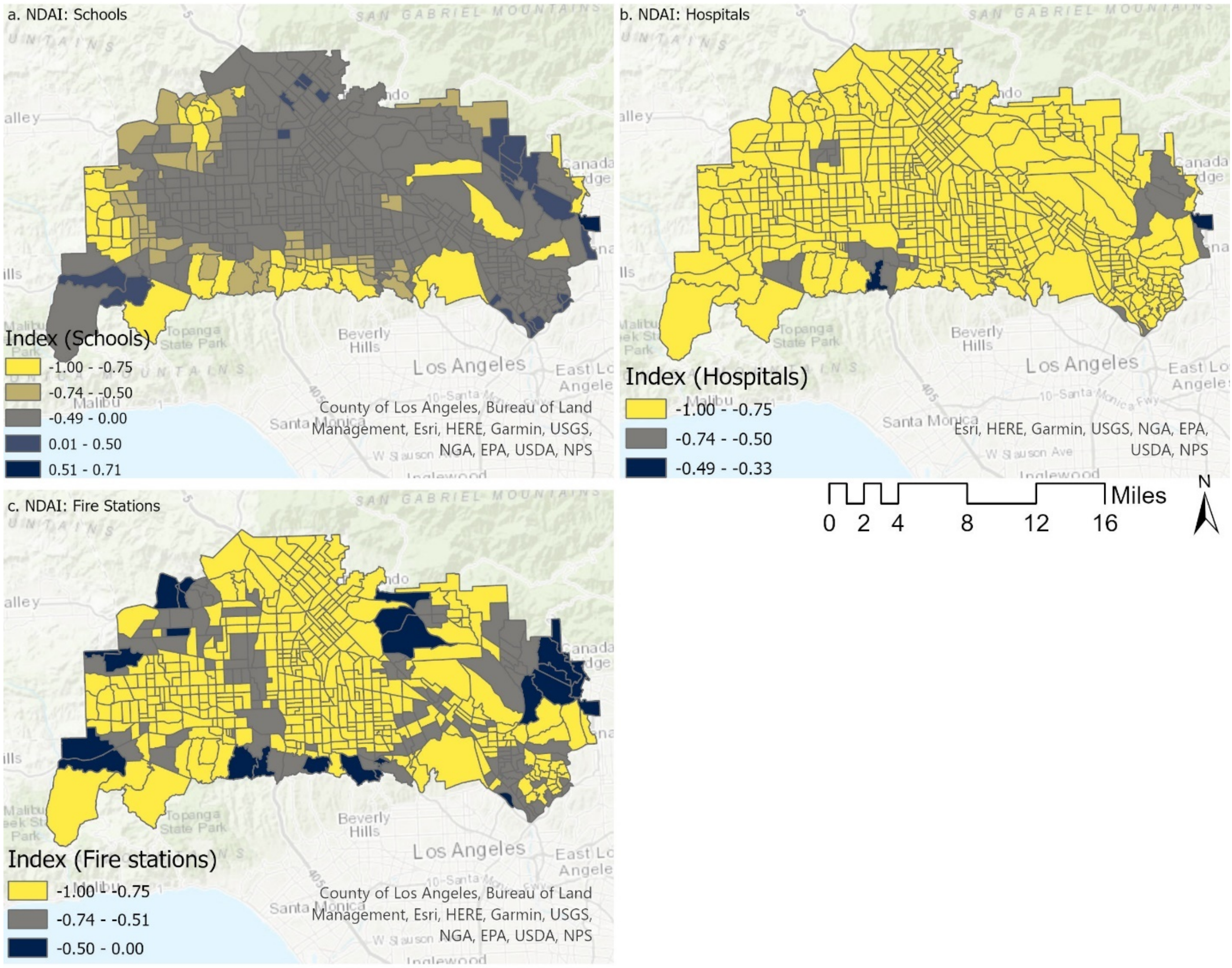
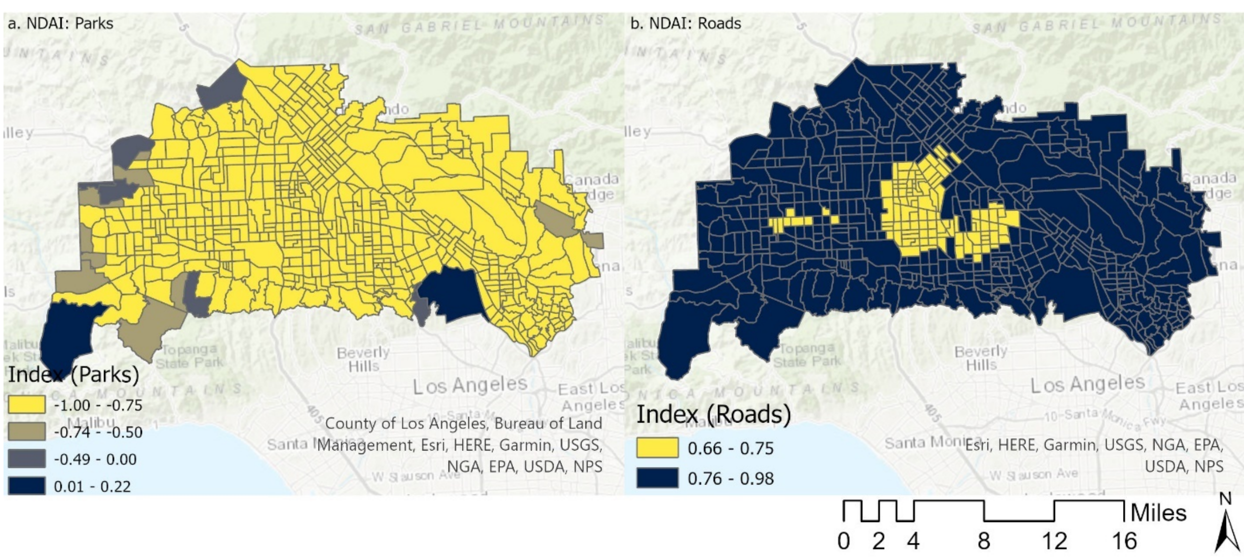


Figure 7. Pre-Disaster NDAI (Parks, Roads)



3. Results

3.1 Seismic Hazards

For seismic hazard, Figures 8 to 10 present the locations (named "accessibility damage hotspots") having a higher decrease in accessibility to nearby census tracts and the five types of facilities caused by the damaged roads. The damage hotspots for accessible census tracts concentrate in the central area (Van Nuys) and southeast protrusion (Glendale) and some scattered spots in the outskirt areas, basically following the sampling pattern as a result of the attenuating impacts with distance from each identified seismic hazard zone. In other words, the accessibility damage decreases as the distance from the identified seismic hazard increases. Regarding facilities, Van Nuys and Glendale became the clustering sites for damage sites of accessibility to schools, hospitals, and roads.

