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MTI MINETA TRANSPORTATION INSTITUTE

Examining the Externalities of Highway Capacity Expansions in California: An Analysis of Land Use and Land Cover (LULC) Using Remote Sensing Technology

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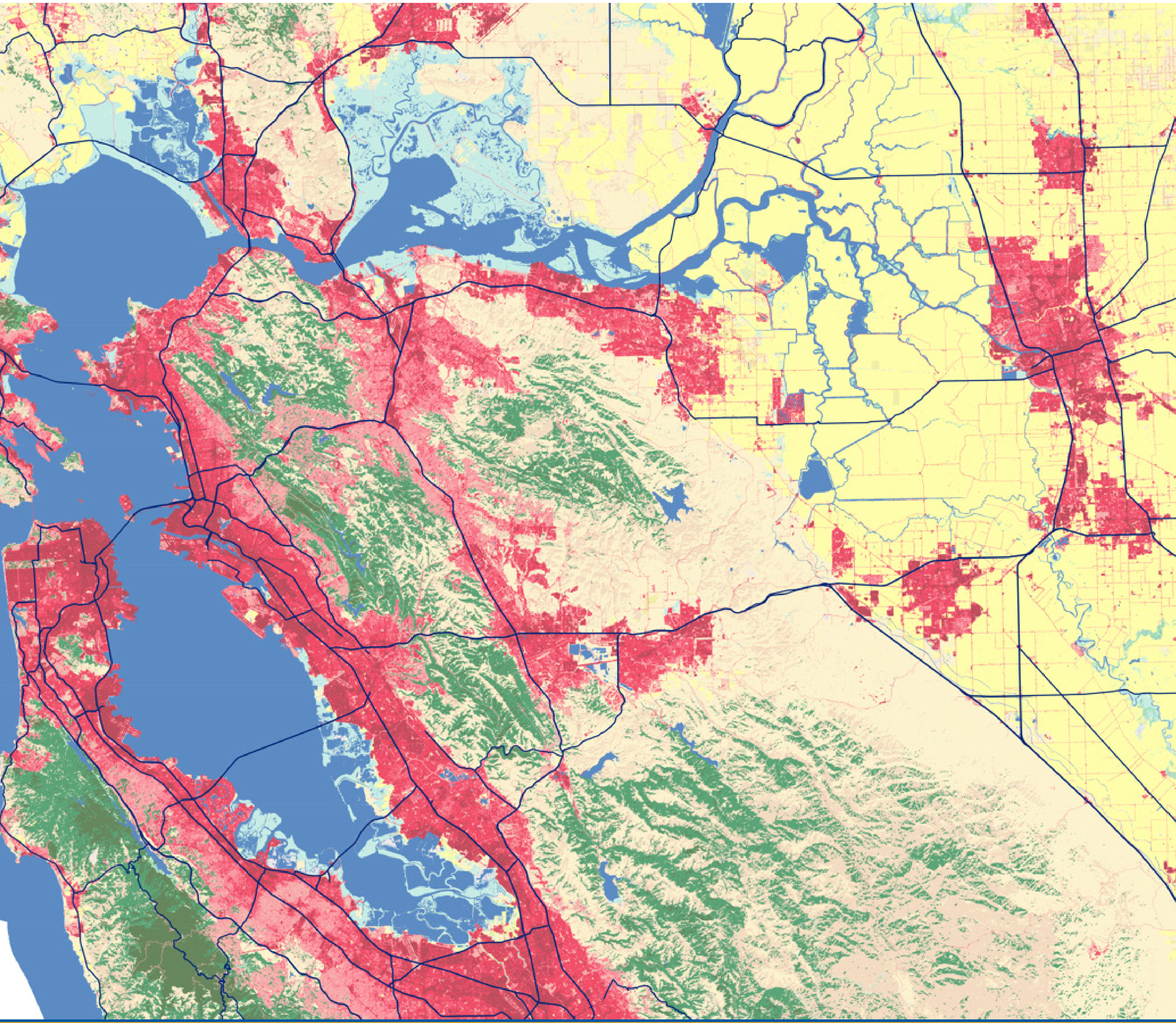

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16. Abstract
Highway capacity expansion has typically been proposed as a tool to alleviate traffic congestion and to mitigate harmful emissions; however, highway capacity expansion has wide impacts on land use and land cover (LULC). Cost-benefit analyses and environmental review processes for roadway capacity expansion and maintenance decisions do not comprehensively consider LULC impacts. This study examined land cover changes directly associated with highway expansion in California and the relationship between land use and the vegetation impacts of highway projects using satellite remote sensing data. The methodology involves a geospatial analysis of Normalized Difference Vegetation Index (NDVI) data in 18 sites across California before and after the highway expansion projects' completion. We accounted for seasonality and included a set of control sites. Findings indicate that the impacts of highway expansion on changes in NDVI are diverse, stressing the importance of the environmental context around each individual project site. Sites that are located near less-developed areas with more extensive natural vegetation (e.g., sprawled areas or exurbs) show significant decline in NDVI values. Virtually all sites with insignificant changes in NDVI after highway expansion are located in areas that already exhibit heavy urban development (e.g., Los Angeles, San José) or are otherwise located near large expanses of bare, non-vegetated earth. Also, project sites that experienced multiple types of construction (i.e., adding more lanes, widening sections, bridge renovation, etc.) were more likely to exhibit decreasing NDVI values compared to project sites that only experienced one type of construction. Decisions about highway construction and capacity expansion should consider the context and the full environmental impacts, including land use and land cover changes over time.

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Executive Summary

Overview

As the largest source of greenhouse gas emissions and criteria air pollutants, transportation is at the center of climate planning efforts in California. To combat climate change, California has implemented some significant changes to help address deficiencies in the way that it plans, implements, and maintains its transportation systems. Some of the most significant changes have specifically sought to address the way that transportation projects are analyzed in the environmental review processes. For example, Senate Bill (SB) 743, which changes the metric for environmental impacts from Level of Service (LOS) to Vehicle Miles Traveled (VMT), was meant to help consider induced demand as a key environmental outcome of highway expansion. Recent legislation has even created additional categorical exemptions under the California Environmental Quality Act, or CEQA for projects found to be VMT-reducing and compliant with relevant local ordinances. Also, the passing of SB 375 created additional CEQA exemptions for projects that align with the regional Sustainable Community Strategies (SCS).

The growing focus on VMT impact mitigation, albeit a move in the right direction for the state's climate goals, presents an incomplete picture of the negative externalities of highway expansions. Most importantly, constructing additional highway lanes has wide impacts on land use (the activities taking place on land) and land cover (the physical attributes of the land surface). The significant and far-reaching environmental impacts of land use and land cover (LULC) change are often not fully captured through current environmental review processes. Disregarding or misestimating the LULC changes of highway capacity expansions can lead to overestimating the benefits of these projects at the expense of habitat or vegetation loss.

Access to satellite remote sensing data can help us better understand and examine the broader non-VMT impacts of highway capacity expansion projects and develop new methods and metrics for environmental impact assessment. This research explores new metrics through which the environmental impacts of highway projects could be comprehensively assessed. Specifically, this research aims to determine whether a well-recognized remotely-sensed vegetation index, such as the Normalized Difference Vegetation Index (NDVI), can offer insights into the impact of highway expansion projects on surrounding vegetation health and environmental composition. The ultimate goal of this research is to provide policymakers with an actionable set of recommendations that can be used to modernize and expedite current environmental review practices.

Study Methodology

The research methods involve two phases: (1) an analysis of the relevant literature and current practices of environmental review for highway projects; and (2) a geospatial analysis examining land cover changes directly associated with highway expansion in California and the relationship between land use and the vegetation impacts of highway projects using satellite remote sensing data.

To determine if NDVI can be used as an indicator for environmental review, the research team first conducted a comprehensive literature review and a review of current environmental review practices. The literature review examined the current and potential uses of NDVI for environmental impact analysis. The review of current practices primarily focused on how current CEQA processes consider non-VMT externalities and what environmental impacts are not currently covered under CEQA. Additionally, the research team explored the environmental review process for projects that are required to undergo NEPA, such as highway expansion projects that involve federal funding sources.

The second phase of the research involved gathering NDVI data surrounding over eighteen highway expansion project sites in California. To analyze the impacts of these highway expansion projects on surrounding NDVI values, we implemented one-, two-, and three-kilometer buffers and collected NDVI data using Google Earth Engine for a year leading up to the project's conclusion and a year following the construction's completion date. We then calculated statistics of the findings for three buffer zones and mapped the results using ArcGIS Pro to determine if there was a significant correlation in the changes observed in the NDVI values.

Key Findings & Conclusions

The results of our literature review and geospatial analysis of highway expansion projects provided new insights into the potential benefits of using NDVI for environmental review processes. The study offered several key findings. First, the patterns of the impacts of highway expansion on changes in NDVI are diverse, indicating that the environmental context of the project plays a significant role in determining the extent of the impact. For example, sites located near less-developed areas with more extensive vegetation (e.g., sprawled areas or exurbs) show larger changes in NDVI values. Conversely, sites located in urban areas or otherwise near large expanses of bare, non-vegetated earth exhibit insignificant vegetation impacts. Also, NDVI values near cropland/farmland were not necessarily impacted by highway expansion because these areas are not covered by naturally growing vegetation, but rather artificially maintained crops, and are therefore less affected by external environmental factors. Lastly, project sites that experienced multiple types of construction/renovation (e.g., adding more lanes, widening sections, bridge renovation, etc.) were more likely to exhibit decreasing NDVI values compared to project sites that only experienced one type of construction. This suggests that aside from project types, the number and combination of projects are important in determining the significance of environmental impacts.

These findings provide significant evidence of the benefits of using wall-to-wall remote sensing data sources such as NDVI to comprehensively measure the impacts of transportation infrastructure development, such as highway expansion projects. While current environmental review practices do account for changes in land use, they only account for land use changes that are directly attributed to the project and do not necessarily cover land use and land cover changes that can be anticipated over time. Also, new guidelines should further emphasize the importance of context in environmental review processes and infrastructure decision-making. Our findings suggest that highway expansion significantly impacts vegetation health in sprawling areas, while impacts in or near denser urban areas are less pronounced. This can inform the development of new guidelines for infrastructure decision-making and environmental review processes that fully consider the environmental context. Lastly, remote sensing technology and new sources of big data can also help evaluate the environmental impacts of infrastructure projects after construction, which can guide future decision-making.

1. Introduction

Transportation is the largest source of greenhouse gas (GHG) emissions and criteria pollutants in California.[1] Highway capacity expansion has typically been proposed as a tool to alleviate traffic congestion and to mitigate GHG emissions and criteria air pollutants. The argument supporting highway expansion has focused on improved vehicle fuel efficiency due to higher speeds and consequently reduced per-mile GHG emissions and criteria air pollutants. However, the efforts to reduce traffic by highway expansion have created a counterproductive outcome because of a phenomenon known as induced travel. In practice, highway capacity expansion reduces the cost of driving by increasing the average speed of traffic, thereby encouraging more people to drive. The passage of Senate Bill (SB) 743 in 2013 shifted the focus of environmental impact assessment from traffic alleviation to vehicle miles traveled (VMT) reduction. As a result, government agencies across the State of California are developing tools and implementing strategies that consider the VMT impacts of developments, including highway expansion projects.

The focus on VMT impact mitigation, albeit a move in the right direction for the state's climate goals, presents an incomplete picture of the negative externalities of highway expansions. Most importantly, constructing additional highway lanes has wide impacts on land use (the activities taking place on land) and land cover (the physical attributes of the land surface). For example, expanding highways results in both increased pavement area and sprawled land uses.[2] Increased pavement area and urban sprawl contributes to a variety of negative environmental impacts, such as loss of habitat, urban heat island effect, increased flooding, reduced groundwater discharge, and aesthetic degradation.[3] Additionally, research has determined that the net flux of carbon from land use and land cover (LULC) changes account for a significant amount of global anthropogenic carbon emissions.[4] Although LULC changes are generally considered a local issue, the

[1] California Air Resources Board, "California Greenhouse Gas Emissions for 2000 to 2019: Trends of Emissions and Other Indicators," (July 28, 2021), https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2019/ghg_inventory_trends_00-19.pdf; California Energy Commission, "Transforming Transportation," (January 2019), https://www.energy.ca.gov/sites/default/files/2019-07/TRAN-TransformingTransportation_1.pdf

[2] Andres Duany, Elizabeth Plater-Zyberk, and Jeff Speck. "Suburban Nation: The Rise of Sprawl and the Decline of the American Dream". Macmillan, 2001.

[3] Todd Litman, "Evaluating Transportation and Land Use Impacts: Considering the Impacts, Benefits, and Costs of Different Land Use Development Patterns," (Victoria Transport Policy Institute, December 2021) https://www.vtpi.org/landuse.pdf

[4] Richard A. Houghton, Jo I. House, Julia Pongratz, Guido R. van Der Werf, Ruth S. Defries, Mathew C. Hansen, C. Le Quéré, and Navin Ramankutty. "Carbon Emissions from Land Use and Land-cover Change." *Biogeosciences* 9, no. 12 (2012): 5125-5142.

environmental impacts of such changes go far beyond the local scale and can even present global environmental challenges.[5]

Despite the significance of the environmental impacts of LULC changes due to highway capacity expansions, there is a clear policy and research gap in this area. Recent research has demonstrated that ignoring or miscalculating induced travel in the CEQA review process for highway expansion projects results in overestimating the congestion-reduction benefits of such projects and underestimating the environmental impacts.[6] Similarly, disregarding or misestimating the LULC changes of highway capacity expansions can lead to overestimating the benefits of these projects. Government agencies in California have started to examine and offset the VMT impact of highway expansion projects, but such analysis and mitigation strategies have not been expanded to other externalities. Additionally, cost-benefit analyses for roadway capacity expansion and maintenance decisions do not comprehensively consider these non-VMT externalities. Simultaneously, while existing research on induced travel due to highway capacity expansion is robust,[7] little is known about the non-VMT externalities (i.e., broader environmental impacts) of such expansion. Only a few studies have attempted to examine the environmental impact of highway construction using remote sensing or other techniques.[8] No other studies have examined the LULC changes directly associated with highway expansion in California using remote sensing data, which is the focus of this project.

[5] Eric F. Lambin, and Helmut J. Geist, eds. *Land-use and land-cover change: local processes and global impacts*. Springer Science & Business Media, 2008; Joyce A. Fry et al., "Completion of the 2006 National Land Cover Database for the Conterminous United States." *PE&RS, Photogrammetric Engineering & Remote Sensing* 77, no. 9 (2011): 858-864.

[6] Jamey Volker, MB, Amy E. Lee, and Susan Handy. "Induced Vehicle Travel in the Environmental Review Process." *Transportation Research Record* 2674, no. 7 (2020): 468–479.

[7] Michael L. Anderson, Lucas W. Davis, and Leila Safavi, "Estimating Induced Travel from Capacity Expansions on Congested Corridors," (report prepared for the California Air Resources Board, March 2021), https://ww2.arb.ca.gov/sites/default/files/2021-04/18RD022.pdf.

