Pepperwood PRESERVE

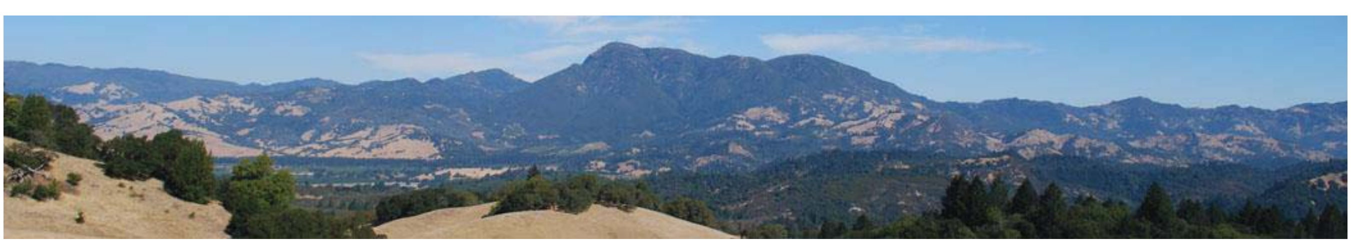
Methodology for Building Habitat Connectivity for Climate Adaptation: Mayacamas to Berryessa Connectivity Network (M2B)

A California Landscape Conservation Cooperative Place-Based Adaptation Project

May 2018

Morgan Gray and Lisa Micheli (Pepperwood)

Adina Merenlender (UC Berkeley)



A Dwight Center for Conservation Science **Technical Report**

PROJECT SUMMARY

Methodology for Building Habitat Connectivity for Climate Adaptation: Mayacamas to Berryessa Connectivity Network (M2B)

Project goals: The goal of this project is to tap into recent advances in habitat mapping, threat assessment, and climate change projections to co-produce a scientifically sound, multi-county habitat connectivity roadmap for the region spanning from the Mayacamas Mountains to the new Berryessa Snow Mountain National Monument in concert with local land managers.

Primary objective: Use advances in habitat mapping, threat assessment, and climate change projections to co-produce a multi-county habitat connectivity roadmap for the region spanning from the Mayacamas Mountains to the new Berryessa Snow Mountain National Monument in concert with local land managers.

1. To evaluate structural (terrestrial) connectivity between existing protected areas using linkage analyses based on indices of human influence.
2. To evaluate riparian connectivity between existing protected areas using linkage analyses based on indices of topography and ruggedness.
3. To quantify the climate benefit of the resulting terrestrial connectivity network using shrinking. Climate space and climate benefit as metrics.
4. To develop outreach materials and linkage-specific reports that provide support in advancing funding and implementation of corridors that enhance connectivity and climate resilience.

Why this is important: Keeping landscapes connected is the most frequently recommended approach to maintain habitat resilience in the face of climate change. However, many local agencies and their partners lack sufficient data to advance on-the-ground projects that account for the connectivity value and climate benefit of the landscape. Here we integrate state of the art spatial modeling, informed by critical input from local-conservation practitioners, to generate a set of regional connectivity planning tools based on ecological function and climate vulnerabilities for advancing habitat corridor initiatives across county borders. This collaboration provides much needed coordination to maximize efforts and funding across the many people and organizations dedicated to protecting the region's plant and animal life.

Project overview: This project builds on a nascent Landscape Connectivity Network facilitated by Pepperwood and is comprised of participants from land trusts, parks and open space districts, and state and federal land managers. We evaluated connectivity for the Mayacamas to Berryessa (M2B) region by conducting a permeability assessment and generating spatial layers and maps of existing continuous wild land areas and riparian zones. These permeability maps were used to generate linkages between core habitats for structural and riparian connectivity. Using a combination of the resulting linkages and climate benefit analyses, the project team and stakeholders identified critical habitats and priority locations where continuous habitat zones narrow to a degree where long-term connectivity is threatened.

Project impact: This project advances existing approaches to climate connectivity modeling by including novel methodological components to climate benefit and landscape heterogeneity into connectivity prioritization. Our results illustrate how three metrics of connectivity can be used – in combination or independently – to identify locations of conservation value that provide connectivity benefits today and under scenarios of landscape change. The structural and riparian linkage analyses quantify existing connectivity and can directly inform conservation management and planning by identifying specific linkages for planning and corridor implementation. The climate benefit analyses identified shrinking climate space and quantified the net cooling provided by linkages to the protected area network. When we compared the overlap between structural and riparian linkages, we found some overlap between the linkages in the southern portion of the study area that is more developed and has smaller existing protected areas. These locations, where both structural and riparian connectivity co-occur should be prioritized. Our climate results show clear differences between the trends for summer and winter variables, highlighting the importance of accounting for seasonality in Mediterranean climates with a coastal influence. Overall, cooler summer temperatures were found in the western portion of the study area closer to the coast, whereas the cooler winter temperatures were found inland to the east. The effect of seasonality was also apparent in our evaluation of future climate spaces and the linkages that offer the greatest climate benefit in degrees of net cooling differ between the two temperature variables. While mean annual temperature can be informative for some analyses, in locations with topographic and climatic diversity, evaluating mean annual temperatures for both summer and winter independently is needed to tease apart the influence of seasonal variation on the landscape.

Successful climate change adaptation requires building networks and growing a shared understanding how land use and climate change will influence future connectivity. By directly involving stakeholders in the modeling process and evaluation of results, we have taken steps to ensure that stakeholders can use the products to inform local and regional strategies. The combination of high-resolution landscape permeability and climate datasets provides local decision makers information and flexible tools for exploring and planning connectivity pathways. The spatial data is complemented by outreach materials and linkage-specific reports that provide support in advancing funding and implementation, primarily on the part of private land trusts and public open space districts – organizations that secure linkages between large protected lands owned by the State of California and Federal Government. The results will thus empower local agencies to work more effectively on-the-ground to enhance connectivity and climate resilience in the Mayacamas to Berryessa Coast Ranges.

Project support: Methodology for Building Habitat Connectivity for Climate Adaptation: Mayacamas to Berryessa Connectivity Network (M2B) is a product of a grant from the California Landscape Conservation Cooperative (Cooperative Agreement number F16AC00574).

Citation: Gray M., L. Micheli, A.M. Merenlender. 2018. *Methodology for building habitat connectivity for climate adaptation: Mayacamas to Berryessa Connectivity Network (M2B).* A technical report by the Dwight Center for Conservation Science at Pepperwood, Santa Rosa CA. 51 pp.