The significance levels of these changes in accessibility before and after a severe pseudo-earthquake, called "accessibility damage significance" for short, are illustrated in Figures 11 to 13. Different from what we find above, only the outskirt areas of the study region indicate significant accessibility damage for parks and fire stations. The uncertainty of seismic hazards is accounted for with the statistical analysis, and the results show the locations most affected in terms of accessibility damage in a severe earthquake.

Under seismic hazards, Figure 14 and Figure 15 show the results of NDAIs for the five types of facilities. For the analysis of NDAIs, we divide schools, hospitals, and roads as one group and parks and fire stations as the other group based on the accessibility change results as presented above. For schools and roads, the negative NDAIs in the central area imply the need for more facilities, while the positive NDAIs are found in the southeast protrusion and suggest the need for more transportation investments. For hospitals, people living in the central area need more transportation and facility improvements. For the second group, in the case of parks, the damage hotspots and statistical analysis results show an increasing need for transportation facilities with increasing distance from the central area. In respect of fire stations, the relatively less developed areas clearly need more transportation investments.

Figure 8. Accessibility Damage Hotspots for Seismic Hazards
(Census Tracts)

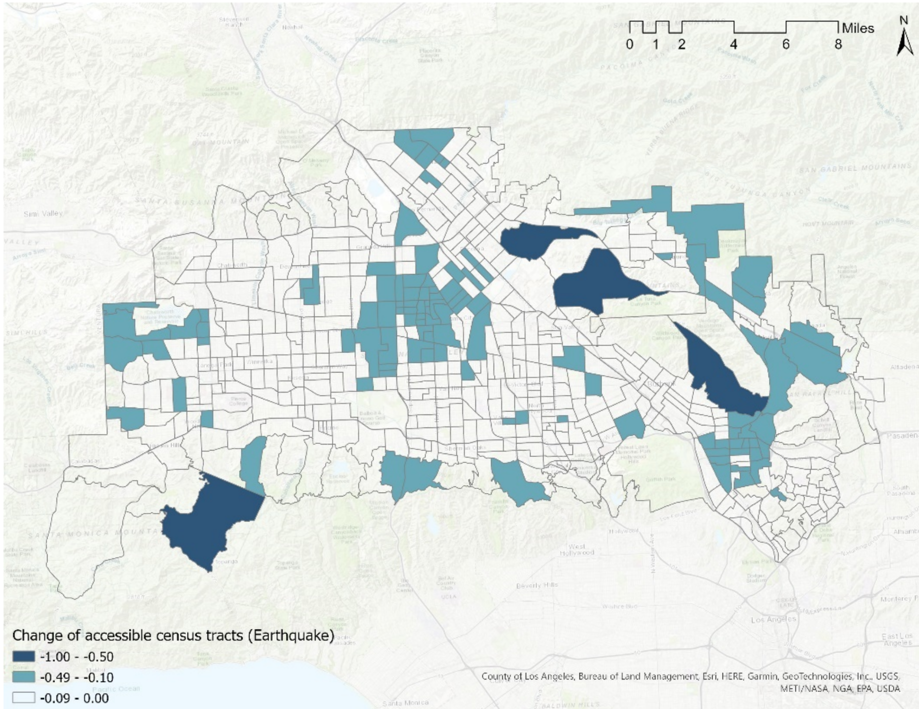


Figure 9. Accessibility Damage Hotspots for Seismic Hazards
(Schools, Hospitals, Fire Stations)

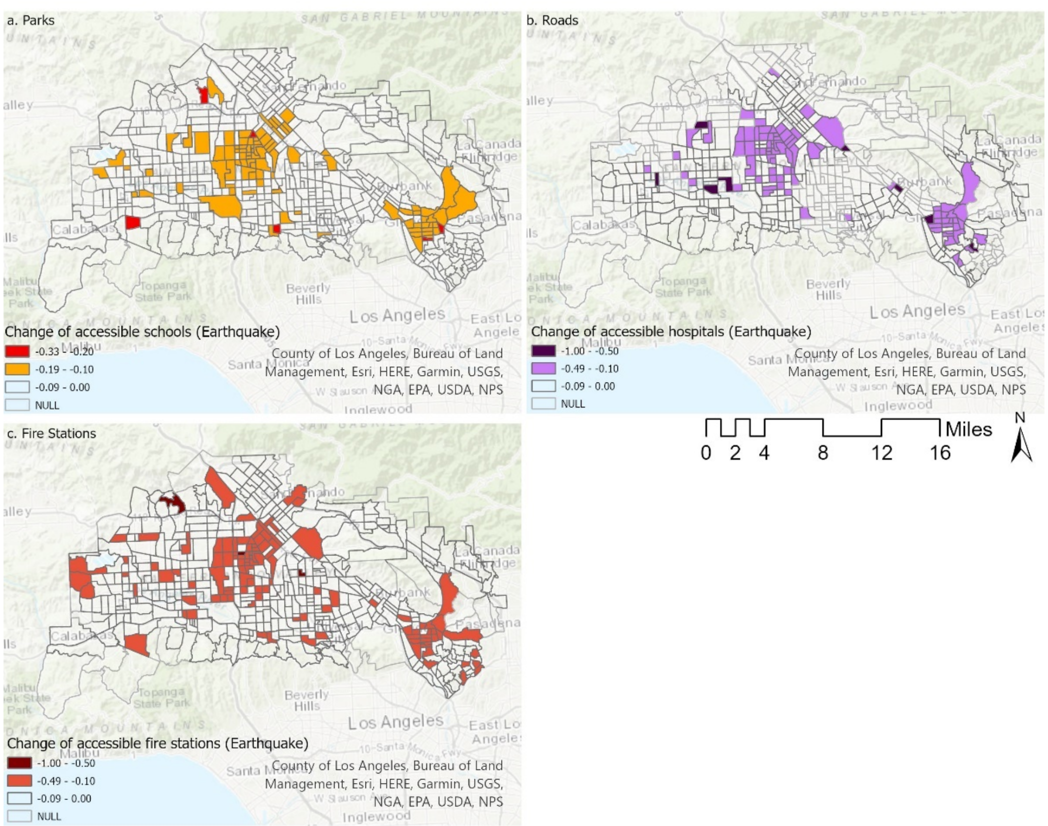


Figure 10. Accessibility Damage Hotspots for Seismic Hazards
(Parks, Roads)