[8] Shuailong Feng et al., "Quantification of the Environmental Impacts of Highway Construction Using Remote Sensing Approach." *Remote Sensing 13,* no. 7 (2021): 1340.

2. Review of Current Literature and Practices

The goal of this chapter is twofold. First, the chapter examines the most recent and relevant academic literature to determine the importance of vegetation coverage and health for the environment. This can help us better understand how highway expansion projects can potentially impact their surrounding environment by altering vegetation or land cover. Second, this literature review will also analyze current practices to identify how current environmental review processes, primarily CEQA, account for environmental externalities such as induced demand and vegetation coverage.

2.1 Vegetation Coverage

The primary non-VMT impact that this research will seek to analyze is the impact of highway expansion projects on vegetation coverage using Normalized Difference Vegetation Index (NDVI) data. The purpose of using vegetation coverage as a metric is due to the significance that vegetation coverage has in maintaining local ecosystems and indicating significant shifts in climate. NDVI is most commonly used to measure the ability of vegetation to absorb sunlight and fuel photosynthetic reactions, normally on a positive to negative scale from +1.0 to -1.0.[9] Positive values are associated with healthy vegetation coverage, while negative values indicate stressed or dying vegetation. Figure 1 below illustrates the relationship between plant health and NDVI values. One of the strengths of using a vegetation index such as NDVI is its versatility. Studies have incorporated NDVI data in a wide scope of research topics, including analyzing changes in Land Use and Land Cover (LULC) and changes in Land Surface Temperature (LST). Additionally, vegetation indices have proven effective for informing climate models such as Soil-Vegetation-Atmosphere-Transfer, Surface Energy Balance, and even Global Climate Models.[10] Global Climate Models are important tools for researchers that enable them to predict changes in climate behavior and understand the influence of different climate features on climate change. These Global Climate Models can be used to both predict changes in climate as well as detect and attribute the possible explanations for these changes.

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[9] Jesslyn Brown, "NDVI, the Foundation for Remote Sensing Phenology," *Www.usgs.gov* (United States Geological Survey, November 2018), last modified November 2018, https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-remote-sensing phenology#:~:text=NDVI%20values%20range%20from%20%2B1.0.

[10] Edward P. Glenn et al., "Relationship between Remotely-Sensed Vegetation Indices, Canopy Attributes and Plant Physiological Processes: What Vegetation Indices Can and Cannot Tell Us about the Landscape," *Sensors* 8, no. 4 (April 1, 2008): 2136–2160, https://doi.org/10.3390/s8042136.

Figure 1. Plant Health Relative to NDVI Value

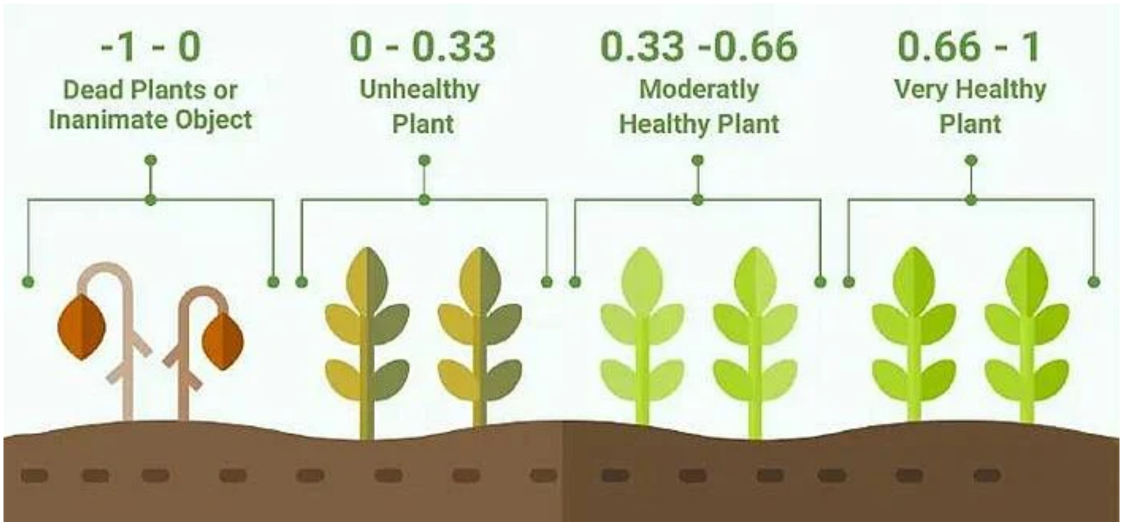

Image Retrieved From: Cropin, NDVI and its Practical Applications in Agriculture, Published December 17, 2021. Accessed September 20, 2023

Using vegetation indices such as NDVI to measure impacts on vegetation coverage is significant because vegetation covering plays a vital role in regulating natural systems as well as communicating environmental health. A technical report for the City of Auckland, New Zealand, referred to how vegetation coverage provides significant environmental services, including "water purification, air quality regulation, noise, and local climate regulation," which are important for both the local environment and overall community health and wellbeing.[11] Another study on the relationship between vegetation cover, air quality, and daily temperature oscillation found a negative association between vegetation cover and the total number of suspended particles in the air, emphasizing the importance of increasing and preserving vegetation cover to improve urban community health.[12] The research has shown that vegetation coverage is primarily lost due to the effects of urban expansion, which capacity-increasing highway projects can trigger.[13]

[11] Robyn Simcock, William Wright, Marie Brown, Craig Bishop, "Effectiveness of Protecting Urban Vegetation: Assessing Vegetation Cover Changes with Urban Expansion and Intensification: Technical Document for Protecting the Urban Forest," https://oldwww.landcareresearch.co.nz/__data/assets/pdf_file/0018/101448/Policy_Brief_13_Protecting_urban_vegetation.pdf.

[12] Carmen Isela Ortega-Rosas et al., "Urban Vegetation Cover Correlates with Environmental Variables in a Desert City: Insights of Mitigation Measures to Climate Change," *Urban Ecosystems* (April 25, 2020), https://doi.org/10.1007/s11252-020-00982-8.

[13] S. L. Feng and S. Liu, "Remote Sensing of Environmental Impacts of Highway Construction: A Case Study of the Wujing Highway in Hunan Province, China," *American Geophysical Union* 2020 (December 1, 2020): B061-0018, accessed July 29, 2023, https://ui.adsabs.harvard.edu/abs/2020AGUFMB061.0018F/abstract.

Relationship between NDVI and Endangered Species

In addition to monitoring the health of human environments, NDVI has also been used to monitor the health of other biological inhabitants, including endangered species. For example, a 2018 study analyzed the relationship between NDVI values and the survival rates of both male and female Sierra Nevada bighorn sheep, which is listed as an endangered species under both the Federal Endangered Species Act and the California Endangered Species Act.[14] The study found a positive relationship between the survivability of both males and females with respect to peak NDVI values, meaning that a higher NDVI value would indicate a higher survival rate amongst the sheep.[15] Another 2020 study found that NDVI was an "important ecological indicator" in predicting the selection of habitats by endangered lizard species and found that a higher NDVI value correlated with higher intensities of selection by desert lizards.[16] Currently, 250 species are listed under the California Endangered Species and, therefore, the importance of a crucial metric such as NDVI to monitor the impacts on the environment's health and the habitat of its endangered species should be recognized.[17] Overall, NDVI has proven to be a crucial tool for analyzing the impacts of changes in NDVI values on the biodiversity of past and future populations.[18]

Connections between NDVI and Climate Resilience

Besides providing key ecological functions and measuring biodiversity health, NDVI has also been used to predict natural climate disasters such as wildfires and to analyze changes in flood patterns. A 2019 study that sought to use NDVI, Land Surface Temperatures (LST), and thermal anomalies to predict wildfire events in Canada was able to create and utilize two separate models that successfully predicted simulated wildfire events with a 97.5% to 98.3% accuracy.[19] In addition to predicting wildfires, NDVI has been used to measure the impacts of LULC changes on flood patterns. Another 2014 study found increases in impervious surfaces surrounding the Fraser River

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[14] U.S. Fish & Wildlife, "Listed Animals," *Environmental Conservation Online System: Listed Animals* (U.S Fish & Wildlife Service , 2019), last modified 2019, https://ecos.fws.gov/ecp0/reports/ad-hoc-species-report?kingdom=V&kingdom=I&status=E&status=T&status=EmE&status=EmT&status=EXPE&status=EXPN&status=SAE&status=SAT&mapstatus=3&fcrithab=on&fstatus=on&fspecrule=on&finvpop=on&fgroup=on&header=Listed+Animals.

[15] Mary M. Conner et al., "Survival Analysis: Informing Recovery of Sierra Nevada Bighorn Sheep," *The Journal of Wildlife Management* 82, no. 7 (May 23, 2018): 1442–1458.

[16] Christopher J. Lortie et al., "Shrub and Vegetation Cover Predict Resource Selection Use by an Endangered Species of Desert Lizard," *Scientific Reports* 10, no. 1 (March 17, 2020).

[17]Habitat Conservation Planning Branch , "Threatened and Endangered Species," Wildlife.ca.gov (California Department of Fish and Wildlife, April 2023), last modified April 2023, accessed July 2, 2023, https://wildlife.ca.gov/conservation/cesa#:~:text=Approximately%20250%20species%20are%20currently.

[18] Ryan N. S, Pettorelli et al., "The Normalized Difference Vegetation Index (NDVI): Unforeseen Successes in Animal Ecology," *Climate Research* 46, no. 1 (January 20, 2011): 15–27.

[19] Younes Oulad Sayad, Hajar Mousannif, and Hassan Al Moatassime, "Predictive Modeling of Wildfires: A New Dataset and Machine Learning Approach," *Fire Safety Journal* 104 (March 2019): 130–146, https://www.sciencedirect.com/science/article/pii/S0379711218303941.

Delta in Montreal, Canada, dramatically affected the flood patterns observed in the area. The study monitored vegetation covering using NDVI to measure impervious surface increases and found that the areas where impervious surfaces increased faced a reduced "time to peak" and produced "higher peak flows in the drainage channels," which impacted the river's flow and the area's flooding conditions.[20]

Another environmental factor that can be impacted by vegetation loss is surrounding Land Surface Temperatures (LSTs). A 2019 study found that reduced quality of vegetation cover can have a positive effect on the surrounding LST and general temperature patterns.[21] LSTs are a significant environmental indicator that can influence surrounding vegetation and inform policymakers about the extent of "Urban Heat Islands" (UHI) and their subsequent effect on the natural and built environment. A study in 2020 by Fabo Liu et al. found a positive correlation between LST and increases in road network mileage.[22] In addition to exacerbating UHI and vegetation loss, increases in LST can also drastically affect human health. A study by I.R. Orimoloye et al. found that increases in ultraviolet radiation due to increases in LST can increase the risk of heat stroke, skin cancer, and heart disease in local populations, especially in people with social or physical vulnerabilities.[23] Another study conducted by Vaclav Nedbal and Jakub Brom found that highway construction can affect the local climate up to 90 meters (9roject. 295 feet) from the highway axis and could result in temperature increases up to 7 degrees Celsius (44 degrees Fahrenheit).[24] These dramatic shifts in climate can have lasting effects on the surrounding environment by further contributing to existing urban heat islands and exacerbating other factors, such as further decreasing vegetation coverage.

Relationship between NDVI and Urban Growth

Vegetation cover can be a significant metric for monitoring changes in the built environment as well. A growing field of research has used NDVI data to measure changes in urban footprints. Similar to the concept of "induced demand," academics have also suggested that highway expansion projects can trigger another phenomenon known as "induced growth," which refers to land use and land cover changes that result from improving transportation systems. In a series of

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[20] Amin M. Owrangi, Robert Lannigan, and Slobodan P. Simonovic, "Interaction between Land-Use Change, Flooding and Human Health in Metro Vancouver, Canada," Natural Hazards 72, no. 2 (February 7, 2014): 1219–30, https://doi.org/10.1007/s11069-014-1064-0.

[21] Mehran Fatemi and Mahdi Narangifard, "Monitoring LULC Changes and Its Impact on the LST and NDVI in District 1 of Shiraz City," *Arabian Journal of Geosciences* 12, no. 4 (February 2019).

[22] Fabao Liu et al., "Analysis of Land Surface Temperature Evolution Based on Regional Road Scope," *Advances in Civil Engineering* 2020 (August 12, 2020): 1–15.

[23] Orimoloye, I. R., S. P. Mazinyo, W. Nel, and A. M. Kalumba. "Spatiotemporal Monitoring of Land Surface Temperature and Estimated Radiation Using Remote Sensing: Human Health Implications for East London, South Africa." *Environmental earth sciences* 77 (2018): 1–10.

[24] Nedbal, Václav, and Jakub Brom. "Impact of Highway Construction on Land Surface Energy Balance and Local Climate Derived from LANDSAT Satellite Data." *Science of The Total Environment* 633 (2018): 658–667.

reports on this phenomenon, R. Cervero determined that freeway investments can lead to significant "induced growth" as real estate development tended to gravitate towards improved freeway corridors and traffic investment areas.[25] Building on this idea, a study by R. Fundberg et al. aimed to determine how highway expansion projects impact surrounding growth. They found that the growth impact depended on the characteristics of the investment, including construction type, and the surrounding land use characteristics. Their 2010 study found that the context of the highway expansion projects played a significant role in determining the growth impact the project would have and that it had the strongest correlation with employment growth in the surrounding area.[26] However, they could not determine if these changes were "new growth" or simply growth that had shifted from surrounding areas.

These growth impacts including land-use changes are important because they contribute to loss in vegetation coverage and biodiversity in existing open and undeveloped lands. Research into the effects of highway construction projects have suggested that these project types can serve as catalysts for land-use changes. A study in 2020 focused on the environmental impacts of the Wujing highway construction process and found that after its construction, forest and cropland were reduced by 28% and 4%, respectively.[27] These changes were largely due to urban expansion, with a 33% increase in the built-up area during the study period.[28]

2.2 Current Practices

While the academic literature analyzed above supports the importance of vegetation coverage as well as the idea that capacity-increasing infrastructure projects such as highway expansion increase the urban footprint, it is unclear whether current environmental review practices capture the full scope of these impacts. This section will specifically look at the California Environmental Quality Act (CEQA) review process to evaluate whether factors such as vegetation coverage and land surface temperature are fully considered.

California Environmental Quality Act

Established by the State of California in 1970, the California Environmental Quality Act (CEQA) serves as the primary tool for the state to assess the environmental impacts of development projects

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[25] Robert Cervero, "Road Expansion, Urban Growth, and Induced Travel: A Path Analysis," *Journal of the American Planning Association* 69, no. 2 (June 30, 2003): 145–163.

[26] Richard G. Funderburg et al., "New Highways and Land Use Change: Results from a Quasi-Experimental Research Design," *Transportation Research Part A: Policy and Practice* 44, no. 2 (February 2010): 76–98.

[27] Shuailong. Feng and S. Liu, "Remote Sensing of Environmental Impacts of Highway Construction: A Case Study of the Wujing Highway in Hunan Province, China," *American Geophysical Union* 2020 (December 1, 2020): B061-0018, accessed July 29, 2023, https://ui.adsabs.harvard.edu/abs/2020AGUFMB061.0018F/abstract.