CONTENTS

LIST OF FIGURES

TERMINOLOGY

Basin Characterization Model (BCM) A model of the interactions of climate with landscape attributes (i.e., topography, soils, underlying geology) that provides historical and projected climate surfaces. For this report, we used model projections at 30-m resolution (Flint & Flint 2012; Pierce et al. 2015).

California Protected Areas Database Plus (CPAD+) A database of protected areas (>50 acres in size) comprised of lands owned in fee and protected for open space purposes from the California Protected Area Database (CPAD; calands.org) as well as additional properties managed by participating stakeholders. In this report, the protected area database (CPAD+) is a combination of CPAD listings that are greater than 50 acres in size and additional properties of interest managed by participating stakeholders.

CNRM-CM5 An Earth system global circulation model generated by the National Centre for Meteorological Research (CNRM) designed to run climate simulations that includes the effects of atmosphere, ocean, sea-ice, land, ocean-atmosphere fluxes, and river routing on climate that provides projections for present and future climate.

Habitat corridor Designated patches or strips of habitat that allow wildlife to safely move between larger blocks of habitat. Highly permeable corridors consist of continuous habitat or landscape linkages connecting core areas that permit all species and other resources (e.g., water) to move easily between these wildland blocks. In this report, a habitat corridor specifically refers to an implementable project area identified by the stakeholders.

Average Summer monthly maximum temperature (JJA Tmax; June, July, August) The average summer maximum temperature in the three warmest months of the year (June – August), which is a prime determinant of heat wave extremes, and an important contributor to potential evapotranspiration and aridity.

Average Winter monthly minimum temperature (DJF Tmin; December, January, February) The average minimum temperature over the three coldest months of the year (December – February), which is a prime determinant of frost and freeze frequency, and chilling hours for winter dormant plants.

Future climate In general, a future climate refers to climate conditions generated by a global circulation model. In this project, we use future climate to describe the projected temperature surface at 30-m resolution derived from the 30-year average of temperatures for 2040 – 2069 generated by the CNRM-CM5 model using representative concentration pathway 8.5.

Large patches A large, contiguous extent of natural habitat that is used as a node for linkage or connectivity analysis. In this report, we define large patches as areas greater than 5000 acres in size that are comprised of continuous, unprotected, and undeveloped (e.g., no agriculture or roads) wildlands.

Least cost path (LCP) A predicted movement path between two locations that accounts for the influence of the landscape, which is represented as a resistance (cost) surface based on environmental factors (e.g., landscape integrity, climate, topography, or vegetation type). Thus, a least cost path represents the route between a source and destination with the fewest obstacles and least resistance to movement. In this report, a least cost path is a linear element that is the symbolic representation of the highest linkage potential (described below) between nodes across the landscape.

Linkage potential The potential for connectivity between natural habitat patches (e.g., protected areas, nodes) used to identify locations that facilitate the movement of multiple species and maintain ecological processes. In this report, the linkage potential is used to evaluate the quality of the landscape between protected area nodes and is represented as linkage potential surfaces.

Nodes Patches of contiguous habitat (i.e., protected areas) that are used as start and end points for linkage or connectivity analysis. In this report, the nodes are protected areas within the CPAD+ database, described above.

Naturalness An index of ecological integrity that estimates the degree of human modification based on stressors such as land use, land cover, as well as the presence of, use of, and distance from roads. In this report, naturalness is defined using an index of human modification based on stressors such as land use, land cover, and presence, use, and distance from roads (Theobald 2013; Dickson et al. 2016; data provided by The Nature Conservancy).

Matrix The physical setting and context of the landscape within which corridors and habitat patches are situated. In this report, the matrix is a component of the landscape, altered from its original state by human land use, which may vary in cover from human-dominated to semi-natural. Corridors and habitat patches are embedded in the matrix.

Net cooling benefit A quantification of the availability of relatively cooler temperatures within a designated area. We calculated the net cooling benefit for each linkage by calculating the absolute difference between the minimum temperature values for each adjoining protected area.

Permeability The degree to which regional landscapes, encompassing a variety of natural, semi-natural and developed land cover types, are conducive to wildlife movement and sustain ecological processes. In this report we use two indices of landscape permeability: (1) Naturalness, as described above, and (2) a combined model derived using three indices of habitat fragmentation: median patch size effect (Reed 2007), mean parcel size effect, and road effect (Forman 2000).

Recent climate In this project we use future climate to describe the 30-year average of temperatures from 1981 – 2010 based on 800-m PRISM data spatially downscaled to 30-m using the gradient-inverse distance squared approach.

Resistance surface A data layer used in connectivity modeling to approximate the difficulty of movement between locations while considering the influence of the landscape (e.g., landscape integrity, temperature, topography, or vegetation type), where a high value is considered highly resistant to movement or resource flow.

Riparian connectivity A measure of connectivity based on enduring physiographic features of ruggedness, topography, and landforms presumed to be important for terrestrial, aquatic, and riparian resource flow that is used to inform linkage potential, least cost paths, corridors, and pathways. Locations with a high value facilitate terrestrial, aquatic, and riparian resource flow.

Structural connectivity A measure of terrestrial connectivity based on the physical arrangements of habitat patches, disturbance, or environmental elements presumed to be important for terrestrial wildlife movement that is used to inform linkage potential, least cost paths, corridors, and pathways. Locations with a high value facilitate terrestrial wildlife movement.

INTRODUCTION

Background

The Mayacamas to Blue Ridge-Berryessa mountain ranges are characterized by globally significant biodiversity, a multi-jurisdictional land management framework, and an engaged scientific community comprised of national leaders in conservation and climate science. The mountains of the North Coast Range provide spines of wilderness that radiate out from rapidly urbanizing regions of the San Francisco Bay Area. Included county, state, federal, and private protected lands have been identified as keystone areas critical to the long-term health of plant and wildlife populations of the region by the Conservation Lands Network (www.bayarealands.org).