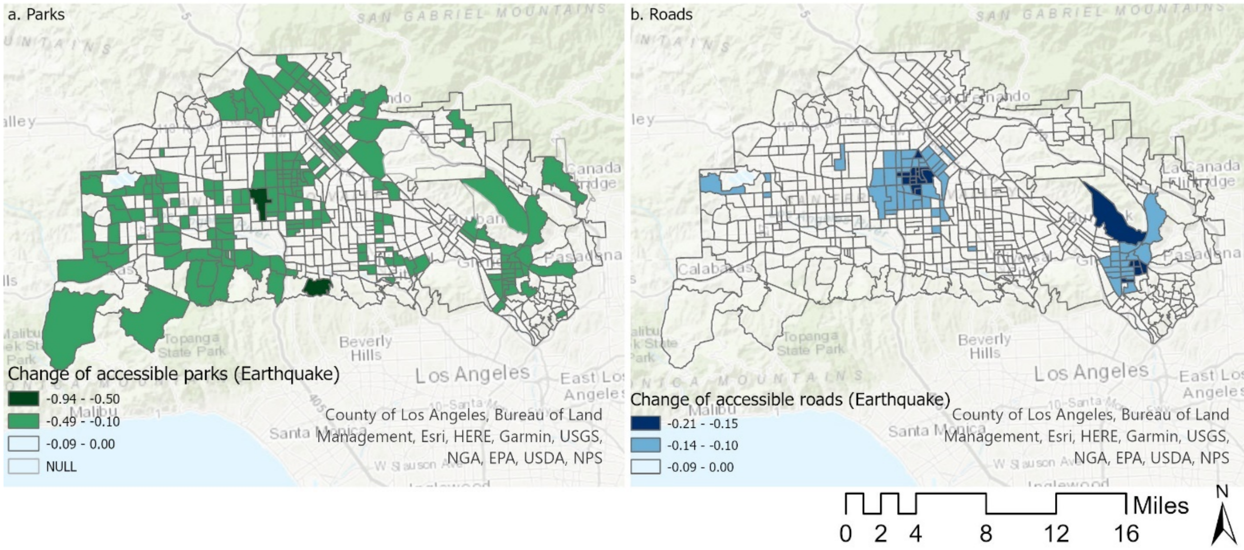


Figure 11. Accessibility Damage Significance for Seismic Hazards
(Census Tracts)

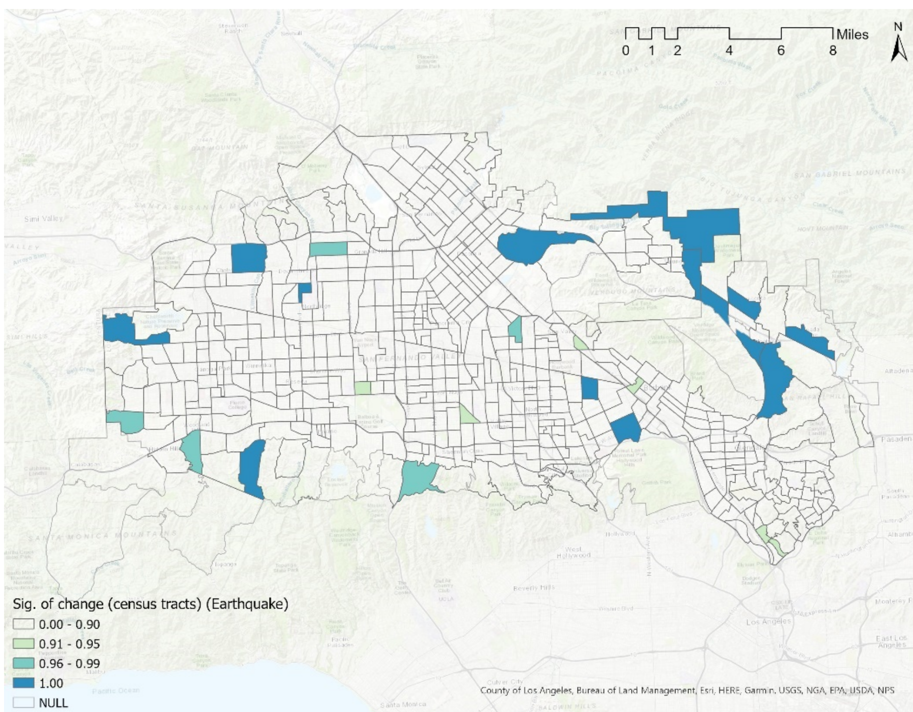


Figure 12. Accessibility Damage Significance for Seismic Hazards
(Schools, Hospitals, Fire Stations)

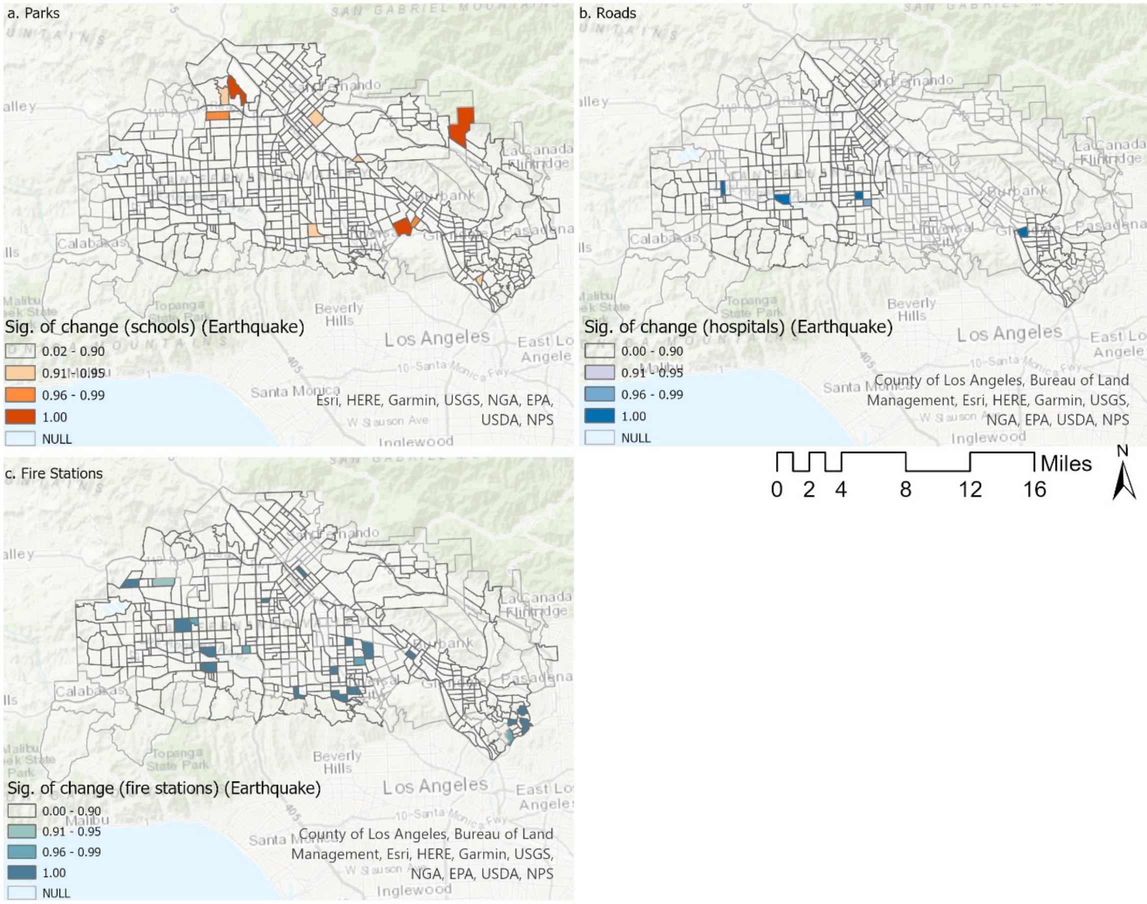


Figure 13. Accessibility Damage Significance for Seismic Hazards
(Parks, Roads)