[28] Shuailong. Feng and S. Liu, "Remote Sensing of Environmental Impacts of Highway Construction: A Case Study of the Wujing Highway in Hunan Province, China," *American Geophysical Union* 2020 (December 1, 2020): B061-0018, accessed July 29, 2023, https://ui.adsabs.harvard.edu/abs/2020AGUFMB061.0018F/abstract.

in California. CEQA's review is based on the scale and scope of the project and its overall potential to impact the surrounding environment. While the process that each project must go through varies and depends on the project's scope, project types such as highway expansion projects can expect similar review processes to be conducted under similar lead agencies. The actual review process depends entirely on the project's size, scope, and environmental context and location. These reviews can vary between an initial study to a full environmental impact review, or even a joint review process involving both CEQA and the National Environmental Protection Act (NEPA). The different types of reviews directly impact the extent to which environmental factors are analyzed. Recent legislation, such as SB 375, has also sought to expedite the review process for projects that lower VMTs and are consistent with regional Sustainable Community Strategies. Yet, the full environmental impacts of these projects, such as land cover changes over time, might not be fully examined.[29]

National Environmental Protection Act

Established by the Nixon administration in 1969, the National Environmental Protection Act (NEPA) requires government-funded projects to undergo an environmental review process similar to CEQA. In certain circumstances, a project may be required to go through both a CEQA and NEPA review. NEPA is an environmental review law very similar in nature to CEQA. Both require defined "projects," or in the NEPA reviews what are referred to as "actions," to go through specific environmental reviews to measure and mitigate the potential environmental impacts of the action depending on the scale and scope that is proposed.[30] For the purposes of environmental review, CEQA and NEPA utilize similar definitions and types of analysis, with slight differences in vocabulary. One example is the use of a similar definition of "cumulative impact," which is important when considering the environmental impacts of highway infrastructure projects.[31]

While it is important to analyze the utilization of NDVI values in both the CEQA and NEPA review processes, this research chooses to focus on the CEQA review process, primarily because NEPA and CEQA have very similar review processes and in certain circumstances utilize similar definitions. Therefore, it can be assumed that the utilization of NDVI in the CEQA review process has the same potential to benefit the NEPA review process. Also, exploring the uses at the state level provides an effective testing process before being implemented at the federal level.

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[29] Institute for Local Government, "The Basics of SB 375," The Basics of SB 375 (Institute for Local Government, January 7, 2009), https://www.ca-ilg.org/post/basics-sb-375.

[30] Governor's Office of Planning and Research, "NEPA and CEQA: Integrating Federal and State Environmental Reviews," *CEQA Documents* (Sacramento, California: Governor's Office of Planning and Research, 2014), https://opr.ca.gov/ceqa/docs/NEPA_CEQA_Handbook_Feb2014.pdf.

[31] Governor's Office of Planning and Research, "NEPA and CEQA: Integrating Federal and State Environmental Reviews," *CEQA Documents* (Sacramento, California: Governor's Office of Planning and Research, 2014), https://opr.ca.gov/ceqa/docs/NEPA_CEQA_Handbook_Feb2014.pdf.

Induced Demand

The California Environmental Quality Act's recent change to utilizing Vehicle Miles Traveled (VMT) as a primary metric to analyze new development has significantly shifted how transportation projects are reviewed in California. As a result of Senate Bill 743, lead agencies are now responsible for analyzing, estimating, and mitigating changes in VMT that may result from a new project.[32] While some current practices claim that capacity-increasing projects such as highway expansions have a positive effect on reducing VMT, recent studies have questioned this determination and suggest that specific capacity-increasing projects can have the opposite effect than intended. One of the earliest studies that focused on the effects of highway expansion projects on traffic models was published in 1963 and found that the effects of highway improvements could be classified into two distinct rounds.[33] The first round of effects refer to the redistribution of traffic in the city's road network leading to more congestion occurring on the improved road system and the decongestion of the previously used systems.[34] The second round of effects refer to the increases in traffic that can be expected because of the system improvement, where it was estimated that in extreme cases, traffic may increase by 30 percent as a result of the improvement.[35] This increase in traffic demand would go on to become a central focus and become what transportation researchers now refer to as "induced demand."

While current environmental review practices account for induced demand in its review process, multiple studies have demonstrated that the review process may not accurately estimate the level of VMT reduction and thus would fail to accurately measure the amount of GHG emissions created by the project. A study that specifically analyzed induced demand within the CEQA review process found that environmental reviews often fail to accurately analyze the induced demand created by highway expansion projects.[36] Using an Induced Travel Calculator that they created, the researchers compared the VMT 12roject12es of the environmental review to their calculations. This report also theorized that the induced demand created by highway expansion projects could minimize the benefits initially attributed to the project and that it can be equally effective to reduce

[32] California Department of Transportation, *SB 743: Rethinking How We Build so Californians Can Drive Less*, *SB 743 Implementation Resources* (State of California, July 2020), https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/sb-743/sb743-factsheet-overview-a11y.pdf.

[33] M. E. Beesley, A. J. Blackburn, and C. D. Foster, "Urban Transport Models and Motorway Investment," *Economica* 30, no. 119 (August 1963): 243, https://doi.org/10.2307/2601545.

[34] M. E. Beesley, A. J. Blackburn, and C. D. Foster, "Urban Transport Models and Motorway Investment," *Economica* 30, no. 119 (August 1963): 243, https://doi.org/10.2307/2601545.

[35] Ibid.

[36] Jamey Volker, MB, Amy E. Lee, and Susan Handy. "Induced Vehicle Travel in the Environmental Review Process." *Transportation Research Record* 2674, no. 7 (2020): 468–479.

highway capacities to achieve VMT reductions.[37] However, the results of these studies have varied between cases.

Senate Bill 375

One of the state's primary tools to establish collaborative action against reducing Greenhouse Gas Emissions (GHGs) has been through Senate Bill (SB) 375, also known as the Sustainable Communities Act. SB 375 was passed in 2008 and gave the authority of GHG regulation over to the California Air Resources Board (CARB) and set regional targets for reducing emissions. This involved regional governments creating and implementing regional transportation plans, known as Sustainable Community Strategies (SCS), that aim to reduce GHG emissions. CARB has identified the transportation sector as the leading source of GHGs in California, accounting for forty percent of total annual GHGs produced in the state.[38] As such, SB 375 identifies the regional transportation planning process as one of the primary mechanisms to reduce emissions to be consistent with AB 32's goals. Finally, SB 375 changed housing element law in order to make it more cohesive with the regional transportation planning process. First, it required housing elements synchronize with regional SCSs and develop common land use assumptions to be used.

In addition to establishing the requirement for regional transportation plans and identifying CARB as the primary regulator of GHG emissions, SB 375 also offered CEQA incentives to encourage projects that are consistent with a regional transportation plan that reduces GHG emissions. Mainly, regulators sought to streamline these projects through the CEQA review process due to their consistency with California's environmental and equity goals. While streamlining projects through the CEQA process limits the number of review rounds the project undergoes, it also limits the potential to uncover environmental impacts that have not previously been considered.

One of the most important aspects of SB 375 was the requirement to review the potential cumulative impacts a project will have on the surrounding environment and include this analysis in the environmental document. In addition to analyzing potential impacts on the natural environment, these cumulative impacts also analyze impacts on the built environment and require decision-makers to weigh potential impacts, such as induced demand. For the purposes of environmental review, CEQA and NEPA have adopted similar definitions of cumulative impacts meaning that any metrics or methods that could assist in these analyses could be applied to both review processes.

[37] Jamey Volker, MB, Amy E. Lee, and Susan Handy. "Induced Vehicle Travel in the Environmental Review Process." *Transportation Research Record* 2674, no. 7 (2020): 468–479.

[38] Institute for Local Government, "The Basics of SB 375," The Basics of SB 375 (Institute for Local Government, January 7, 2009), https://www.ca-ilg.org/post/basics-sb-375.

Cumulative Impact and Indirect Impact Analysis

Currently, the California Environmental Quality Act (CEQA) review processes include the analysis of 19 different environmental factors a project could impact. However, the extent of evaluation of these factors can significantly vary depending on the project's geography, scope, and existing plans to address these factors. One existing CEQA tool that could capture these complexities is the Cumulative and Indirect Impact analysis required under CEQA. Indirect impacts under CEQA are defined as impacts that are not immediately related to the project but are "reasonably foreseeable and caused by a 14rojectt."[39] One type of these indirect impacts specifically refers to "growth-inducing impacts." CEQA specifically defines that a growth-inducing impact could occur if:

> *…the proposed project could foster economic or population growth, or the construction of additional housing, either directly or indirectly, in the surrounding environment. Included in this are projects that would remove obstacles to population growth (a major expansion of a wastewater treatment plant might, for example, allow for more construction in the service areas). Increases in the population may tax existing community service facilities, requiring construction of new facilities that could cause significant environmental effects.*[40]

Based on findings from the academic literature, capacity-increasing projects could be considered as triggering a "growth-inducing impact" as well as "indirect impacts" under the current definitions outlined in CEQA.[41] Current theories about induced demand and induced growth support that these project types could significantly impact vegetation covering and further damage existing ecosystems. However, since CEQA review is determined on a project-by-project basis, it is unknown whether capacity-increasing efforts such as highway expansion projects would automatically trigger a cumulative impact review.[42]

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[39] Caltrans "Guidance for Preparers of Cumulative Impact Assessments CEQA Guidelines for Cumulative and Indirect Impacts" https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/ser/ceqa-guidelines-for-cumulative-and-indirect-impacts-a11y.pdf.

[40]Caltrans "Guidance for Preparers of Cumulative Impact Assessments CEQA Guidelines for Cumulative and Indirect Impacts" https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/ser/ceqa-guidelines-for-cumulative-and-indirect-impacts-a11y.pdf.

[41] Ibid.

[42] Giulia Gualco-Nelson, "Reversing Course in California: Moving CEQA Forward," *Ecology Law Quarterly* 44, no. 2 (October 3, 2017): 155–177.

Using Appendix G Checklist to Determine the Significance of Impacts

A primary way lead agencies identify the impacts created by a project is through the use of the Appendix G checklist, which provides guiding questions and statements that can be used to identify significant impact findings as well as the potential for cumulative impacts. This checklist is significant as it plays a role in many environmental review practices to guide the initial review. The document is separated into 19 different topics that must be analyzed during the environmental review and presents guiding questions meant to assist reviewers in determining what topics will be impacted and to what extent. However, the current guidance that the document provides can be inconsistent both within itself as well as with current academic literature. The "Population and Housing" section of this checklist explicitly mentions the impact of highway expansion projects on surrounding land use.[43] However, the "Traffic and Transportation," "Air Quality," and "Land Use" factors in the Appendix G checklist make no reference to the connection between capacity-increasing highway projects and induced demand despite a significant number of academic studies highlighting this connection. While a separate review process does exist that requires projects to calculate induced demand, its lack of inclusion in the Appendix G checklist suggests that this is not a primary consideration.

When referring to "Biological Resources" which includes vegetation covering, the checklist frequently refers to local plans and endangered plant species lists as primary considerations.[44] Furthermore, the CEQA checklist noted above does not mention how a project could influence Land Surface Temperatures (LSTs), even though there is documentation about the correlation between the addition of highway infrastructure increases and LSTs. While the Appendix G checklist can vary between projects, CEQA's guiding questions and statements for consideration suggest that the process varies greatly on a project-by-project basis and heavily relies on local planning documents to account for these factors, which can produce varying results between projects.

2.3 Key Takeaways

While the California Environmental Quality Act (CEQA) has made significant progress in capturing a wider scope of impacts induced by highway construction and capacity-increasing projects, there are still significant gaps in this review process that limit their ability to analyze vital environmental impacts such as changes in vegetation coverage. Ultimately, the CEQA process still heavily varies based on project-by-project modeling and defers to local planning documents to capture specific project impacts.

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[43] Caltrans, *CEQA Appendix G: Environmental Checklist Form* (State of California: California Department of Transportation, 2016), https://resources.ca.gov/CNRALegacyFiles/ceqa/docs/ab52/final-approved-appendix-G.pdf.

[44] Caltrans, *CEQA Appendix G: Environmental Checklist Form* (State of California: California Department of Transportation, 2016), https://resources.ca.gov/CNRALegacyFiles/ceqa/docs/ab52/final-approved-appendix-G.pdf.

Academic literature and technical reports acknowledge the importance of vegetation coverage and Land Surface Temperature (LST) in measuring environmental impacts. Studies have shown that these are significant environmental indicators that can be impacted directly and indirectly by capacity-increasing projects. Studies have shown that vegetation covering is critical in regulating air quality, surface and subsurface temperatures, and soil quality. Vegetation cover is most likely impacted by urban expansion spurred by growth-inducing projects, such as highway expansions. Nevertheless, few of these studies applied the scope of capacity-increasing infrastructure projects, such as highway expansion, and none examined how indicators such as NDVI could be used in the CEQA review process.

While academic literature supports the importance of maintaining vegetation coverage, the current environmental review process does not consistently account for certain environmental impacts in the review process. Metrics such as LST are referenced in the goals listed by Caltrans in long-range plans, such as its statewide transportation plan, but currently there are no monitoring procedures that would allow them to properly measure changes and make connections to the long-term impacts of these changes. Additionally, it was determined that until recently, reviewing agencies were not properly estimating crucial elements, such as the induced demand created by highway expansion projects, which directly affects the scope of review required for projects. Based on reviews of current practices, it can be argued that the review process heavily emphasizes local plans to account for environmental externalities such as impacts on vegetation cover, which can lead to varying results for projects in different geographical areas.

Given the recent progress made in research and data collection practices, lead agencies reviewing highway projects under CEQA have the ability to utilize robust and open data sources such as NDVI to quantify the impacts of highway expansion projects and to create a more uniform project review process. Current CEQA review processes can vary greatly depending on the project's location, lead agency, and the existing legislation that informs the environmental impact review process. NDVI offers but one example of a highly adaptable data source that could be used as a baseline metric for environmental health to inform policymakers of the highway expansion impacts. More importantly, there are many other resources, such as Google Earth, that are readily available and easily accessible to new users.

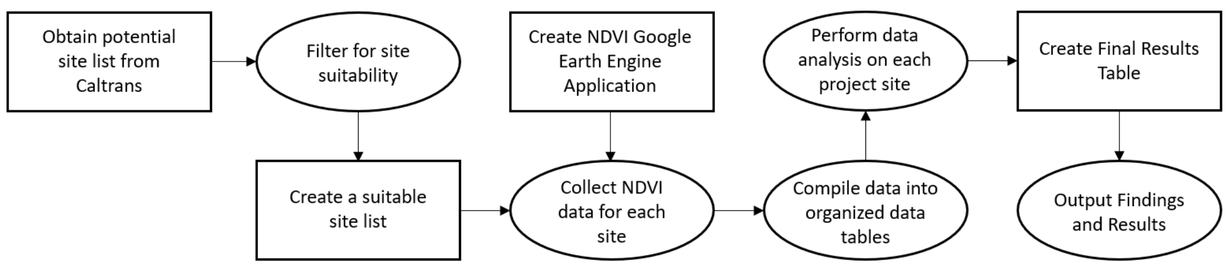
This project explores the idea of using NDVI data to examine the vegetation impacts of highway projects before and after highway construction completion. A better understanding of how highway projects impact their surrounding environment and how the context of each project influences these impacts can shed light on developing much-needed new tools for environmental review processes.