In this study, we evaluate connectivity between the Mayacamas and Berryessa ranges to build a landscape connectivity network for corridor identification and implementation. The study area includes the new Berryessa Snow Mountain National Monument, a major conservation investment that spans multiple counties. Key focal resources include the diverse flora of the California Floristic Province and wildlife populations that still feature representation of top trophic level carnivores and mesocarnivores. This project fills a critical gap in a landscape-level conservation strategy and supporting research for the inland regions of the North Coast –between the Coastal Zone and Central Valley – an internationally recognized biodiversity hotspot. It is also one of the first projects of its scale to specifically address habitat connectivity for resilience to climate change in a manner that could be exported to other eco-regions. Through this project, we are increasing public awareness and streamlining outreach efforts, an especially important component in the project region where most land is privately held. This collaboration provides much needed coordination to maximize efforts and funding across the many people and organizations dedicated to protecting the region's plant and animal life.

In this region, the top stressors to conservation targets include habitat fragmentation, climate change, drought, and catastrophic fire. Anthropogenic climate change is driving shifts in species distributions on every continent (Chen et al. 2011; Lenoir & Svenning 2015; Pecl et al. 2017) and impelling a universal redistribution of species, with pervasive and substantial impacts on ecosystem functioning and human well-being. At the same time, the world is experiencing unprecedented increases in human population growth, with associated land conversion, natural habitat loss, and fragmentation (Tilman et al. 2017). As climate changes, species must tolerate the change, move, adapt, or face extinction (Berg et al. 2010). However, the distributional responses of some species lag behind climate change (Poloczanska et al. 2013), and lack of habitat connectivity or access to adequate transitional microhabitats can impede the shifts of others (Corlett & Westcott 2013). Species that cannot track shifting climate conditions through suitable habitat are at risk of detrimental genetic effects (Roelke et al. 1993; Epps et al. 2005), increased disease susceptibility (Charlesworth et al. 2009), and greater risk of extinction (Fahrig & Merriam 1994).

Future climate analogs – i.e., future climatic conditions analogous to those existing today (Ohlemüller et al. 2006; Carroll et al. 2015) – must therefore be within reach.

A species' ability to reach locations across space is measured by "habitat connectivity", which is the degree to which organisms can move through a landscape (Hilty et al. 2006). More recently, "climate connectivity" has emerged as a related metric to assess how well a species can track its current climatic conditions during projected climate change (Hilty et al. 2012; McGuire et al. 2016). Connectivity is one of the most frequently promoted strategies to help species adapt to climate change (Heller & Zavaleta 2009), often in the context of linkages that connect two or more fixed protected areas. However, many static networks have a limited ability to accommodate species range shifts due to the combined impacts of land use and climate change. Evaluations of connectivity between protected areas have failed to consider how reductions of suitable habitat – as a result of land conversion, habitat loss, or fragmentation – will interact with climate change. Proactive protected area network planning and management depend upon explicit inclusion of these ecosystem responses in decision-making and strategic frameworks. Insights about linkages that facilitate resilience to climate change need to be incorporated into conservation assessments to ensure adequate habitat connectivity, mitigate exposure to extreme microclimates, and provide more time and space for species to relocate.

Project Objectives and Approach

The goal of this project is to tap into recent advances in habitat mapping, threat assessment, and climate change projections to co-produce a scientifically sound, multi-county habitat connectivity roadmap for the region spanning from the Mayacamas Mountains to the new Berryessa Snow Mountain National Monument in concert with local land managers. The Inner Coast Range comprises an approximately 2-million-acre landscape recognized as a biodiversity hotspot threatened by both habitat fragmentation and climate change. This project builds on a nascent Landscape Connectivity Network facilitated by Pepperwood and is comprised of land trusts, parks and open space districts, with state and federal land managers. In partnership with University of California Berkeley, the network is generating place-based, decision-support knowledge designed to support the design and implementation of habitat connectivity projects on the ground across multiple jurisdictions.

We evaluate connectivity for the M2B region by conducting a permeability assessment and generating spatial layers and maps of existing continuous wild land areas and riparian zones. These permeability maps were used to generate linkages between core habitats for structural (terrestrial) and riparian connectivity. Using a combination of the resulting linkages and climate benefit analyses, the project team and stakeholders identified critical habitats and priority locations where continuous habitat zones narrow to a degree where long-term connectivity is threatened.

Outcomes and Benefits

A series of integrated spatial layers were co-created with local managers and made available on an open-access data visualization platform (databasin.org). Three main categories of datasets and models were generated, including:

- Structural connectivity: Linkage analyses using existing protected areas as nodes and connectivity based on vegetation and human influence.
- Riparian connectivity: Linkage analyses using existing protected areas as nodes and connectivity based on topography and ruggedness.
- Climate benefit of linkage network.

The spatial data is complemented by outreach materials and linkage-specific reports that provide support in advancing funding and implementation, primarily on the part of private land trusts and public open space districts – organizations that secure linkages between large protected lands owned by the State of California and Federal Government. The results will thus empower local agencies to work more effectively on-the-ground to enhance connectivity and climate resilience in the Mayacamas to Berryessa Coast Ranges.

Successful climate change adaptation requires building networks and growing a shared understanding how land use and climate change will influence future connectivity. By directly involving stakeholders in the modeling process and evaluation of results, we have taken steps to ensure that stakeholders can use the products to inform local and regional strategies. The combination of high-resolution landscape permeability and climate datasets provides local decision makers information and flexible tools for exploring and planning connectivity pathways.

METHODS

Study Area

Our project area (1,167,143 ha) included the inland region of the North Coast from 10 counties in Northern California: Colusa, Glenn, Lake, Marin, Mendocino, Napa, Solano, Sonoma, Tehama, and Yolo (centroid: 529504 m, 4315244 m; north: 4412694 m, south: 4214915 m, east: 584757 m, west: 459722 m; NAD 1983 UTM Zone 10N) (Figure 1). The project area was within the California Floristic Province, one of 25 global biodiversity hotspots that provides critical habitat for 584 vertebrates and 2,125 endemic plants (Myers et al. 2000). The four primary land cover types within the study area were (1) forest and woodland (46.4%), (2) shrub land and grassland (40.3%), (3) agricultural land (6.2%, maximum of 13.1% in Napa County), and (4) land that is developed or otherwise of human use (3.7%) (Department of Forestry and Fire Protection, Fire and Resource Assessment Program (FRAP), 2015). The project area was delineated using a combination of three landscape features: watersheds (HUC8), primary roads, elevation (>100 m).