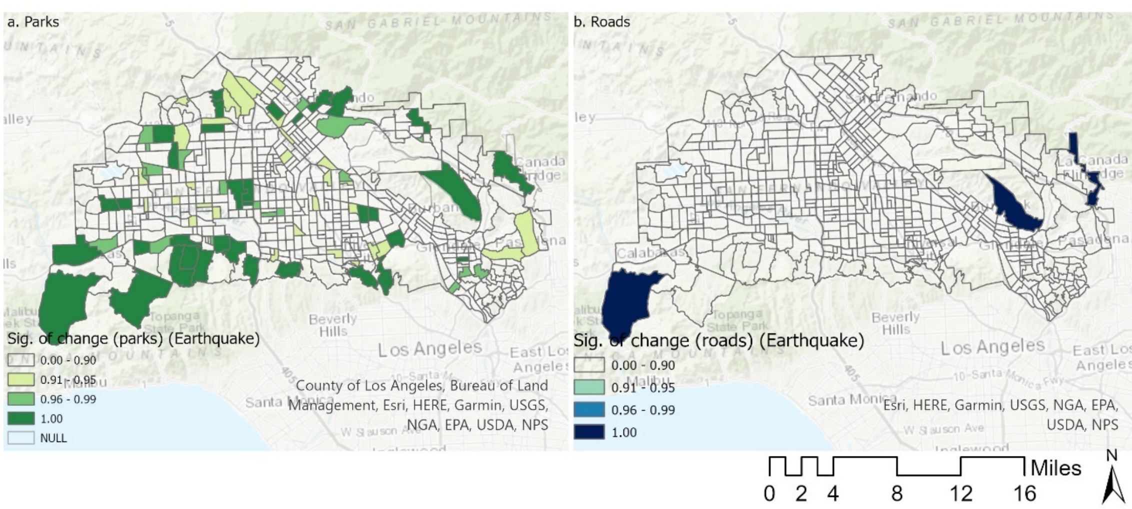


Figure 14. NDAIs for Seismic Hazards (Schools, Hospitals, Fire Stations)

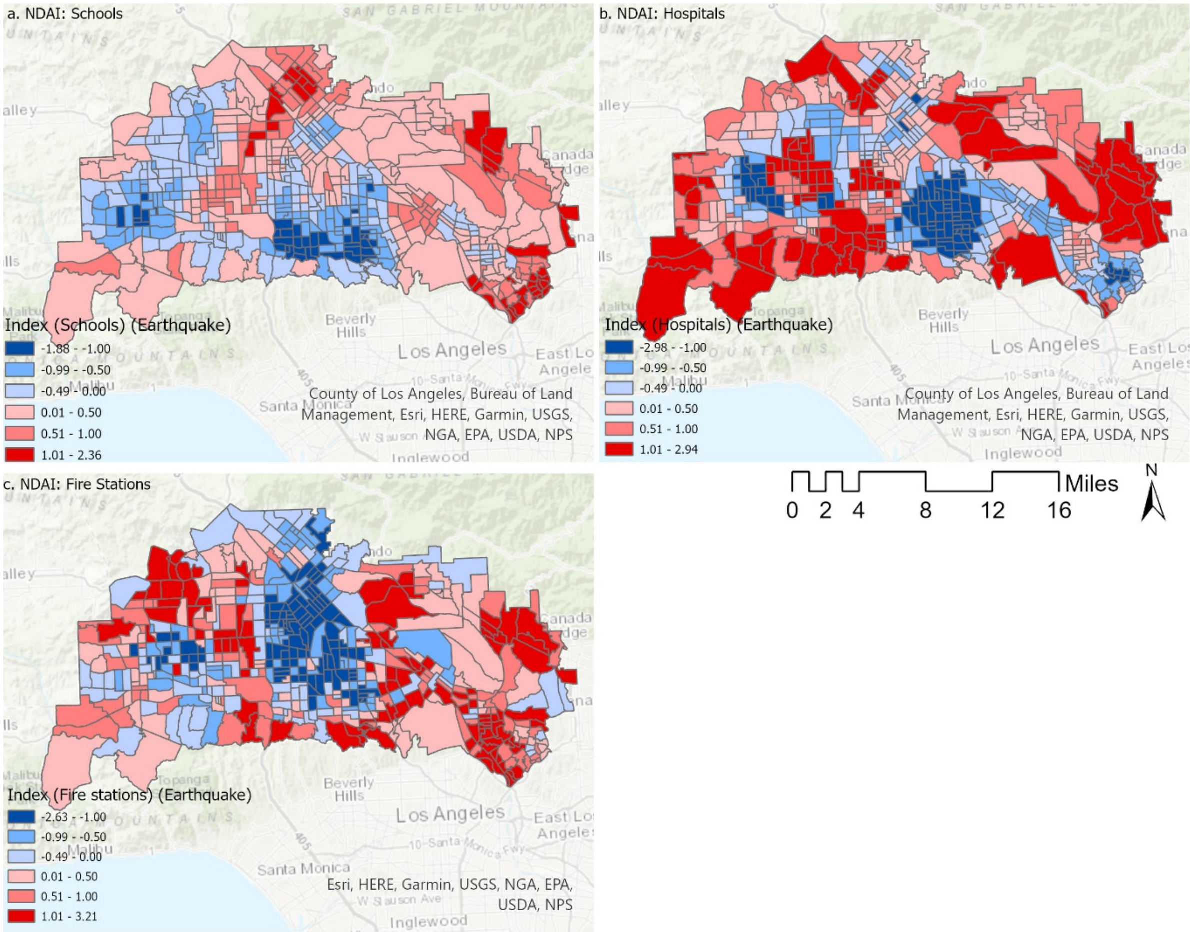
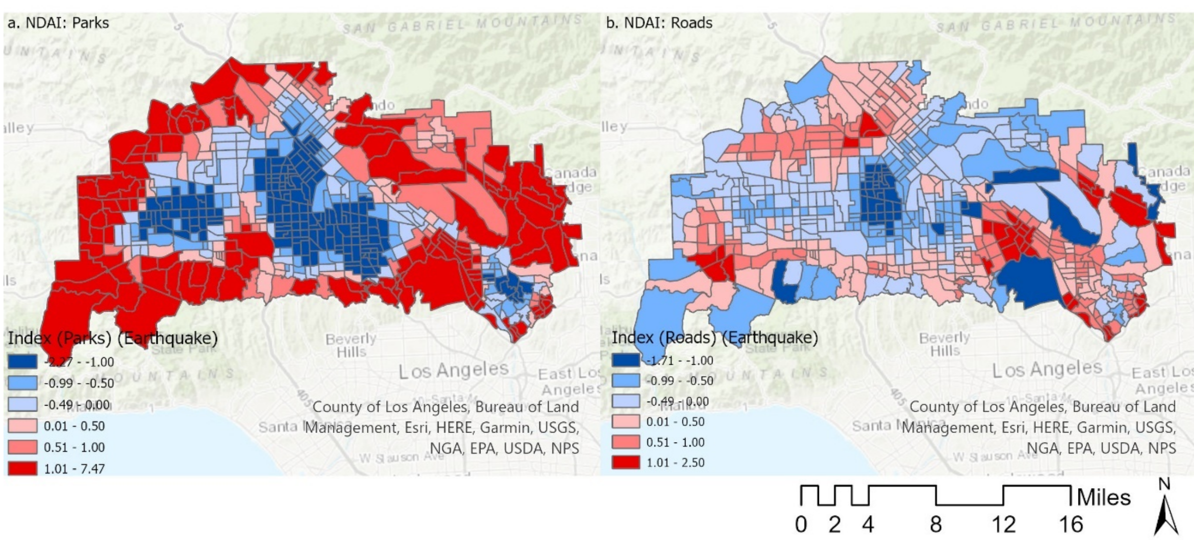