3. Methodology

3.1 Workflow

The following section describes the general workflow of our research, which examines vegetation health before and after the completion of various highway expansion projects around California using satellite remote sending data. This workflow involves: (1) creating a list of suitable highway expansion project sites to study based on temporal data availability, (2) locating each site and ensuring valid geographic suitability, (3) creating an online data acquisition tool via the Google Earth Engine that allows us to gather Normalized Difference Vegetation Index (NDVI) data for each site from satellite remote sensing open datasets, and (4) analyzing this data to determine how land cover is affected before and after the closeout date for each site, and how land use and context influence the vegetation impacts of highway projects. This workflow is illustrated in Figure 2.

Figure 2. Methodology Workflow



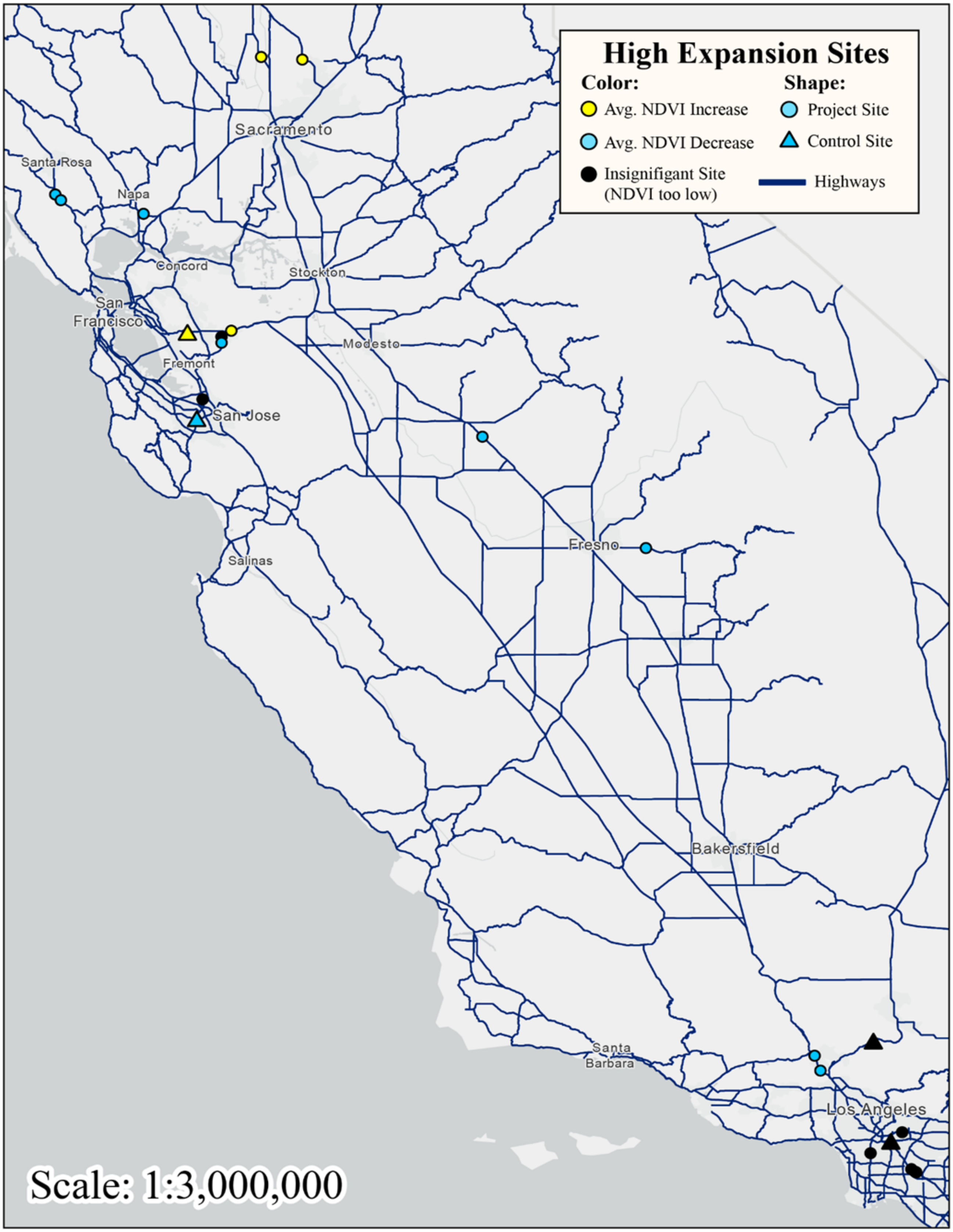
3.2 Data Sources

After establishing our workflow and methodology for the project, we began compiling the necessary data sources, starting with site selection. At the start of the project, Caltrans provided us with a list of 53 potential highway expansion project sites. These sites varied widely both spatially and temporally, with locales ranging from Los Angeles to Northern California, and closeout dates (CODs) ranging from 12/31/2012 to 08/17/2021. The closeout date represents the day that the highway expansion project was deemed as complete and road fully reopened to daily traffic. Of this list of 53 potential study sites, we needed to determine which ones were suitable for our analysis. The two main criteria that made a site unfavorable for analysis were: (1) if the highway expansion project was too close to large bodies of water (such as coastal highways or sections of highway that passed by large rivers and/or lake systems), and (2) if the COD of the project fell outside of our remote-sensing data temporal ranges. After this filtering, we were left with a list of 18 highway expansion sites that we deemed suitable for further analysis, mostly residing in the Bay Area and Los Angeles County. Table 1 shows the list of project sites, and Figure 3 illustrates the location of both the study and control sites

Table 1. Full Site Table

Site ID	County	Closeout Date	Route	Post-Miles
0300000206	Sutter	12/05/2017	99	11.000/14.300
0300020583	Placer	01/23/2015	65	R15.000/R23.800
0400000140	Sonoma	08/19/2019	101	8.900/13.900
0400000799	Santa Clara	01/16/2015	880	4.700/8.700
0400002022	Napa	08/08/2018	12	0.000/3.200
0400020004	Sonoma	10/14/2013	101	7.100/8.900
0400020580	Alameda	01/14/2016	84	25.500/27.100
0400020581	Alameda	03/12/2020	84	22.900/25.700
0400021248	Alameda	09/30/2016	580	R8.400/R21.600
0600000381	Fresno	10/19/2020	180	R71.800/74.500
0700000339	Los Angeles	08/16/2018	5	1.800/3.000
0700000390	Los Angeles	06/02/2015	5	R43.600/R50.000
0700000514	Los Angeles	12/31/2012	110	10.000/22.000
0700000514	Los Angeles	12/31/2012	10	17.100/48.300
0700001831	Los Angeles	06/14/2016	5	1.200/2.100
0700001833	Los Angeles	02/20/2020	5	2.700/4.000
0700020201	Los Angeles	01/21/2016	5	31.600/36.000
1000000430	Merced	12/19/2017	99	4.600/12.700

Figure 3. Full Site Map (Including Control Sites)

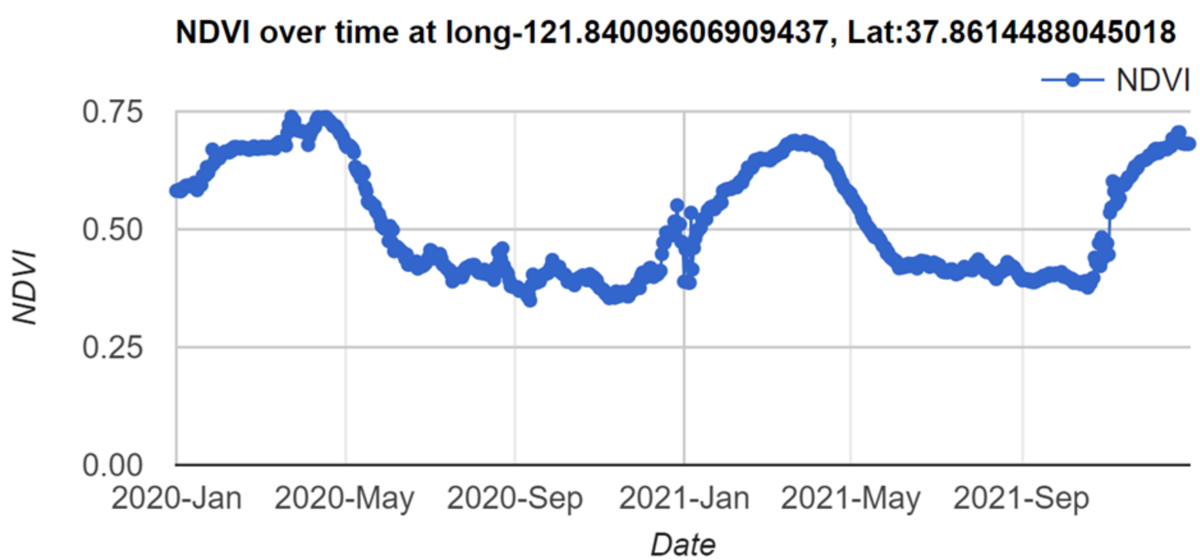


For our data gathering tools, we first needed source data that would allow us to extract NDVI data from anywhere in California within a reasonable temporal range. For this, we used open-access multispectral and thermal imagery data provided by the MODIS satellite data collection platform, which allowed for the easy extraction of NDVI values. The collected NDVI data could then be visualized and downloaded in various formats. The MODIS dataset was particularly well suited for our purposes, given its comprehensive coverage of California across most of the required time frames, high resolution, and seamless integration capabilities with our Google Earth Engine system.

3.3 Open-Source Data Collection Platform

For this study, we developed a tool for data collection to cater to this project's specific needs, as well as broader initiatives necessitating similar remote sensing data. The creation of this collection tool began with an introduction to Google Earth Engine, a platform on which you can create a wide variety of research applications. As a prominent host for online remote sensing data, Google Earth Engine offers coding and programming capabilities, facilitating the visualization, acquisition, and analysis of data in real time. The writing of the Google Earth Engine applications began with the importing of the relevant MODIS dataset (i.e., multispectral imagery for NDVI). From there, the general parameters and extents needed to be set to define the spatial reference. Next, the relevant imported dataset needed to be accessed by the application, which would then filter the data to only use imagery from the specified time span (chosen via a text box input) and location (selected by clicking the location on the provided map). The data was then filtered again to only use the relevant spectral bands, before being processed and averaged. This processed data was then translated into a color-scale raster image that was overlaid onto the displayed map. In addition to the colored overlay, the processed data would also be turned into a data chart (see Figure 4), which could be exported and downloaded as a .csv file.

Figure 4. Example NDVI Data Chart



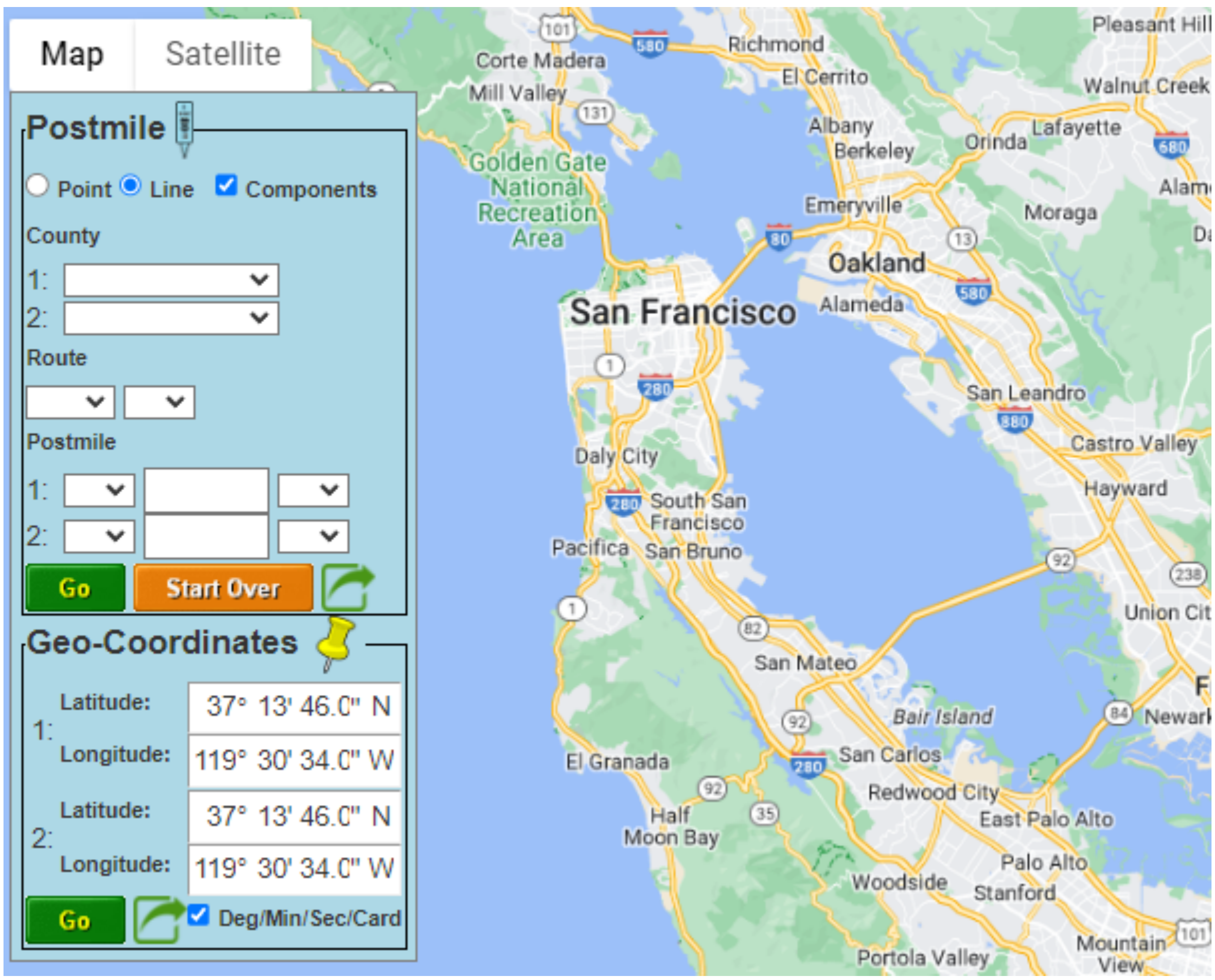
This .csv file was the product we were ultimately after, as it could be later processed and analyzed to help determine correlation between highway expansion projects and changes in NDVI.

3.4 Data Collection

Necessary Tools and Applications

For data acquisition, the process begins with opening all the necessary tools needed to collect the chosen data type. In addition to the NDVI, this includes: the list of 18 highway expansion project sites, Microsoft Excel to compile the collected data, and an online postmile tool from Caltrans for finding roadway sections based on an abbreviated code (DIST-CO-RTE-PM) (see Figure 5), which we had access to for each site via the aforementioned project site list.