Climate in the region is Mediterranean with historically mild, wet winters and hot, dry summers. Habitat fragmentation and climate change are already creating serious issues in the region – issues that will only continue to grow in frequency and severity. As temperatures increase and rainfall becomes more sporadic, plants and animals will need to move to more suitable climates to survive. Their necessary relocation is made difficult by a fragmented landscape that lacks suitable corridors connecting the large open spaces they need to thrive.

Protected Area Nodes (CPAD+)

A protected area is a defined geographical space (e.g., national park, wilderness area, nature reserve), managed to achieve long-term nature conservation (IUCN 2008). Thus, while future climatic conditions at some sites may not remain suitable for certain species, the collection of protected areas as a whole may protect species by facilitating species relocation between neighboring sites (Hilty et al. 2012; Sutherland et al. 2013). In this study, protected area locations were collated from the California Protected Area Database (calands.org), amended to include additional properties managed by participating stakeholders (Audubon Canyon Ranch, Lake County Land Trust, Land Trust of Napa County, Sonoma County Agricultural Preservation Open Space District, and Sonoma Land Trust). We dissolved the boundaries between all connected protected areas and excluded properties smaller than 50 acres, resulting in a final selection of 302 polygons (CPAD+). All spatial analyses were conducted using ArcGIS 10.4.1 software (ESRI, Redlands, CA, USA).

Structural Permeability: Ecological Integrity Model

For the structural permeability model, our aim was to identify broad regions of terrestrial connectivity that have the potential to facilitate the movement of multiple species and maintain ecological processes. The first way we evaluated landscape permeability was using an index of ecological integrity that estimates the degree of human modification based on stressors such as land use, land cover, and presence, use, and distance from roads (Theobald 2013; Dickson et al. 2016; data provided by The Nature Conservancy) (Figure 2). Permeability values for these data ranged from 0 to 1, with a cell size of 90 m by 90 m (8100 m^2).

Structural Permeability: Combined Model

The second way we evaluated structural permeability was by creating a combined permeability model using regression models derived from mesocarnivore and bird assemblage response to human-modified land cover and landscape configuration as inputs (Gray et al. 2016). For each permeability map, we used as input a regression model derived from indices of habitat fragmentation: median patch size effect (Reed 2007), mean parcel size effect, and road effect (Forman 2000). We applied each regression model to create a map using both the permeability value and the geographical position and orientation of all relevant landscape elements in the study area. Outputs from each model were scaled from 0 to 1 with a cell size of 30 m by 30 m (900 m^2), and combined to create the final permeability layer, with equal weight assigned to road effect, mean parcel size effect, and median patch size effect (Figure 3).

Road Effect

There is overwhelming evidence of the effects of roads on natural communities (Fahrig & Rytwinski 2009), and, thus, we calculated distance from road, scaled by traffic volume (y_{ROADS}), as an index of animal response to transportation infrastructure (Figure 4). We calculated y_{ROADS} based on empirical data from several prior studies that evaluated the impact of roads on wildlife (Reijnen et al. 1996; Forman & Deblinger 1998; Forman 2000). Forman (2000) described the correlation between the distance to a road and bird species abundance and diversity; the closer a location is to a road, and the greater the road's traffic level, the larger the road effect – resulting in a corresponding decrease in abundance and diversity of urban avoiding birds. This approach assumes that the maximum magnitude of the road effect and effect-distance are proportional to the volume of traffic along the road.

The road effect was defined as the traffic level of and proximity to highways and streets according to traffic volume data (2015 Annual Average Daily Traffic from the Caltrans Traffic Census database). We assigned an effect distance to all highways and streets based on their traffic volume using the following equation:

$$x_{ED} = 0.0126 w_{TV} + 178.75$$

where w_{TV} is the average traffic volume of the road, and x_{ED} is the road effect-distance (Forman 2000) (Appendix 1). We assumed the magnitude of effect of any given road would decline linearly with increasing distance from the road. Thus, the road effect for each grid cell was calculated using the following equation:

$$y_{ROADS} = -\left(\frac{1}{\max(x_{ED})}\right) z_{ROADS} + \frac{x_{ED} - max(x_{ED})}{max(x_{ED}) + 1}$$

where z_{ROADS} is the Euclidean distance from the nearest road and y_{ROADS} is the magnitude of the road effect.

Mean Parcel Size Effect

Parcel maps may be a useful surrogate to measure development density and patterns. This surrogate is needed because land cover has been shown to be a poor predictor of land use intensity for low-density residential development, which is the dominant development pattern in our study area and, by some accounts, the fastest growing land use type in the United States (Theobald 2005). Empirically, prior research shows a substantial relationship between parcel size and the presence of some bird species and guilds (Merenlender et al. 2009). Specifically, Merenlender et al. (2009) found that mean parcel size, calculated within a 500 m fixed radius buffer, was positively correlated with relative abundance of birds considered to be urban avoiders (e.g., Northern Flicker, Hutton's Vireo) in avian communities throughout the north coast region of California.

We calculated the mean parcel size effect as a metric of a local-scale index of human land-use intensity according to regional parcel data (Figure 5). We calculated the mean parcel size within a 480 m rectangular buffer around all cells in the study area. We then calculated the mean parcel size effect for each grid cell using the following equation:

$$y_{PARCEL} = \frac{0.0211(x_{PARCEL})^{\frac{1}{3}} + 0.0155}{max(y_{PARCEL})}$$

where x_{PARCEL} is the mean parcel size within a 480 m radius buffer, and y_{PARCEL} is the effect of mean parcel size on landscape permeability (Merenlender et al. 2009).

Median Patch Size Effect

There is increasing recognition that area-informed metrics are useful to explain variation in wildlife abundance and movement capacity, and perform well in analyses of landscape connectivity (Bender et al. 2003). We calculated the median patch size effect as a metric of habitat integrity (Figure 6), which we derived using data from a study investigating the correlation between patch size and mesocarnivore (e.g. coyote, bobcat, gray fox) occurrence in northern California, which found that the frequency of mesocarnivore detections increased with the size and contiguity of adjacent patches (Reed 2007).

The median patch size effect was defined as the median area of habitat patches within a fixed buffer radius, and is a landscape-scale, area-informed index of habitat integrity calculated using the contiguity and relative size of proximate habitat patches. We defined a patch as a contiguous area of habitat with natural vegetation cover and whose land use(s) is compatible with the establishment of mesocarnivore home ranges.