Figure 15. NDAIs for Seismic Hazards (Parks, Roads)



3.2 Wildfire Hazards

For wildfire hazards, the results are displayed in Figures 16 to 18. Steep accessibility changes are named "accessibility damage hotspots." Following the pattern of wildfire hazard sampling (see Figure 5), the distribution of accessibility damage hotspots for nearby census tracts, schools, hospitals, and roads clusters in the northern hills. For parks and fire stations, their spatial patterns in terms of the accessibility damage hotspots are similar to the case of seismic hazards.

The results of accessibility damage significance in Figures 19 to 21 show that the eastern and western ends of the study region suffer from significant accessibility damage. No significant accessibility damage is found for schools, hospitals, and roads. Outskirt areas such as Van Nuys which are far from most parks are expected to face significant damage in accessibility to parks. Glendale has a similar issue, but in this case it is due to limited and easily disconnected routes to the nearby green space. Urban planners need to pay special attention to those areas with significant accessibility damage to fire stations, given their role in extinguishing a fire for residential houses when wildfire threats extend into the Valley.

As shown in Figure 22 and Figure 23, the spatial pattern of the calculated NDAIs for each type of facility is quite similar to the corresponding one for seismic hazards (Figure 7). For example, transportation investments (e.g., preserving the connection of transportation network) are needed for most census tracts to improve their accessibility to schools, hospitals, and roads. Overall, the results of the NDAIs suggest that the outskirt and other relatively lower-developed areas need more transportation investments.

Figure 16. Accessibility Damage Hotspots for Wildfire Hazards (Census Tracts)

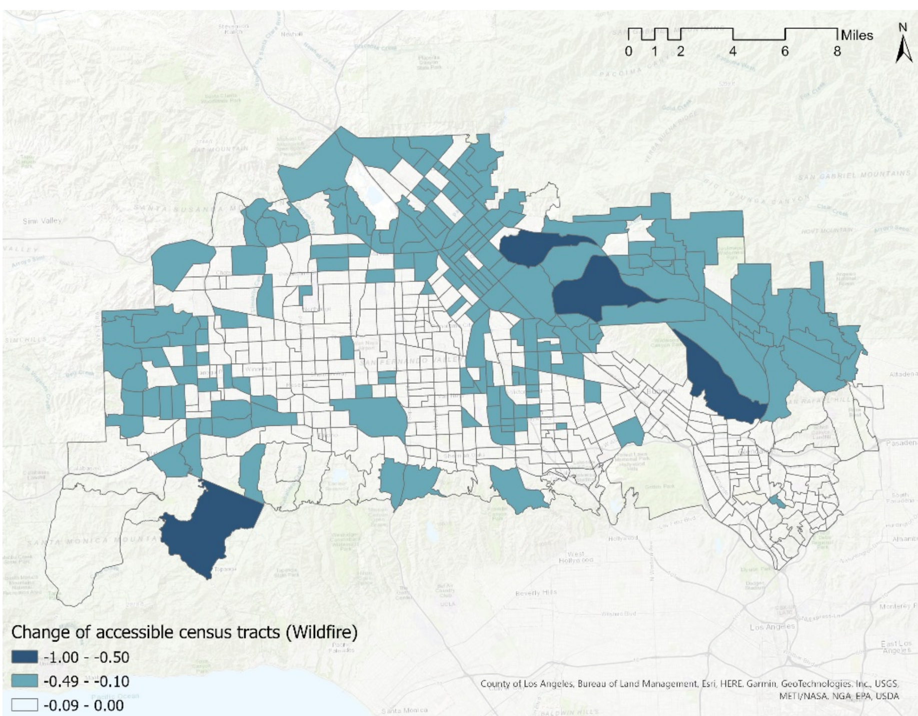


Figure 17. Accessibility Damage Hotspots for Wildfire Hazards (Schools, Hospitals, Fire Stations)