Figure 5. Caltrans Post-Mile Locator Tool



Site Selection and Application Setup

After opening all the requisite tools, data can be collected for each site. Once a project site is chosen, the abbreviated code, which provides the district, county, route number, and post-mile numbers for each project site, is input into the aforementioned online postmile tool and located. The next step is to then find the project site on the Google Earth Engine application, as well as determine the starting date. For the starting date, we want to set a date (formatted as *YYYY-MM-DD*) that is exactly one year before the listed COD for the selected project site. Since the NDVI applications collect 2 years' worth of data, this provides data for one year before and one year after the COD. For example, a highway expansion project site with a COD of 2016-07-15 should have a starting date of 2015-07-15. This will provide LST/NDVI data from 2015-07-15 to 2017-07-14.

Data Collection Process

Once the Google Earth Engine application is set up with the correct starting date and site location, the data can be properly collected. Using a consistent ruler or measuring tool and the scale provided by the application, we began producing the relevant data by clicking along one side of the highway expansion project at a buffer distance of one kilometer, taking note of which end and side of the project site we started with (for example, starting at the southern end, on the western side). This will help with consistency later, in case data needs to be recollected. With each click, a chart is produced, from which a .csv file can be extracted and saved. The .csv file includes a list of dates for which the data was collected, as well as the NDVI values right next to it. We inserted two additional columns between the dates and data sections, one for the COD variable (this will be set to either "0" if the date is before the COD, or "1" if the date is on or after the COD), and another for the solar radiation balancing factor, which will be used to help account for changes in seasonality. Additionally, noting the starting date and location in the data table for the given project site is important to ensure consistency. This first .csv file will serve as the master data table for the associated site and buffer. After formatting the first .csv file, the next step is filling out the rest of the master data table. This is done by clicking each produced data chart, extracting the .csv file, and copying the NDVI data column to be placed into the master data table, right next to the previous data column. Due to limitations within the Google Earth Engine application, only five data charts can be easily extracted and used at one time, so the application needs to be refreshed every five data charts. After every refresh, the starting date needs to be re-entered, and the highway expansion project site needs to be located again. This process of clicking, extracting the data columns from the .csv files, pasting the data columns into the master data table, and refreshing the application was repeated until we collected data along the entire project site, on both sides, at a one-kilometer buffer. Figure 6 offers an example of a master data table.

Figure 6. Master Data Table Example

system:time	COD Var.	NDVI												
14-Jan-15	0	0.408	0.326	0.342	0.322	0.28		0.192	0.168	0.269	0.089	0.443		Start Date: 2015-01-14
15-Jan-15	0	0.408	0.328	0.353	0.32	0.286		0.198	0.156	0.278	0.088	0.437		First 5: East
16-Jan-15	0	0.408	0.326	0.349	0.32	0.286		0.189	0.139	0.303	0.096	0.443		Last 5: West
17-Jan-15	0	0.414	0.325	0.355	0.316	0.292		0.195	0.092	0.321	0.118	0.465		South to North
18-Jan-15	0	0.412	0.332	0.34	0.321	0.289		0.19	0.081	0.317	0.117	0.431		
19-Jan-15	0	0.413	0.331	0.345	0.321	0.293		0.188	0.086	0.307	0.118	0.437		
20-Jan-15	0	0.415	0.333	0.345	0.321	0.291		0.187	0.061	0.306	0.116	0.445		
21-Jan-15	0	0.419	0.334	0.345	0.31	0.283		0.188	0.059	0.306	0.117	0.448		
22-Jan-15	0	0.414	0.331	0.34	0.31	0.294		0.197	0.053	0.288	0.136	0.447		
23-Jan-15	0	0.413	0.33	0.339	0.315	0.299		0.2	0.052	0.289	0.131	0.451		
24-Jan-15	0	0.407	0.326	0.327	0.323	0.289		0.2	0.057	0.276	0.127	0.442		
25-Jan-15	0	0.408	0.326	0.326	0.323	0.288		0.2	0.057	0.275	0.131	0.426		
26-Jan-15	0	0.408	0.326	0.326	0.325	0.288		0.199	0.067	0.272	0.131	0.426		
27-Jan-15	0	0.393	0.321	0.327	0.331	0.284		0.2	0.076	0.269	0.132	0.426		
28-Jan-15	0	0.392	0.32	0.326	0.331	0.283		0.199	0.076	0.268	0.132	0.427		
29-Jan-15	0	0.389	0.319	0.32	0.333	0.286		0.205	0.08	0.258	0.142	0.425		
30-Jan-15	0	0.388	0.318	0.319	0.333	0.284		0.205	0.082	0.257	0.142	0.423		
31-Jan-15	0	0.387	0.317	0.318	0.333	0.283		0.207	0.081	0.256	0.14	0.421		
1-Feb-15	0	0.386	0.318	0.32	0.338	0.294		0.207	0.081	0.267	0.137	0.418		
2-Feb-15	0	0.389	0.322	0.308	0.346	0.29		0.217	0.08	0.233	0.199	0.379		
3-Feb-15	0	0.394	0.318	0.321	0.35	0.299		0.221	0.092	0.247	0.158	0.412		

Master Data Table Example

Depending on the length of the highway expansion project in question, we collected anywhere from 5–30 data points per side, or 10–60 data points per buffer. For the NDVI data collection, we repeated this process for both the two-kilometer and three-kilometer buffers, resulting in three separate master data tables (one for each buffer), totaling between 30–180 data points per site. In addition, four NDVI control sites (sections of highway that experienced no recent expansion/renovations) were selected to compare with our highway expansion sites.

3.5 Data Analysis

To examine the impacts of highway projects on land cover or vegetation change, we compared the average NDVI values for each highway expansion site from both before and after the stated COD. To do so, we first calculated the average NDVI values for both sides of the highway from before the COD, then repeated the process for both sides of the highway for after the COD. We then calculated the difference between these two averages and compared it to the average change in NDVI from our control sites. This comparison helped determine whether the changes in NDVI for the highway expansion sites were within natural parameters, or if the NDVI was being affected by the highway expansion project itself.

4. Results and Discussion

4.1 NDVI Results Table

After calculating the average differences among all the highway expansion project sites and control sites, we compiled all the results into a single table (see Table 2); these are later explored by sub-region. Included in this and subsequent tables is the site identification number (or approximate location in the case of our control sites), the respective buffers of each site, the county in which each site is located, the closeout date (COD) for each site, what kind of project the site entailed, and the average difference between the pre-COD NDVI values and post-COD NDVI values for each site/buffer.

Table 2. NDVI Results Table

Site ID	County	COD (mm/dd/yy)	Project Type	Average Initial NDVI Value	1 km Buffer Average Difference	2 km Buffer Average Difference	3 km Buffer Average Difference
CS-1 (Acton)*	Los Angeles	01/21/16	Control Site	0.27	-0.0144	-0.0154	-0.0202
CS-2 (Castro Valley)	Sutter	01/14/16	Control Site	0.52	0.0323	0.0307	0.0294
CS-3 (Fruitdale)	Santa Clara	01/16/15	Control Site	0.33	-0.0004	-0.0022	-0.0023
CS-4 (Wellington Heights)*	Los Angeles	12/31/12	Control Site	0.25	-0.0088	-0.0133	-0.0057
0300000206	Sutter	12/05/17	Adding Lanes	0.43	0.0297	0.0866	0.0888
0300020583	Placer	01/23/15	Adding Lanes	0.39	0.0191	0.0179	0.0069
0400020580*	Alameda	01/14/16	Bridge/Highway Widening	0.28	0.0272	0.0153	0.0225
0400020581	Alameda	03/12/20	Expressway Widening	0.42	-0.0342	-0.0366	-0.0425
0400021248	Alameda	09/30/16	Roadway Widening	0.37	0.0125	0.0109	0.0201
0400002022	Napa	08/08/18	Highway Widening/Ret. Walls	0.53	-0.0052	-0.0111	-0.0145
0400000799*	Santa Clara	01/16/15	Adding Lanes	0.26	0.0254	0.0295	0.0222
0400000140	Sonoma	08/19/19	Bridge/Highway Widening	0.52	-0.0327	-0.0344	-0.0369
0400020004	Sonoma	10/14/13	Bridge/Roadway Widening	0.53	-0.0725	-0.0735	-0.0836
0600000381	Fresno	10/19/20	New Highway	0.46	-0.0104	-0.0230	-0.0267
0700000339*	Los Angeles	08/16/18	Freeway Widening, Bridge Construction	0.23	0.0087	0.0228	0.0128
0700000390	Los Angeles	06/02/15	Bridge/Roadway Widening	0.42	-0.0288	-0.0184	-0.0155
0700000514 (Route 10)*	Los Angeles	12/31/12	High Occupancy Toll Lanes	0.26	-0.0122	-0.0077	-0.0151

Site ID	County	COD (mm/dd/yy)	Project Type	Average Initial NDVI Value	1 km Buffer Average Difference	2 km Buffer Average Difference	3 km Buffer Average Difference
0700000514 (Route 110)*	Los Angeles	12/31/12	High Occupancy Toll Lanes	0.20	-0.0058	-0.0046	-0.0129
0700001831*	Los Angeles	06/14/16	Freeway Widening	0.25	-0.0102	0.0025	0.0099
0700001833*	Los Angeles	02/20/20	Freeway Widening	0.24	-0.0125	-0.0038	-0.0119
0700020201	Los Angeles	01/21/16	Freeway Widening/HOV Lanes	0.30	-0.0114	-0.0139	-0.0180
1000000430	Merced	12/19/17	Freeway/Interchange construction, adding lanes	0.50	-0.0150	0.0025	-0.0014

Note: Sites marked with "" are deemed insignificant, as their pre-COD NDVI values indicate that there was very little to no vegetation to begin with.*

4.2 NDVI Results Maps – Overview

In addition to the data table in the following section, we also compiled the results into a series of maps using ArcGIS Pro, which were further formatted using Adobe Illustrator. Since the project and control sites are spread across most of California, we have broken up the full dataset into 5 smaller sub-regions to properly display the data for easy viewing. The sub-regions are as follows: Santa Clarita (Table 3; Figure 7), Bay Area (Table 4; Figure 8), Fresno (Table 5; Figure 9), LA County (Table 6; Figure 10), and Sutter and Placer Counties (Table 7; Figure 11). Each map also includes a basemap displaying the region's land usage, such as levels of urban development, farmland, and bare earth. For the purposes of the following maps, farmland is displayed as yellow, forested areas are displayed as green, shrub/grasslands are displayed as tan/beige, water is displayed as blue, and urban development is displayed as a color gradient ranging from light pink (light development) to dark red (heavy development). This symbology will be expanded upon within a legend that will be included with each regional map below.

4.3 Results and Discussion

Significant Findings

Context Effects on NDVI

One of our most significant findings was that, in terms of negative NDVI change, the most heavily impacted locations were those in less-developed areas with more extensive, wild vegetation. While some agricultural areas were also negatively affected (see regional sections below for more details), we found that, on average, areas with a heavy agricultural presence tended to have more consistent or increasing NDVI values. From this, we can deduce that agricultural vegetation (e.g., tended farmland) is not easily subject to drops in NDVI, at least in response to highway expansion in the short term. This is most clearly seen in our Sutter and Placer Counties map (Figure 11), where both project sites show increases in average NDVI values, including our highest average change of the dataset. However, wild vegetation (e.g., grass/shrublands) is more adversely affected. This is best seen in our Bay Area map (Figure 8), where a number of negatively affected sites can be observed, all of which are located within areas consisting of wild vegetation (as opposed to cropland). Furthermore, these project sites lie on the outskirts of major urban centers, indicating a less developed or lower density setting.

Multiple Construction Types

The type of highway expansion project also seemed to have significant impacts on the changes in NDVI. From the data analysis, we found that, in general, project sites that experienced multiple types of construction/renovation (e.g., adding more lanes, widening sections, bridge renovation, etc.) were more likely to exhibit decreasing NDVI values compared to project sites that only experienced one type of construction. This can most likely be attributed to the cumulative impacts of several projects, as opposed to a project with one singular purpose. This correlation is most evident in our Bay Area map (Figure 8), where our three most negatively impacted sites (0400000140, 0400020581, and 0400020004) experienced a combination of construction project types. By contrast, our most positively impacted sites (0300000206 and 0400000799) only experienced one type of construction.

Insignificant Sites

Lastly, we found that project sites within heavily urbanized areas, such as Los Angeles or San José, were more often than not insignificant in terms of NDVI. In this case, "insignificant" means that the NDVI values around the project site were too low for there to be much vegetation, if any, in the first place. Without a high enough base level NDVI, any changes that do occur between pre-and post-highway expansion cannot be accurately measured or rationalized. A good example of this is the Los Angeles map (Figure 10), where every site, including the control site, has very low NDVI values, meaning that there is already little to no vegetation available to be measured or impacted.

General Trends

Upon initial inspection of the resulting maps (included in the region-specific subsections below) and data table, it is evident that the impacts of highway expansion on changes in NDVI are diverse, indicating the importance of the environmental context around each individual project site. However, when viewing the data as a whole, some general patterns do start to emerge. For one, most of our insignificant sites (6/9), which had NDVI values that indicated little to no vegetation in the first place, are located in Los Angeles, an area that already exhibits extremely heavy urban development. This also makes sense looking at the data table, which shows these same six sites exhibiting relatively little change in their NDVI between their pre- and post-COD values. Two more of these insignificant sites were also located in heavily urbanized areas, namely downtown San José and the developed areas of Livermore. These displayed a similar story, where heavy urbanization has resulted in vegetation levels that were already very low, even before any highway expansion projects occurred. The final insignificant site, one of our control locations, is located near Santa Clarita, just north of Los Angeles. While there is no nearby heavy urban development, this site is located near large expanses of bare, non-vegetated earth, which does have a negative impact on the localized NDVI values. In short, all of our insignificant sites, whether they were control or test sites, are located in areas where vegetation is unable to readily grow and expand on its own (i.e., not agriculture/maintained). Between these nine insignificant sites, our method of measuring NDVI values can be validated as accurate and reliable for the purposes of our research since these locations have valid reasons to already have extremely low NDVI values. By contrast, sites that are located near less-developed areas with more extensive vegetation (e.g., exurbs) show more significant changes in their NDVI values.