As input data for y_{PATCH}, we used a map of terrestrial vegetation cover from existing land cover data (FRAP 2015), excluding land classified as urban, agriculture, barren, or water, as well as all land parcels less than 5 acres (~2 ha) to produce a map of vegetation patches. From the map of vegetation patches, we removed all highways and streets, buffered by their road-effect distance (x_{ED}). After roads were excluded, we created a shapefile of patches with an area greater than 50 acres (~20ha). We then calculated the median patch size effect for each grid cell using the following equation:

$$y_{PATCH} = \frac{0.2356(x_{PATCH})^{1/2} + 1.385}{max(y_{PATCH})}$$

where x_{PATCH} is the median patch size within a 2500 m radius buffer, and y_{PATCH} is the effect of habitat integrity on landscape resistance, measured as the density of native mesocarnivore detections along a survey transect (Reed 2007).

Riparian Permeability

Even when dry, riparian corridors are important for wildlife movement and hydrologic connectivity. Gentle topography can be preferred for terrestrial wildlife movement (Gray et al. 2016). To evaluate the riparian connectivity, we created a resistance surface based on a terrain ruggedness index (Riley et al. 1999) that was modified to include topographically-defined creek corridors, and two landform types (valley bottom and narrow valley bottom; (Theobald et al. 2015)) to represent landscape features with zero cost for terrestrial wildlife movement (Figure 7).

Regional Linkages: Structural and Riparian

There are several ways to evaluate landscape connectivity and predict optimal corridors to connect habitat patches. In this analysis, we generated linkages using a node-based method for two reasons. First, one of the aims of this project is to identify priority areas for connectivity among existing protected areas. Second, it became clear during methods development that stakeholders are interested in identifying potential connections between existing protected areas, rather than generating a map of linkages that may not overlap with their managed lands.

Linkage Mapper (McRae & Kavanagh 2011) is a computer program that uses maps of core habitat areas and raster maps of resistance to movement to identify and map least-cost linkages between core areas. Each cell in a resistance map is attributed with a value reflecting the difficulty of moving across that cell. Cost-weighted distance analyses create maps of least-cost corridors between core areas that are then normalized and overlaid to create a single composite corridor map that shows the relative value of each grid cell in providing connectivity between core areas.

To evaluate structural and riparian connectivity across the study area, we used Linkage Mapper to create cost-weighted distance maps and least-cost corridor maps between adjacent pairs of protected areas with areas greater than 50 acres (n = 302). As a cost surface for the structural connectivity linkages, we used the inverse of the ecological integrity permeability model output as an approximation of the degree of human modification (Theobald 2013; Dickson et al. 2016). We then used Linkage Mapper to generate least cost paths (LCP) and linkages (truncated at a cost-weighted distance of 10,000 km) between perimeters of up to three adjacent protected areas to show the most cost-effective route between a source and destination protected areas (Figures 8 – 9). As a cost surface for the riparian connectivity linkages, we used the inverse of the riparian permeability model output as a representation of landscape features with zero cost for terrestrial wildlife movement. We used Linkage Mapper to generate linkages (truncated at a cost-weighted distance of 1,000 km) between perimeters of up to three adjacent protected areas (Figure 10).

Structural connectivity analysis based on the human modification indicator of ecological integrity resulted in broad linkages between protected areas with a total of 660 LCPs. Structural linkages clearly avoided cities and increased in density with distance from major roads. Riparian connectivity based on the enduring physiographic features of ruggedness, topography, and landforms showed many thin linkages between protected areas. Riparian linkages overlapped with major roads, which also follow topography across valley bottoms, and were most dense in the southern part of the study region near the tidal estuary of San Pablo Bay, CA.

Climate Layers: Current and Future (CNRM-CM5, RCP 8.5)

Early impacts of climate change are already apparent in California. Statewide annual temperatures have increased 0.83 °C in the last century, heat waves are becoming more common, and snow is melting earlier in the spring (EPA 2016). Temperature is a direct indicator of climate change, and is an important factor affecting agriculture, forestry, water supply and human and ecosystem health. Since 1895, annual average temperatures have increased by about 0.83 °C California (WRCC 2013). Over the past century, minimum, average, and maximum temperatures have all been increasing. Minimum temperatures – which correspond to night time lows – have been increasing at a faster rate than both maximum (daytime highs) and average temperatures since the mid-1970s (WRCC 2013). The study area includes land used for agriculture, which is economically important. Both decreasing winter chill and increasing extreme heat events are detrimental to the production of high value crops. Extreme heat events can result in heat-related deaths and illnesses, decreased agricultural production, increased irrigation requirements, and greater electricity demands. In addition to the importance temperature has on economic and public health, temperature variables have been identified as key drivers in multivariate climate velocity (Hamann et al. 2015).

To evaluate the extent to which the protected area network maintains climate connectivity, we evaluated the climate benefit provided by each linkage. As input, we used existing climate models (RCP 8.5) generated using the Basin Characterization Model for recent (1980 – 2010) and mid-century (2040 – 2069) (Flint & Flint 2012; Pierce et al. 2015). The Basin Characterization Model (BCM) models the interactions of climate (e.g., rainfall and temperature) with empirically measured landscape attributes including topography, soils, and underlying geology. This dataset provides historical and projected climate and hydrologic surfaces for the region. The BCM uses a minimum time step of monthly results at the scale of a 30 m grid, allowing the generation of scenarios at annual, seasonal, or monthly time steps. The final analyses were done using the CNRM-CM5 scenario, a model predicting an "intermediate" future climate space. We conducted preliminary analyses with the CCSM-4 and MIROC-ESM scenarios, which model futures with "normal" precipitation and hot/dry conditions, respectively. Given the seasonal nuances of temperature in California's ecosystem and economy, we evaluated mean summer maximum (average of June, July, and August means; JJA) and mean winter minimum (average of December, January, and February means; DJF) temperatures.

We extrapolated the model results across the study area to visualize the distribution of the two temperature variables within the study area under recent and mid-century time periods (Figures 11 – 14). To compare the temperature distribution between the recent and mid-century time points, we divided the temperature values into 0.25 °C increments, calculated the number of cells in each 0.25 °C increment, and generated abundance plots. Finally, we generated summary statistics for each temperature variable.

The average change between current and future for mean summer maximum was 2.6 °C (range: 1.3 – 4.2 °C) (Figure 15) and for mean winter minimum was 2.0 °C (range: 0.4 – 3.2 °C) (Figure 16). There were no negative changes between current and future temperature for either variable. For both variables, the histogram showing the temperature distribution appeared visually similar; same distribution of values overall, shifted toward warmer temperatures.