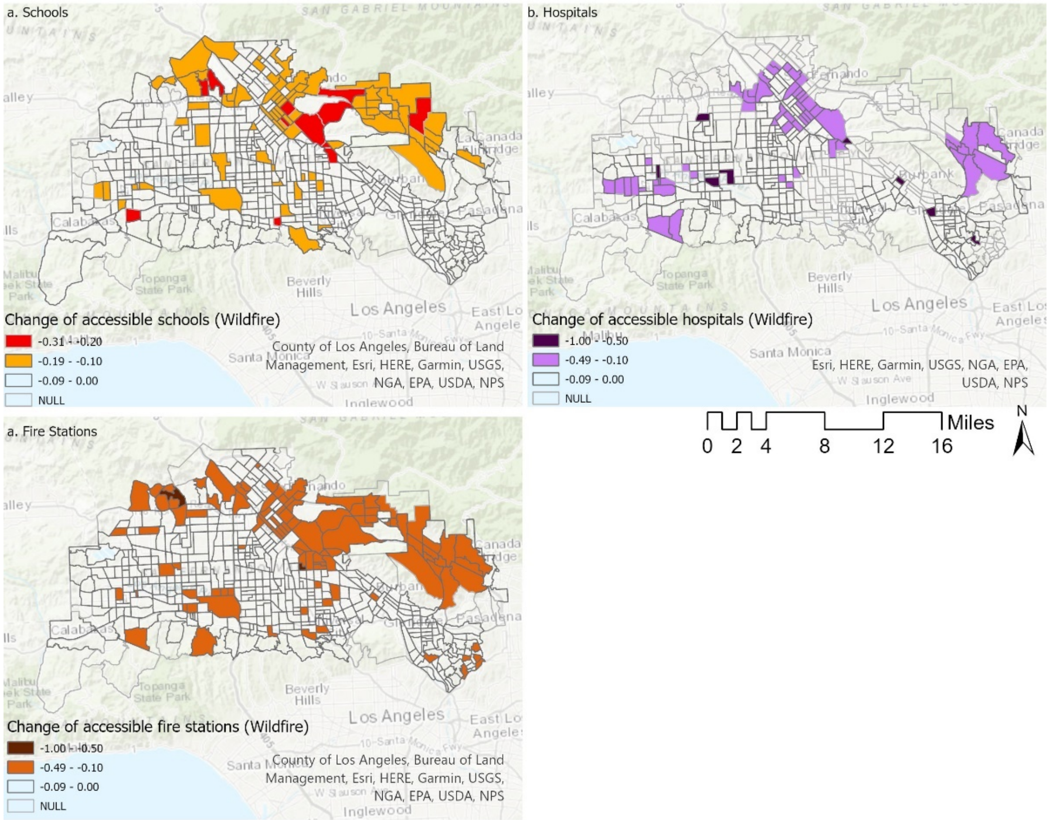


Figure 18. Accessibility Damage Hotspots for Wildfire Hazards (Parks, Roads)

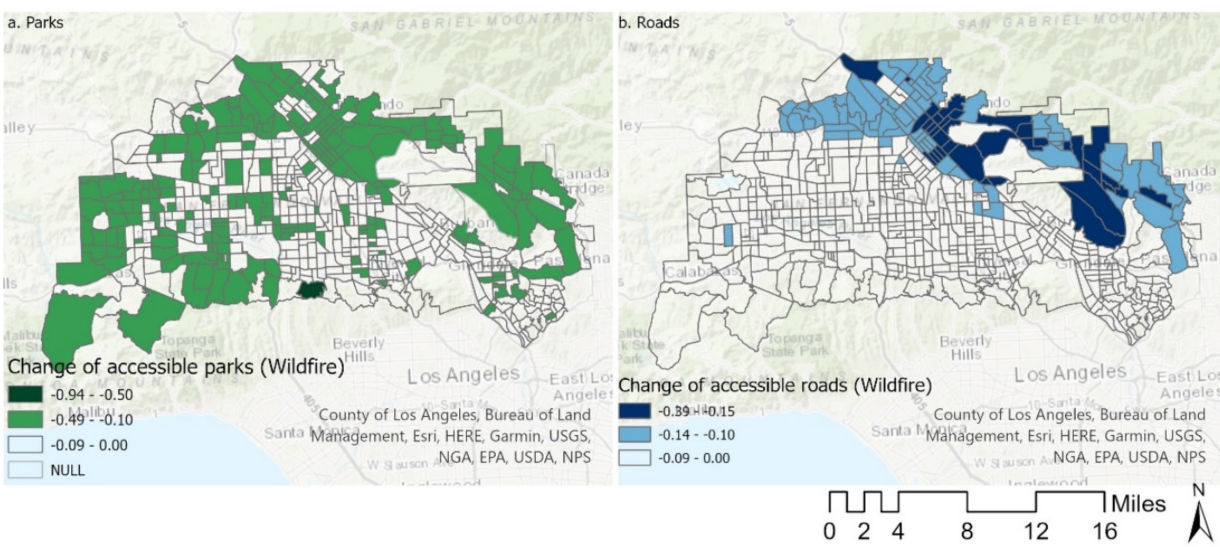


Figure 19. Accessibility Damage Significance for Wildfire Hazards
(Census Tracts)

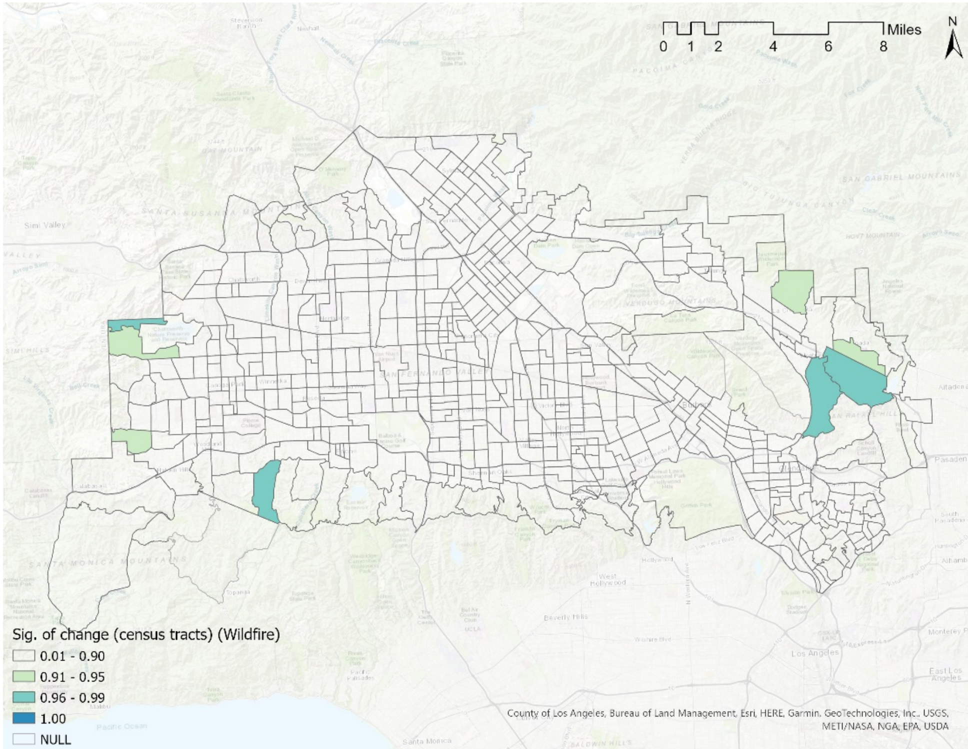


Figure 20. Accessibility Damage Significance for Wildfire Hazards
(Schools, Hospitals, Fire Stations)