Santa Clarita (LA County)

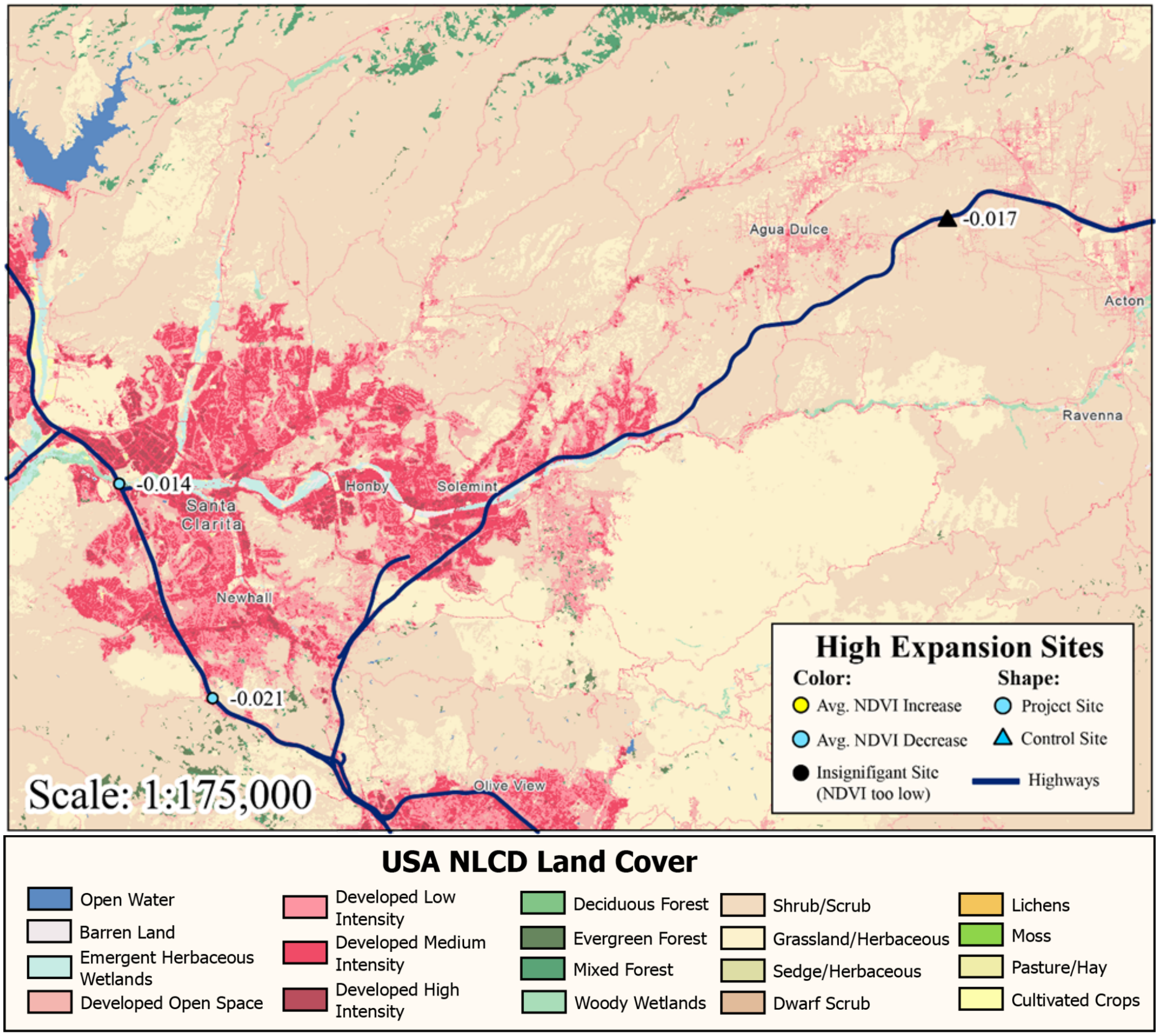
Slightly north of Los Angeles, our first sub-regional map (Figure 7) covers the Santa Clarita area. Santa Clarita is considered a satellite city: located at the edge of the largest metropolitan area in California and experiencing high levels of cross-commuting with LA. This area contains another one of our control sites, located along a stretch of highway just east of Santa Clarita. However, based on its initial NDVI values (around 0.26), this site was deemed insignificant. This can most likely be attributed to the area surrounding the control site, which consists mostly of bare earth with very little vegetation. The two test sites, however, experienced both significant highway expansion/construction and exhibited negative changes in NDVI (Table 3). In addition, their initial NDVI values were high enough to verify that there was ample vegetation to measure. This can most likely be attributed to the project sites being located just outside of major urban development centers, far enough away to be where vegetation can grow relatively freely. However, despite these significant drops in NDVI, the visual changes are extremely difficult to see with the naked eye, as evidenced by before and after satellite images of various project sites (see Appendices). These difficulties can be attributed to a number of variables, with the primary causes being satellite instrumentation causing inconsistent image quality/color saturation, as well as irregular image capture intervals not allowing accurate comparisons. Therefore, the collected NDVI data will be a more accurate measure of the plant health metric.

Table 3. Santa Clarita Results Table

Site ID	County	COD (mm/dd/yy)	Project Type	Average Initial NDVI Value	1 km Buffer Average Difference	2 km Buffer Average Difference	3 km Buffer Average Difference
CS-1 (Acton)*	Los Angeles	01/21/16	Control Site	0.27	-0.0144	-0.0154	-0.0202
0700000390	Los Angeles	06/02/15	Bridge/Roadway Widening	0.42	-0.0288	-0.0184	-0.0155
0700020201	Los Angeles	01/21/16	Freeway Widening/HOV Lanes	0.30	-0.0114	-0.0139	-0.0180

Note: *Sites marked with "*" are deemed insignificant, as their pre-COD NDVI values indicate that there was very little to no vegetation to begin with.*

Figure 7. Santa Clarita Map and Land Cover Legend



Bay Area

Our second sub-regional map, depicted in Figure 8, covers the Bay Area and some surrounding areas and is our largest study area. Because of this large extent, this map contains the most data points of all the maps, as well as the widest range of results, which is more than likely correlated to the significant variety of climates and environments present in the study area. Starting with the control sites, the Castro Valley control site shows a significant positive increase in NDVI (Table 4). This is most likely due to the site undergoing no significant construction, as well as being a forested area with high levels of vegetation. Our Fruitdale control site, on the other hand, is in a fairly urbanized area and shows very little change in average NDVI. Given that it was intended to be a site with no significant construction, this consistent NDVI is expected. Our two insignificant sites for this map, 0400020580 and 0400000799, both measured average NDVI levels consistently below our significance threshold of 0.3, which is an industry standard for significant baseline NDVI.[45,46] Site 0400000799 is located in the heavily populated and developed area of San José, so a low NDVI value is to be expected. Site 0400020580 is harder to explain, however, since the land use map shows that the site is located near large sections of grasslands, in addition to medium intensity urban development. Based on this, the most likely reason for this low NDVI is that the vegetation in the project area was already unhealthy prior to the completion of the highway expansion project. This would also make sense with the average increase in NDVI, since the unhealthy vegetation may have improved over time. Sites 0400020581, 0400000140, and 0400020004 (located south of Livermore, south of Santa Rosa, and northwest of Petaluma respectively) all show significant decreases in average NDVI. Site 0400002022 also measures a decreasing average NDVI value, but at a significantly smaller magnitude than the previous three sites. Our final site on this map, Site 0400021248, is the only significant test site in the region that measured an increase in average NDVI values post-COD. This increase, however, is relatively small in magnitude, especially compared to other sites with increasing average NDVI.

[45] Eugenia V. Varlamova and Vladimir S. Solovyev, "Investigation of Eastern Siberia Vegetation Index Variations on Long-Term Satellite Data," 24th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics (2018).

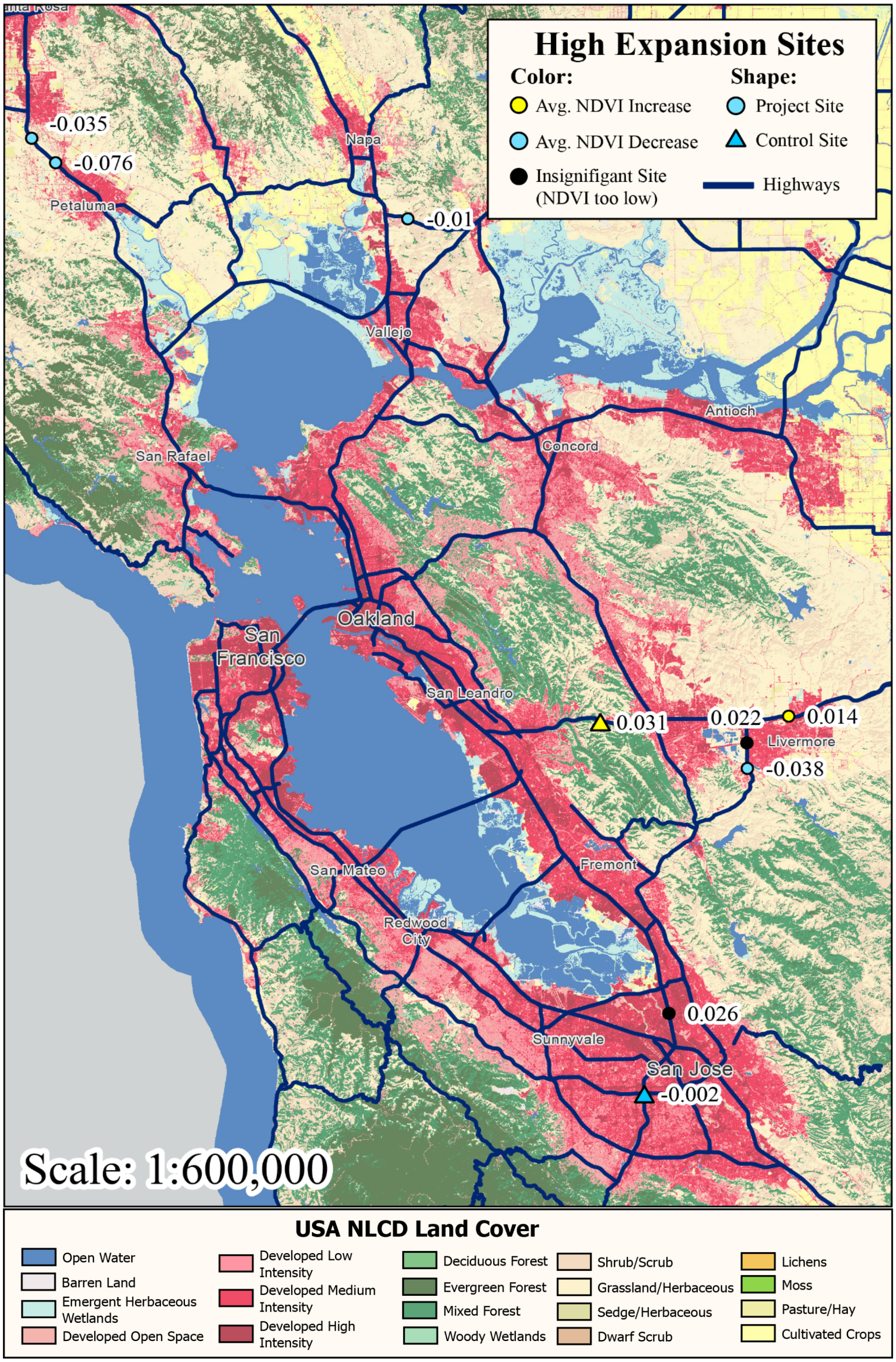
[46] A.K. Bhandari, A. Kumar, and G.K. Singh, "Feature Extraction using Normalized Difference Vegetation Index (NDVI): A Case Study of Jabalpur City," *Procedia Technology* (2012).

Table 4. Bay Area Results Table

Site ID	County	COD (mm/dd/yy)	Project Type	Average Initial NDVI Value	1 km Buffer Average Difference	2 km Buffer Average Difference	3 km Buffer Average Difference
CS-2 (Castro Valley)	Sutter	01/14/16	Control Site	0.52	0.0323	0.0307	0.0294
CS-3 (Fruitdale)	Santa Clara	01/16/15	Control Site	0.33	-0.0004	-0.0022	-0.0023
0400020580*	Alameda	01/14/16	Bridge/Highway Widening	0.28	0.0272	0.0153	0.0225
0400020581	Alameda	03/12/20	Expressway Widening	0.42	-0.0342	-0.0366	-0.0425
0400021248	Alameda	09/30/16	Roadway Widening	0.37	0.0125	0.0109	0.0201
0400002022	Napa	08/08/18	Highway Widening/Ret. Walls	0.53	-0.0052	-0.0111	-0.0145
0400000799*	Santa Clara	01/16/15	Adding Lanes	0.26	0.0254	0.0295	0.0222
0400000140	Sonoma	08/19/19	Bridge/Highway Widening	0.52	-0.0327	-0.0344	-0.0369
0400020004	Sonoma	10/14/13	Bridge/Roadway Widening	0.53	-0.0725	-0.0735	-0.0836

Note: *Sites marked with "*" are deemed insignificant, as their pre-COD NDVI values indicate that there was very little to no vegetation to begin with.*

Figure 8. Bay Area Map



Fresno

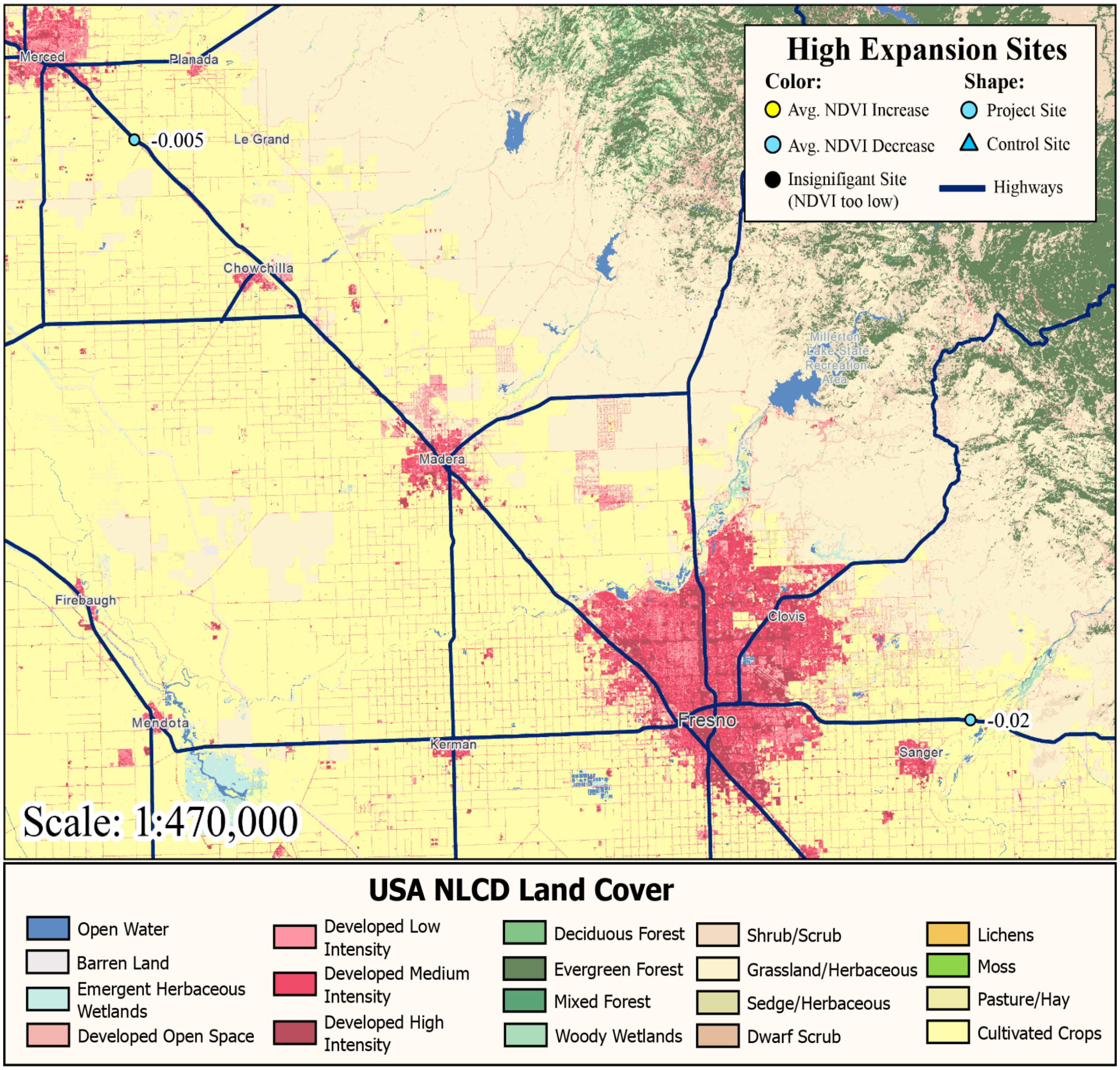
Figure 9 shows the Fresno area of central California, which includes the largest city in the greater Central Valley region (Fresno) and contains a mix of dense urbanization, cultivated farmland, and wild vegetation. This map contains two test sites, both of which exhibit the NDVI decreasing on average when comparing pre- and post-COD values (Table 5). Site 0600000381 in particular shows rather significant changes in NDVI, especially as you move out to the 2 km and 3 km buffers. Site 1000000430, however, is less clear cut. While the average NDVI change is negative, it is exceedingly small, calculated to be approximately -0.005. This can be attributed to the fact that the measured NDVI values range between positive and negative, depending on the buffer. Looking at Table 5 below, while the 1 km and 3 km buffers depicted a drop in NDVI, the 2 km buffer measured as having an increase in NDVI. When averaged out, this came out to be nearly zero, only slightly leaning towards negative.