Climate Benefit

Conservation practitioners are generally interested in linkages that will facilitate movement of species to cooler climates in response to climate change. The assumption is that a network of connected protected areas may provide the opportunity for range shifts if future climatic conditions at some sites are no longer suitable. Thus, connecting neighboring protected areas with a linkage may provide a temperature benefit in the form of access to cooler locations.

We quantified the temperature benefit added to each protected area by maintaining a linkage with a neighboring protected area using net cooling as an indicator of resilience to climate change. We considered the linkage area unsuitable for permanent habitat, so climate benefits were only realized by connecting to a protected area. Consequently, we did not consider the values within the linkage when calculating the final benefit of connecting two protected areas. To calculate the net cooling benefit for each linkage, we found the difference between the lowest grid cell values for winter minimum temperatures for each protected area connected by a linkage. This value represented the net cooling the network presents over any one individual protected area. We assigned this value to the adjoining linkage to represent the added benefit of the network in maintaining cooler winter minimum temperatures. Similarly, we calculated the difference between the lowest grid cell values for summer maximum within each protected area to represent the added benefit of the network in maintaining cooler summer maximum temperatures. We then identified locations offering the greatest climatic benefits to the protected area network by mapping the climate benefit for each variable into the future (Figures 17 – 18).

The average potential net cooling from structural linkages between protected areas was 1.8 °C for mean summer maximum mean (range: 0.0 – 13.5 °C) and 0.8 °C for mean winter minimum (range: 0.0 – 6.8 °C).

Shrinking Climate Space

Climate change scenarios may also be incorporated into habitat connectivity planning by using estimates of future climate to inform protected area and linkage designation. For example, by tracking how a species' climatic envelope changes across a landscape under future climate scenarios (Lawler et al. 2013) or through inferred shifts in species distributions based on the velocity of change (Burrows et al. 2014). Other studies have assessed climate connectivity together with current landscape permeability (Schloss et al. 2012). The utility of these species-based approaches for conservation planning is limited by the high levels of uncertainty inherent to current and future species distribution models, the computational demands of modeling a representative number of species, and the coarse resolution of their data inputs. An alternative to species-driven models is to evaluate the distribution of future climate space, or the area of land climatically suitable for a particular species. Using climate space to prioritize locations aggregates the overall similarity of conditions that should benefit many species to offer the greatest climate space benefit under the assumption that maintaining access to cooler climates is a high priority (Game et al. 2011).

To determine the change in climate space for each variable, we compared the difference in climate space area between the current and future models. For each variable, we extracted the current and future values for the entire study region at 30 m resolution and divided them into 0.25 °C increments. For each 0.25 °C increment, we subtracted the count of cells for the current model from that for the future model, then divided this difference by the future count. For example, if the sum of all cells in the 30 – 30.25 °C bin was 100 in the current scenario and 71 in the future scenario, the 30 – 30.25 °C increment lost 29% of its area. We then visualized the difference between current and future climate space by mapping the percent lost for each individual variable, and for both variables combined, into the future (Figures 19 – 21).

Our analyses showed only a few "severely shrinking" (> 50% loss) areas were located outside the protected area network. The locations projected to experience the most severely shrinking climate spaces were in the north of the study area at high elevations.

DISCUSSION

Here, we advance existing methods of climate connectivity modeling by including novel methodological components to climate benefit and landscape heterogeneity into connectivity prioritization. Our results illustrate how three metrics of connectivity can be used – in combination or independently – to identify priority locations between existing protected areas. The linkage analyses quantify existing connectivity and can directly inform conservation management and planning by identifying specific linkages for planning and corridor implementation. The climate benefit analyses identified shrinking climate space and quantified the net cooling provided by linkages to the protected area network. Our results improve our ability to identify locations of conservation value that provide connectivity benefits today and under scenarios of landscape change.

Our climate results show clear differences between the trends for summer and winter variables, highlighting the importance of accounting for seasonality in Mediterranean climates with a coastal influence. Overall, cooler summer temperatures were found in the western portion of the study area closer to the coast, whereas the cooler winter temperatures were found inland to the east. The effect of seasonality was also apparent in our evaluation of future climate spaces and the linkages that offer the greatest climate benefit in degrees of net cooling differ between the two temperature variables. While mean annual temperature can be informative for some analyses, in locations with topographic and climatic diversity, evaluating mean annual summer maximum and mean winter minimum temperatures independently is needed to tease apart the influence of seasonal variation on the landscape. This study offers insights for assessing land management priorities affected by seasonality, which can be important for conservation planning depending on the desired outcome for future land management. Specifically, connectivity goals may differ when the need for cooler winters (e.g., for agriculture or invasive species) and cooler summers (e.g., for fire management or climatic gradients for adaptation) are prioritized.

When we compared structural and riparian linkages, we found some overlap between the linkages in the southern portion of the study area that is more developed and has smaller existing protected areas. These locations, where both structural and riparian connectivity co-occur should be prioritized. These analyses could be applied in other, similarly fragmented locations where connectivity is desired to improve the ecological integrity of the landscape.

CONCLUSION

Data Applications

To put the parcel scale data used in this connectivity assessment into a meaningful regional context, the data products described in this report were used to identify six corridor projects within the M2B study area to advance corridor planning and implementation by project stakeholders (Figure 22). The corridor projects varied in scale from a single linkage connecting two protected areas (e.g., Pepperwood Preserve to Modini Mayacamas Preserve) to a regional connectivity design comprised of multiple linkages between several protected areas (e.g., The Heart of M2B). In collaboration with stakeholders, each corridor project identified a parcel-scale priority linkage area, assessed the potential climate adaptation benefits of linkage implementation, quantified conservation benefits unique to the site of interest, specified critical partners for linkage implementation, and identified potential next steps for corridor implementation. A guidance document was created for each corridor project to describe how the connectivity assessments were used to characterize the corridor project, which may be used to generate additional assessments by practitioners for other sites of interest. The availability of statewide data for all analyses conducted in this project, as well as the content of this methodology report and the guidance documents for the six corridor projects, ensure our approach is reproducible for all of California and can be used to engage land managers and identify parcel scale efforts, with the flexibility to include project-specific data sources that complement the M2B products.