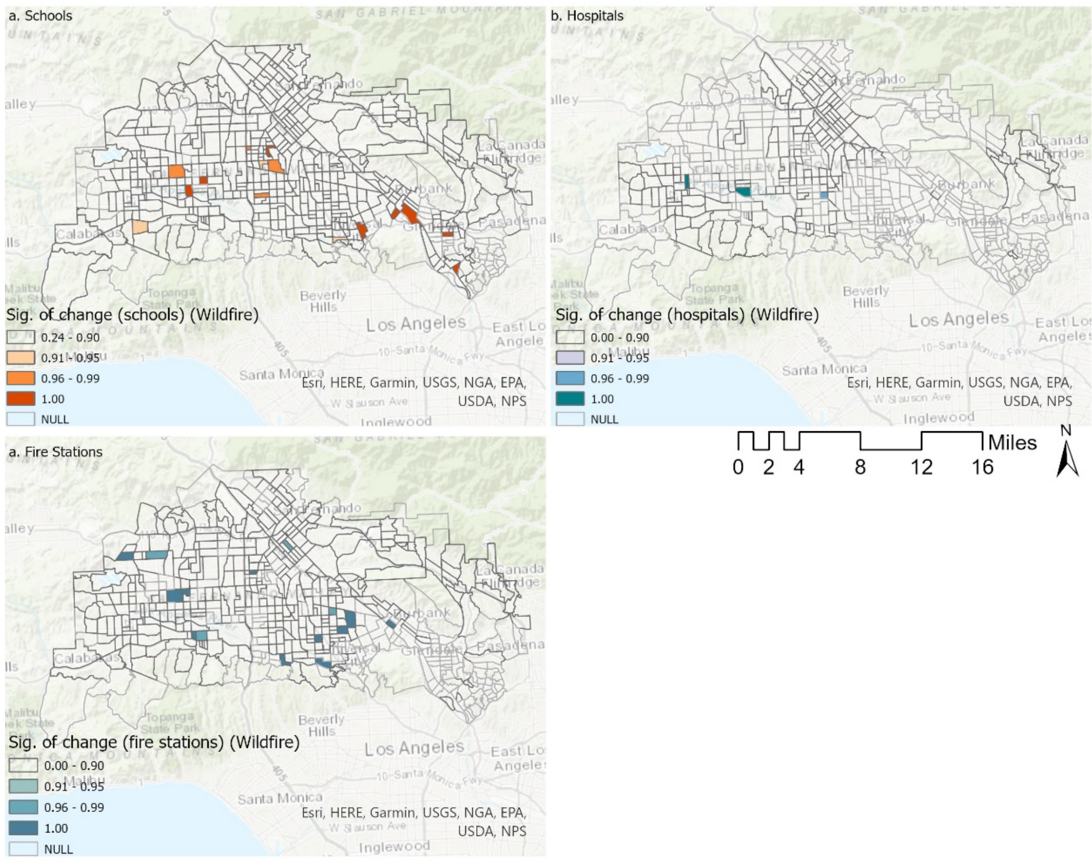


Figure 21. Accessibility Damage Significance for Wildfire Hazards
(Parks, Roads)

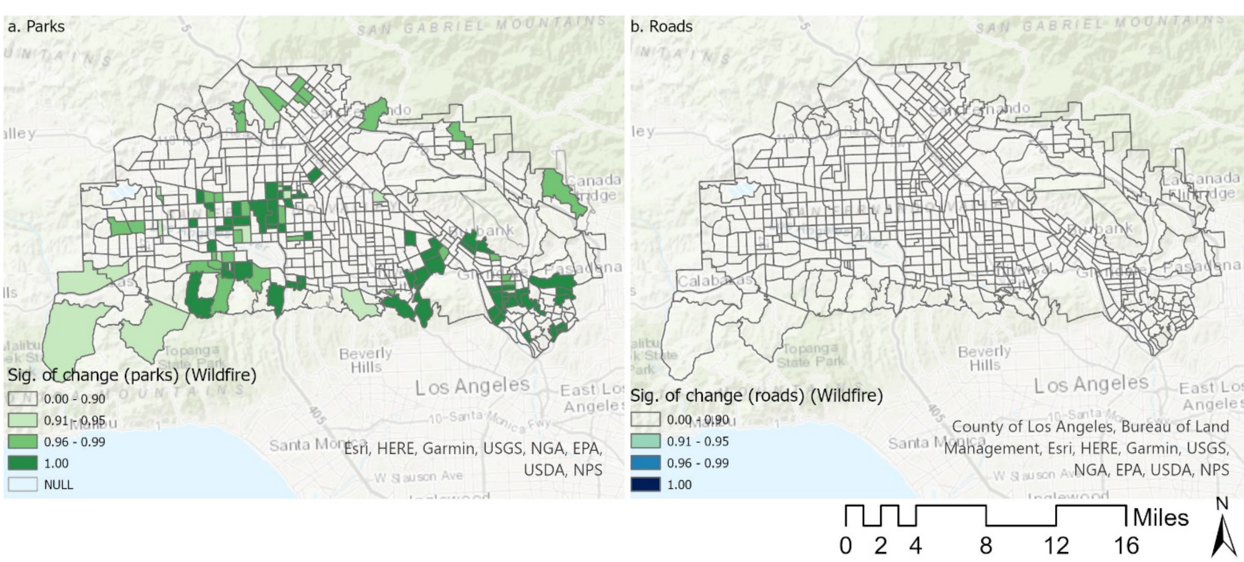


Figure 22. NDAIs for Wildfire Hazards (Schools, Hospitals, Fire Stations)