Table 5. Fresno Results Table

Site ID	County	COD (mm/dd/yy)	Project Type	Average Initial NDVI Value	1 km Buffer Average Difference	2 km Buffer Average Difference	3 km Buffer Average Difference
0600000381	Fresno	10/19/20	New Highway	0.46	-0.0104	-0.0230	-0.0267
1000000430	Merce d	12/19/17	Freeway/Interchange construction, adding lanes	0.50	-0.0150	0.0025	-0.0014

Note: *Sites marked with "*" are deemed insignificant, as their pre-COD NDVI values indicate that there was very little to no vegetation to begin with.*

Figure 9. Fresno Map



LA County (Los Angeles and Surrounding Communities)

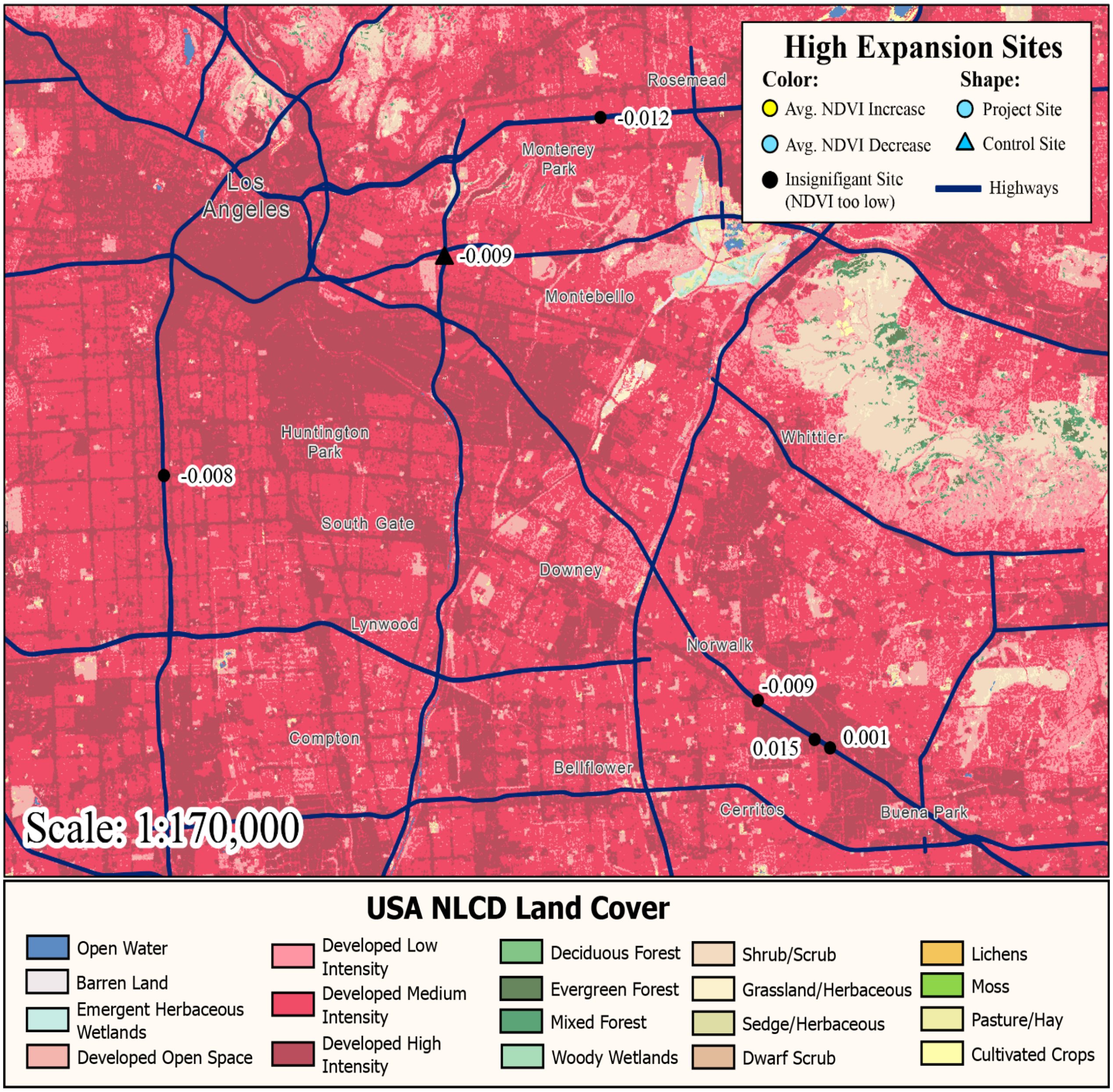
Our most southward sub-regional map highlights the city of Los Angeles and the immediate surrounding area. The most apparent geographic aspect of this map is the overwhelming amount of heavy urban development, with only small swathes of land showing non-anthropogenic elements. Of the six sites included in this map (five project sites and one control site), all measured NDVI values were low enough to be deemed insignificant, since there was already very little/no vegetation to measure. This insignificance is backed up by the small average differences between the pre- and post-COD NDVI values (i.e., often a difference around +/- 0.01) (Table 6; Figure 10). For reference, NDVI is measured on a scale of -1.0 to 1.0, with the difference between unhealthy and healthy vegetation being as much as 0.6. On this scale, a change of 0.01 or less is debatably negligible. While this map does not provide much in the way of significant data for our final results, it does help validate our NDVI data collection methodology, since it shows that our data collection application is measuring reasonable NDVI values for a heavily developed urban area.

Table 6. Downtown Los Angeles Results Table

Site ID	County	COD (mm/dd/yy)	Project Type	Average Initial NDVI Value	1 km Buffer Average Difference	2 km Buffer Average Difference	3 km Buffer Average Difference
CS-4 (Wellington Heights)*	Los Angeles	12/31/12	Control Site	0.25	-0.0088	-0.0133	-0.0057
0700000339*	Los Angeles	08/16/18	Freeway Widening, Bridge Construction	0.23	0.0087	0.0228	0.0128
0700000514 (Route 10)*	Los Angeles	12/31/12	High Occupancy Toll Lanes	0.26	-0.0122	-0.0077	-0.0151
0700000514 (Route 110)*	Los Angeles	12/31/12	High Occupancy Toll Lanes	0.20	-0.0058	-0.0046	-0.0129
0700001831*	Los Angeles	06/14/16	Freeway Widening	0.25	-0.0102	0.0025	0.0099
0700001833*	Los Angeles	02/20/20	Freeway Widening	0.24	-0.0125	-0.0038	-0.0119

Note: *Sites marked with "*" are deemed insignificant, as their pre-COD NDVI values indicate that there was very little to no vegetation to begin with.*

Figure 10. Los Angeles Map



Sutter and Placer Counties

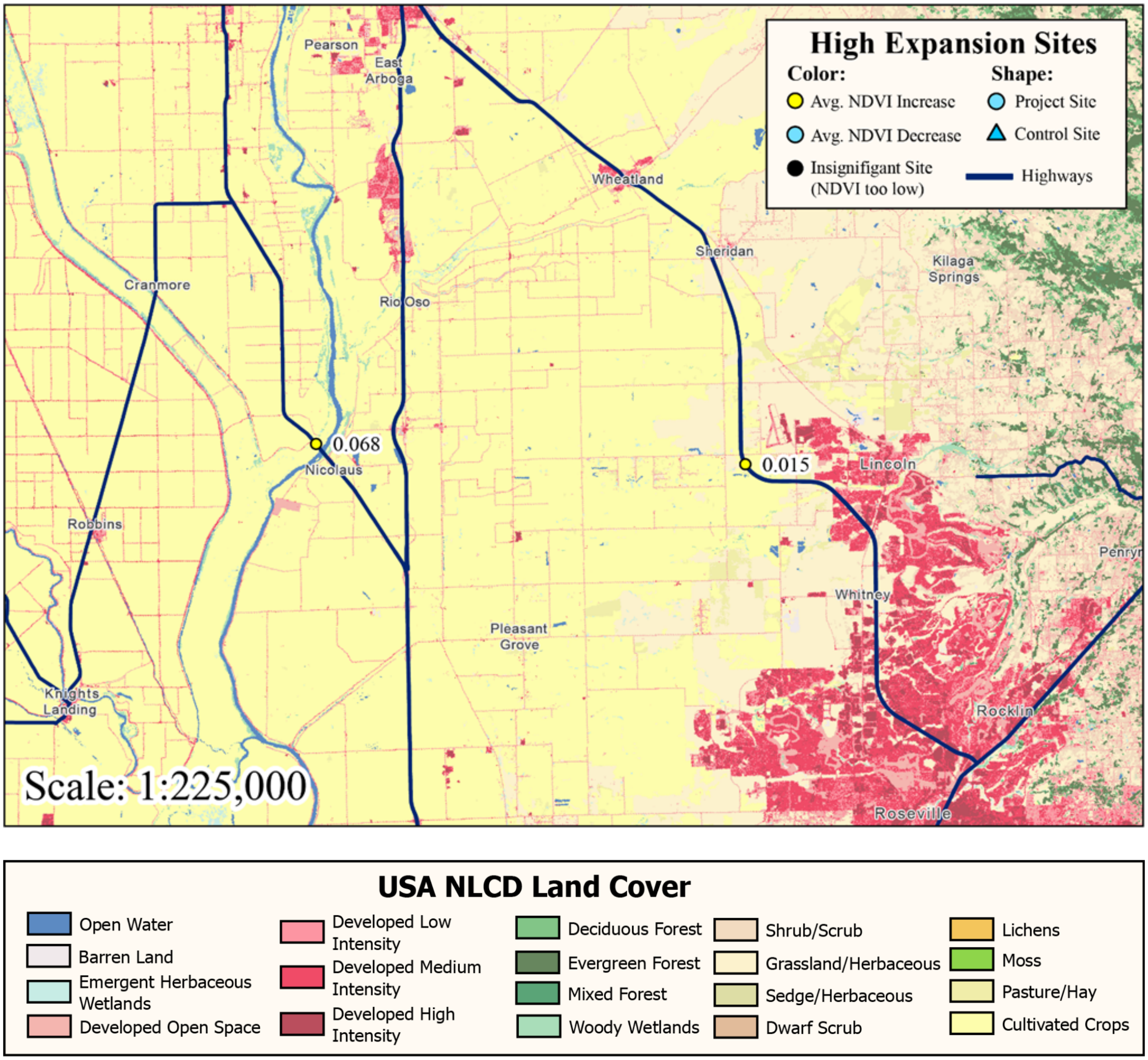
Our northernmost sites, which extend into both Sutter and Placer County and are used extensively for both farming and grazing, contain two of our test sites and are located to the north-west of Roseville, near the city of Sacramento. These two project sites both experienced the same type of construction (i.e., adding more lanes), are surrounded by cultivated crops, and show increases in average NDVI values, including the highest average increase within our data set (+0.068) (Table 7; Figure 11). For ease of referencing, we've included the data table and regional map for these project sites below (this will also be done for each of the following region-specific sections). Based on the land use data provided by the basemap (mostly cultivated crops/farmland), it's possible that this increase can be attributed to a particularly bountiful growing season, as opposed to naturally occurring vegetation growing healthier/larger post-highway expansion.

Table 7. Sutter and Placer Counties Results Table

Site ID	County	COD (mm/dd/yy)	Project Type	Average Initial NDVI Value	1 km Buffer Average Difference	2 km Buffer Average Difference	3 km Buffer Average Difference
0300000206	Sutter	12/05/17	Adding Lanes	0.43	0.0297	0.0866	0.0888
0300020583	Placer	01/23/15	Adding Lanes	0.39	0.0191	0.0179	0.0069

Note: *Sites marked with "*" are deemed insignificant, as their pre-COD NDVI values indicate that there was very little to no vegetation to begin with.*

Figure 11. Sutter and Placer Counties Map



5. Summary & Conclusions

This section is organized into two main parts. First, this chapter summarizes some of the most significant findings discussed in the literature review and the analysis of the impact of highway expansion projects on NDVI values. The second section uses those key findings to create a list of actionable recommendations for policymakers to better inform the current environmental review process, specifically regarding highway expansion projects. The chapter concludes with a discussion of the limitations of this study.

5.1 Summary of Key Findings

1) **Vegetation indices such as NDVI can provide a wide array of information about the natural environment and can be used to model and predict climate behaviors.**

   Vegetation health can provide key insights into the health of the surrounding environment. Specifically, vegetation indices such as NDVI are incredibly versatile in environmental analysis and can provide insights into the health of wildlife species, overall environmental health, and climate resilience factors, such as the risk of flooding and wildfires. Despite the widespread use of NDVI in academic geospatial research, there is little application of NDVI in current environmental review practices. Monitoring satellite remote sensing data on vegetation health, such as NDVI values, can provide crucial insight into some of the long-term impacts of highway expansion projects and ensure that proper mitigation measures can be implemented.