Connectivity between natural areas is crucial to mitigate climate change effects on biodiversity across human-modified landscapes. Linkages that offer climate adaptation and landscape connectivity benefits are particularly important in species-rich and topographically-diverse areas like Mediterranean landscapes. Climate connectivity is often evaluated using average temperature data as input, which fails to capture seasonal temperature extremes. Our climate results showed clear differences between the trends for summer and winter variables, highlighting the importance of accounting for seasonality in Mediterranean climates with a coastal influence. A statewide evaluation of additional future scenarios would provide the opportunity to explore the spatial trends and climate benefit predictions for seasonal temperatures and provide data that may be used to improve connectivity planning for biodiversity conservation in Mediterranean landscapes.

Next Steps

These high-resolution data products illustrate regional riparian, structural, and climate connectivity that may be used to estimate connectivity at the scale needed for conservation actions (e.g., acquisition, restoration, easements). California is a leader in climate policy and conservation funding and implementation yet lacks science-based prioritizations of areas that will provide the best opportunities to enable species to adapt to climate impacts. By including practitioners during methods development and results dissemination, we increased the compatibility between the data products and the needs, planning, and management workflows of end-users. By engaging a range of stakeholders to shape the analysis and interpret model results, these products will create enabling conditions for effective implementation actions, such as land acquisition, infrastructure retrofits, and vegetation restoration. With a greater understanding of the role connectivity within protected area networks plays in climate change adaptation, land managers can advance on-the-ground implementation by securing linkages between large state and federally-owned protected lands. Further, these results provide scalable visualization tools and scientific credibility to facilitate local and regional conservation fundraising efforts and create a framework that can be refined and expanded across the US to enhance connectivity and climate resilience. In this way, we aim to synchronize the timing of connectivity science and outreach, a recommended approach to reduce delays in enacting connectivity plans and their implementation (Brodie et al. 2016).

As projections for California suggest that climate change will only increase end of dry-season climatic water deficits, drought risks, and fire probabilities, finding cost-effective ways of generating more meaningful data to prioritize fuels treatments is a critical need to enhance community resilience. Terrestrial ecosystems play a critical role in mediating the rate of global climate change by influencing fluxes and stocks of carbon, water, and nutrients. As such, sequestration of carbon by terrestrial ecosystems has been identified by Governor Brown as one of six 'pillars' to achieve the State's new greenhouse gas emissions goals. Specifically, the State is targeting no net carbon loss by 2020 primarily via the role of forests, and based on recent regional analyses, aboveground carbon stocks have increased by only 3.4% over the past decade. This small net change reflects significant losses from land that has experienced wildfire and drought, pointing to the importance of proactive conservation and management of terrestrial ecosystems to maximize the value of forests in mitigating state carbon emissions objectives. Unfortunately, fire management of native vegetation on wild and working lands to effectively manage fuel loads in forests and rural areas presents the greatest challenge to enhance net carbon sequestration, as there are still significant knowledge gaps in ecosystem carbon accounting related to the impacts of wildfires in these areas. As fuel load accumulation resulting from fire suppression, combined with drought, have been hypothesized as factors increasing fire severity and rate of spread in recent fire events, additional research is needed to evaluate tradeoffs between carbon storage and emissions associated with fuels management in the context of drought- and fire-prone landscapes. Research is needed that will improve the quality and relevancy of the knowledge base available to inform priorities for forest management and improve access to information critical to targeting landscape-level vegetation, fire, and drought management indicators and priorities.

Maintaining landscape connectivity is a first step in securing healthy ecosystems and the wildlife populations they support. However, land managers need reliable data to see fluctuations in wildlife numbers and movements, and to make informed decisions about how to then protect and restore the wildlife habitats under their care. Traditionally, wildlife data has been very difficult and costly to collect, putting it well beyond the reach of many land managers. In recent years however, wildlife cameras (camera traps) have emerged as a cost effective, noninvasive way to measure wildlife diversity, distribution, and abundance over time, and to share that information with elected officials and the public. A number of San Francisco Bay Area agencies and organizations have installed camera traps on their lands. However, data collection and analysis are done independently, leading to inefficiencies, extra costs, unused data, and an inability to answer critical large-scale questions such as the placement and efficacy of wildlife corridors. Furthermore, sustained camera trapping, rather than short-term "snapshots," is needed to answer important questions about longer term patterns such as the effects of drought, climate change, habitat restoration, or land use change. It is clear that a coordinated, sustainable, long-term approach to support and expand these collective efforts is needed to inform key landscape connectivity and stewardship strategies. Specifically, connectivity assessments will benefit from standardized monitoring efforts, a central data repository, and a framework for analyzing local and regional trends to inform conservation at reserve and regional scales.

Connectivity and climate change research have called attention to global and continental patterns of climate change and provided projections of how species might respond. Recently conservation scientists have begun using global/continental climate models to evaluate climate connectivity among protected area networks, showing that linkages can provide climate benefits to networks (Martinuzzi et al. 2015), and how the matrix of human modification can influence climate connectivity (McGuire et al. 2016). Urban expansion around protected areas is projected to expand by 67% under business-as-usual conditions (Martinuzzi et al. 2015), highlighting the importance of predicting future land use change for biodiversity persistence within protected areas and connectivity planning between them. Consequently, there is a need to explore the interaction between changing land use and climate in climate connectivity analyses. Future analyses that include land use change projections should be conducted.

ACKNOWLEDGEMENTS

Financial support for this project was provided by the California Landscape Conservation Cooperative. We thank Lorraine Flint and Alan Flint (United States Geologic Survey) for assistance with downscaling of climate projections. Our gratitude goes to the following stakeholders who participated in the co-creation of these methods: Sherry Adams and Jeanne Wirka (Audubon Canyon Ranch); Kay-Leigh Barnitz and Jim Weigand (Bureau of Land Management); Cathy Koehler (Lake County Land Trust and McLaughlin Preserve); Tom Smythe (Lake County Land Trust); Mike Palladini (Napa Land Trust); Karen Gaffney, Alex Roa, and Allison Schichtel (Sonoma County Ag. Preservation & Open Space District); Hattie Brown (Sonoma County Regional Parks); and Wendy Eliot (Sonoma Land Trust), Trevor George, Ann Johnston, and Tony Nelson (Sonoma Land Trust).