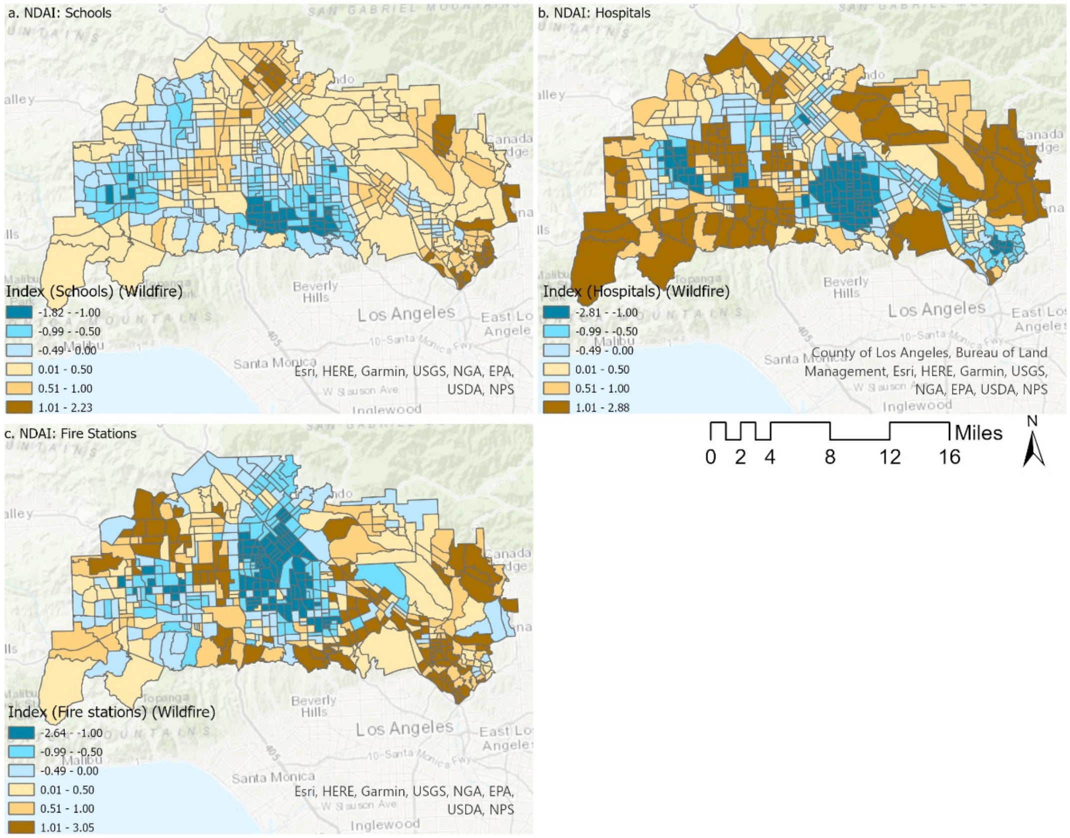
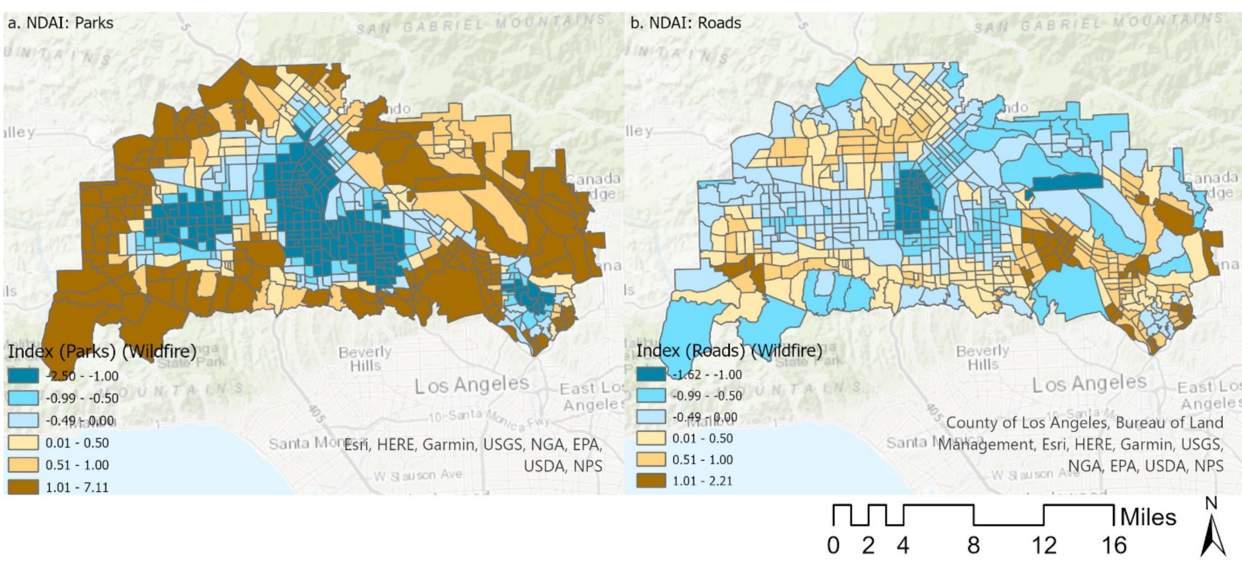


Figure 23. NDAIs for Wildfire Hazards (Parks, Roads)



4. Summary & Conclusions

Increasingly frequent and severe natural events have been continuously threatening residents' life and property. These hazards include wildfire, droughts, hurricanes, and sea-level rises, as well as earthquakes and landslides. Therefore, it is important for decision-makers and urban planners to understand these events' potential impacts on people's daily lives to prepare for the challenges resulting from these natural hazards. One of the key potential impacts is related to people's accessibility to emergency and lifesaving (E&L) facilities, which play an important role in the response phase of the natural hazard management circle but have mostly been ignored in the past resilience studies.

This study attempts to fill this gap with a focus on the development of an analytical research framework to investigate the resilience of the accessibility to emergency and lifesaving facilities under natural hazards. San Fernando Valley in California was selected as the study region with two major natural hazards (earthquake and wildfire) and a semi--closed transportation system. This research framework includes the following four major steps:

- First, using the cumulative-opportunity approach, we calculated accessibility to parks, schools, hospitals, fire stations, and roads respectively within 5 minutes by driving at the census tract level for the case of pre-disaster.
- Second, by considering the potential impact of natural hazards, we recalculated accessibility to these facilities after taking out a part of the transportation network falling in a hazard zone for 30 iterations.
- Third, statistical comparisons were conducted to identify the most affected areas facing a significant drop in accessibility.
- Lastly, we created a normalized difference accessibility index (NDAI) to indicate whether facility allocation or transportation network should be used to improve the resilience of accessibility in these hotspots.

The key findings from this analytical framework are summarized as follows.

- There are spatial variations in the accessibility damage hotspots based on the types of "opportunities." For example, under both seismic and wildfire hazards, the accessibility to schools, hospitals, and roads is mostly affected around Van Nuys and Glendale, while the impact on park and fire station accessibility is relatively more evenly distributed.
- The statistical comparisons point out the locations with significant accessibility damages to different types of facilities. Under seismic hazards, significant results in accessibility to nearby census tracts are only found in the outskirt areas, and fewer locations indicate significant accessibility damage for schools, hospitals, and roads. For the case of wildfire

hazards, special attention should be paid to the locations with significant accessibility damage to parks and fire stations, such as Van Nuys and Glendale.

- The calculated NDAIs for the five types of facilities suggest that the outskirt areas and relatively less developed areas in the study region would need more transportation investments such as an enhanced road network to improve the accessibility resilience, no matter whether the concern is seismic or wildfire hazards.

With this analytical research framework, decision-makers and urban planners will be able to identify the most vulnerable locations by considering different types of natural hazards and different types of emergency and lifesaving facilities. Therefore, corresponding facilities and transportation investments can be recommended for improving accessibility resilience efficiently for areas that need them the most.

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