2) **Results of CEQA review practices can vary depending on who the lead agency is and what environmental planning infrastructure exists to mitigate the impacts on non-VMT externalities. Use of new sources of data and innovative tools can help conduct CEQA reviews more consistently across the state.**

   While the CEQA process has greatly transformed and developed since its inception in 1970, major review and monitoring practices have remained relatively unchanged. Current CEQA practices heavily rely on the existence of local planning documents to account for regional environmental impacts leading to the possibility of inconsistent scopes of review for similar projects. Progressions in technology and software provide an opportunity to increase the consistency and expedite environmental review, but the application of metrics such as NDVI requires further research to determine the suitability and scalability of those systems.

3) **Patterns of the impacts of highway projects on changes in NDVI are diverse, indicating the importance of environmental context as well as project types and combinations.**

One of the most important findings of this project is that highway expansion projects do not impact the environment in the same way. Context, such as urban vs. rural, sprawled vs. compact, natural landscapes vs. agricultural lands, and bountiful vegetation coverage vs. bare lands, can influence the magnitude of highway impacts on vegetation. Additionally, not all highway capacity improvement projects are the same. Our analysis suggests that a combination of projects have a more pronounced impact on vegetation as opposed to a single lane expansion project. Further research is required to determine the nuances of highway impacts on vegetation in various contexts.

4) **Sites that are located near less-developed areas with more extensive vegetation (e.g., sprawled areas or exurbs) show significant changes in NDVI values.**

The sites located in sprawled areas tended to have a more significant change in their NDVI values after the completion of the highway expansion project. One explanation for this is that sprawled areas and exurbs are more likely to be near undeveloped areas covered with natural

vegetation. This could also suggest that the environments of areas with less existing development will experience a greater impact due to highway expansion projects and may require a more focused scope of environmental review to mitigate these impacts. This finding also supports the popular planning notion that development in denser urban areas is better for the environment.

5) **Virtually all the insignificant sites are located in areas that already exhibit heavy urban development (e.g., Los Angeles, San José) or are otherwise located near large expanses of bare, non-vegetated earth.**

The sites that were identified in urbanized areas (e.g., Los Angeles, San José) tended to result in insignificant or inconclusive results. This signals that the use of NDVI to analyze the impacts of highway expansion projects is most impactful in areas with an abundance of naturally occurring vegetation to properly capture the impact. The finding also suggests that highway expansion projects in or near dense urban areas are less harmful for vegetation when compared with similar projects in sprawled or undeveloped areas.

6) **NDVI values near cropland/farmland were not necessarily impacted by highway expansion because these areas are not covered by naturally growing vegetation**.

Project sites identified near agricultural land uses (i.e., Placer and Sutter Counties) tended to show the lowest impact on NDVI values primarily because naturally occurring vegetation did not cover these areas. This is not unexpected because farmland is artificially maintained, and thus it is not as vulnerable as natural vegetation. Nonetheless, this finding might seem contradictory to some other studies, which have suggested that the addition of highway infrastructure contributed to significant reductions in forested areas and farmland due to urbanization occurring after the highway project was completed. Yet, due to the limited time boundaries considered in this study, it is likely that our models did not capture the long-term impacts of highway expansion projects on induced growth and, by extension, loss of agricultural lands.

7) **Project sites that experienced multiple types of construction/renovation (e.g., adding more lanes, widening sections, bridge renovation, etc.) were more likely to exhibit decreasing NDVI values compared to project sites that only experienced one type of construction**.

   The finding that different construction types had different impacts on NDVI is relevant to studies conducted by Caltrans, which note that different highway expansion projects can have different impacts on existing conditions. The Caltrans report primarily focuses on how to evaluate transportation impacts and mitigate VMT increases that may result from a highway project. The report also refers to how different types of highway expansion projects (e.g., lane widening, lane additions, addition of toll roads, etc.) have different impacts on VMT.[47] This study suggests that aside from project types, the number and combination of projects are important in determining the significance of environmental impacts. Thus, the findings of this research align with the report released by Caltrans.

5.2 Recommendations for Policymakers

1) **Decisions about highway construction and capacity expansion should consider the full environmental impacts, including land use and land cover changes over time**: While current environmental review practices do account for changes in land use, they only account for land use changes that are directly attributed to the project and do not necessarily cover land use and land cover changes that can be anticipated over time. Accounting for the land use and land cover changes that occur over time due to the project can allow us to better understand and alleviate the long-term environmental consequences of highway construction and capacity expansion projects. Consideration of full environmental impacts are also essential for conducting accurate cost-benefit analyses for infrastructure investment decisions. Simple cost-benefit analysis tools often underestimate the environmental costs, but sophisticated tools can paint a more accurate picture of the environmental impacts of infrastructure projects.

2) **New guidelines should further emphasize the importance of context in environmental review processes and infrastructure decision making**: Our findings suggest that highway expansion significantly impacts vegetation health in sprawling areas, while impacts in or

[47] California Department of Transportation (Caltrans), *Transportation Analysis Framework First Edition* Evaluating Transportation Impacts of State Highway System Projects* (California Department of Transportation, 2020), accessed July 29, 2023, https://dot.ca.gov/-/media/dot-media/programs/sustainability/documents/2020-09-10-1st-edition-taf-fnl-a11y-new-.pdf.

near denser urban areas are less pronounced. Further research can determine the extent and the ways in which context influences highway expansion's impacts on the environment. This can inform the development of new guidelines for infrastructure decision making and environmental review processes that fully consider the environmental context.

3) **Using remote sensing technology and new sources of big data can inform the environmental review processes and decision making about infrastructure projects**: Given recent advancements in technologies, such as Geographic Information Systems (GIS) and Remote Image Sensing (RIS), and the introduction of open-source data-sharing platforms, the environmental review processes can be improved. Using NDVI as a resource to identify areas that are more susceptible to impacts can provide decision-makers with additional information that can be used to guide resource investment to prioritize areas that are not as susceptible to the negative environmental impacts of highway expansion. Using remote sensing technology and new sources of big data, such as NDVI, can also help evaluate the environmental impacts of infrastructure projects after construction, which can guide future decision making.

5.3 Study Limitations and Directions for Future Research

For this research project, we developed a set of tools for data collection that operate on the Google Earth Engine platform, tailored to both this project's specific needs and broader initiatives requiring similar remote sensing data. Our applications, equipped with a user-friendly interface, enable the simple extraction of Normalized Difference Vegetation Index (NDVI) values from MODIS satellite products, which can then be displayed on the platform and downloaded in either TIFF or CSV formats, catering to a variety of potential data utilization needs. These cover any location in California within a customizable temporal range. The tool capitalizes on open-access multispectral and thermal imagery data from the MODIS satellite data collection platform. The Google Earth Engine platform also allows potential for further automation of the process, which would make the applications invaluable when dealing with larger datasets or study areas.

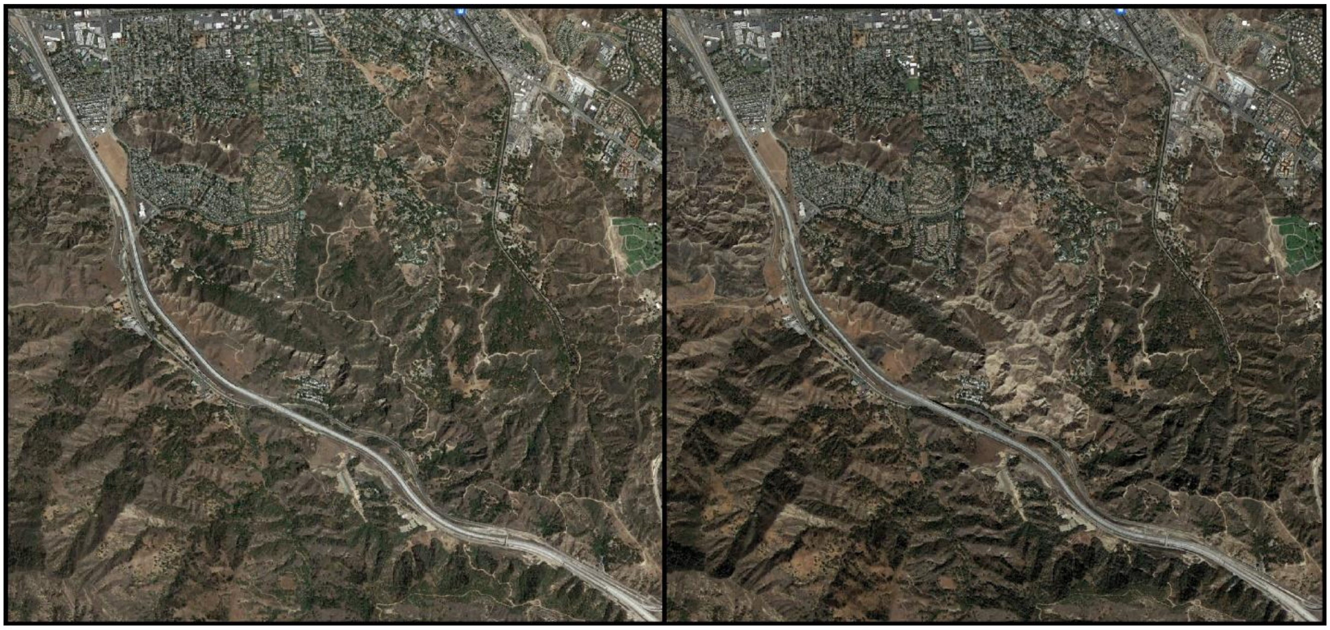
However, despite its strengths, our research acknowledges the inherent limitations associated with remote sensing data. Generally, a comprehensive measurement requires the application of multi-source data fusion or assimilation algorithms. This need arises from the fact that no single satellite can provide high-resolution Earth-surface data at both high spatial and temporal scales simultaneously. Specifically, the MODIS data utilized in this study has a daily temporal resolution and a 500 m spatial resolution, while other data sources such as Landsat and Sentinel offer a higher spatial resolution of 30 m but a lower temporal resolution ranging from 10–16 days. Moreover, remote sensing data primarily provides surface skin patterns and often necessitates ground and in-situ measurements for validation and calibration. Therefore, to enrich the understanding and accuracy of our findings, supplementary data collection methods should be integrated to complement the remote sensing data.

Google Earth Engine, our chosen platform for hosting remote sensing data, offers extensive coding and programming capabilities, thereby enabling real-time visualization, acquisition, and analysis of data. Our study boasts a robust and comprehensive statistical analysis, sampling from more than 40 sites. However, the selected sites might not wholly encapsulate the vast geographical and climatic variability within California, meaning a larger/more diverse sample size might prove more accurate.

The chosen data was particularly apt for our needs due to its extensive coverage of California, its high resolution, and its seamless integration capabilities within our Google Earth Engine system. Nevertheless, the potential for even more refined studies exists. Future research directions could involve integrating more local or ground measurements into the current data collection efforts. These could include ultra-high spatial resolution drone mapping data with sub-meter accuracy and in-situ measurements using ground instruments. Such information could provide crucial training and validating points to corroborate broader remote sensed data.

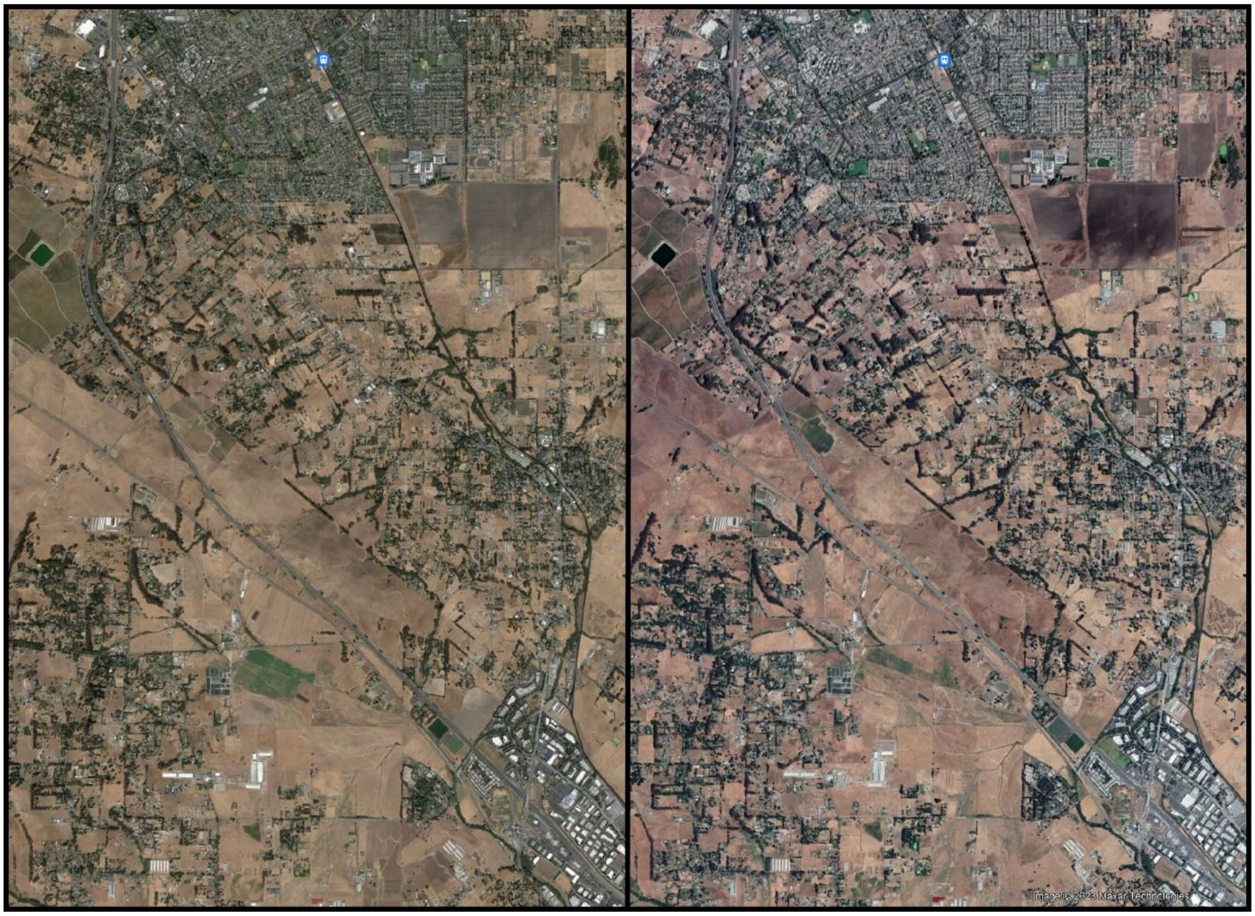
Additionally, this study could expand to use thermal remote sensing data to evaluate the impact of highway expansion on urban heat island effects, a topic that has been extensively investigated in previous literature. We have implemented online data acquisition tools and are actively exploring these additional directions. This multi-faceted approach could ultimately provide a more detailed, nuanced, and validated understanding of the patterns and impacts we aim to study.

Appendix A: Before and After Images of Select Highway Project Sites



Site LA-0700000390
8/29/2014 (left) compared to 10/29/2016 (right)

Site NAP-0400002022
5/29/2017 (top) compared to 5/30/2019 (bottom)



Site SON-0400000140
9/29/2018 (left) compared to 10/29/2020 (right)

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