LITERATURE CITED

Bender DJ, Tischendorf L, Fahrig L. 2003. Using patch isolation metrics to predict animal movement in binary landscapes. Landscape Ecology **18**:17–39.

Berg MP, Toby Kiers E, Driessen G, van der Heijden M, Kooi BW, Kuenen F, Liefting M, Verhoef HA, Ellers J. 2010. Adapt or disperse: Understanding species persistence in a changing world. Global Change Biology **16**:587–598.

Brodie JF, Paxton M, Nagulendran K, Balamurugan G, Reuben Clements G, Reynolds G, Jain A, Hon J. 2016. Connecting science , policy , and implementation for landscape - scale habitat connectivity. Conservation Biology **30**:950–961.

Burrows MT et al. 2014. Geographical limits to species-range shifts are suggested by climate velocity. Nature **507**:492–495.

Carroll C, Lawler JJ, Roberts DR, Hamann A. 2015. Biotic and climatic velocity identify contrasting areas of vulnerability to climate change. PLoS ONE **10**:e0140486. Chapman and Hall.

Charlesworth D, Charlesworth D, Willis JH, Willis JH. 2009. The genetics of inbreeding depression. Nature reviews. Genetics **10**:783–96. Nature Publishing Group.

Chen I, Hill JK, Ohlemüller R, Roy DB, Thomas CD. 2011. Rapid range shifts of species of climate warming. Science **333**:1024–1026.

Corlett RT, Westcott DA. 2013. Will plant movements keep up with climate change? Trends in ecology & evolution **28**.

Epps CW, Palsbøll PJ, Wehausen JD, Roderick GK, Ramey RR, McCullough DR. 2005. Highways block gene flow and cause a rapid decline in genetic diversity of desert bighorn sheep. Ecology Letters **8**:1029–1038.

Fahrig L, Merriam G. 1994. Conservation of fragmented populations. Conservation Biology **8**:50–59.

Fahrig L, Rytwinski T. 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecology & Society **14**.

Flint LE, Flint AL. 2012. Downscaling future climate scenarios to fine scales for hydrologic and ecological modeling and analysis. Ecological processes **1**:1–15. Springer.

Forman RT, Deblinger RD. 1998. The ecological road-effect zone for transportation planning and Massachusetts highway example.

Forman RTT. 2000. Estimate of the area affected ecologically by the road system in the United States.

Conservation Biology **14**:31–35.

Game ET, Lipsett-Moore G, Saxon E, Peterson N, Sheppard S. 2011. Incorporating climate change adaptation into national conservation assessments. Global Change Biology **17**:3150–3160.

Gray M, Wilmers CC, Reed SE, Merenlender AM. 2016. Landscape feature-based permeability models relate to puma occurrence. Landscape and Urban Planning **147**:50–58. Elsevier B.V.

Hamann A, Roberts DR, Barber QE, Carroll C, Nielsen SE. 2015. Velocity of climate change algorithms for guiding conservation and management. Global Change Biology **21**:997–1004.

Heller N, Zavaleta E. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biological Conservation **142**:14–32. Elsevier Ltd.

Hilty JA, Chester CC, Cross MS. 2012. Climate and Conservation: Landscape and Seascape Science, Planning, and Action. Island Press.

Hilty JA, Lidicker WZ, Merenlender A. 2006. Corridor Ecology: The Science and Practice of Linking Landscapes for Biodiversity Conservation. Island Press.

Lawler JJ, Ruesch AS, Olden JD, McRae BH. 2013. Projected climate-driven faunal movement routes. Ecology letters **16**:1014–22.

Lenoir J, Svenning JC. 2015. Climate-related range shifts - a global multidimensional synthesis and new research directions. Ecography **38**:15–28.

Martinuzzi S, Radeloff VC, Joppa LN, Hamilton CM, Helmers DP, Plantinga AJ, Lewis DJ. 2015. Scenarios of future land use change around United States' protected areas.

McGuire JL, Lawler JJ, McRae BH, Nuñez TA, Theobald DM. 2016. Achieving climate connectivity in a fragmented landscape. Proceedings of the National Academy of Sciences **113**:7195–7200.

McRae B, Kavanagh D. 2011. Linkage Mapper Connectivity Analysis Software. The Nature Conservancy.

Merenlender A, Reed S, Heise K. 2009. Exurban development influences woodland bird composition. Landscape and Urban Planning **92**:255–263. Elsevier B.V.

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GA, Kent J. 2000. Biodiversity hotspots for conservation priorities. Nature **403**:853–858. Green College, Oxford University, Headington, UK. myers1n@aol.com.

Ohlemüller R, Gritti ES, Sykes MT, Thomas CD. 2006. Quantifying components of risk for European woody species under climate change. Global Change Biology **12**:1788–1799. Blackwell Publishing Ltd.

Pecl GT et al. 2017. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science **355**:eaai9214.

Pierce DW, Cayan DR, Maurer EP, Abatzoglou JT, Hegewisch KC. 2015. Improved Bias Correction Techniques for Hydrological Simulations of Climate Change. Journal of Hydrometeorology **16**:2421–2442.

Poloczanska E et al. 2013. Global imprint of climate change on marine life. Nature Climate Change:1–7.

Reed SE. 2007. Dissertation:1–134.

Reijnen R, Foppen R, Meeuwsen H. 1996. The effects of traffic on the density of breeding birds in Dutch agricultural grasslands. Biological conservation **75**:255–260. Elsevier.

Roelke ME et al. 1993. The consequences of demographic reduction and genetic depletion in the endangered Florida panther. Current biology : CB **3**:340–50. Elsevier.

Schloss CA, Nuñez TA, Lawler JJ. 2012. Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. Proceedings of the National Academy of Sciences of the United States of America **109**:8606–11.

Sutherland WJ et al. 2013. Identification of 100 fundamental ecological questions. Journal of Ecology **101**:58–67.

Theobald DM. 2005. Landscape patterns of exurban growth in the USA from 1980 to 2020. Ecology and Society **10**.

Theobald DM, Harrison-Atlas D, Monahan WB, Albano CM. 2015. Ecologically-relevant maps of landforms and physiographic diversity for climate adaptation planning. PLoS ONE **10**:1–17.

Tilman D, Clark M, Williams DR, Kimmel K, Polasky S, Packer C. 2017. Future threats to biodiversity and pathways to their prevention. Nature **546**:73–81.

FIGURES

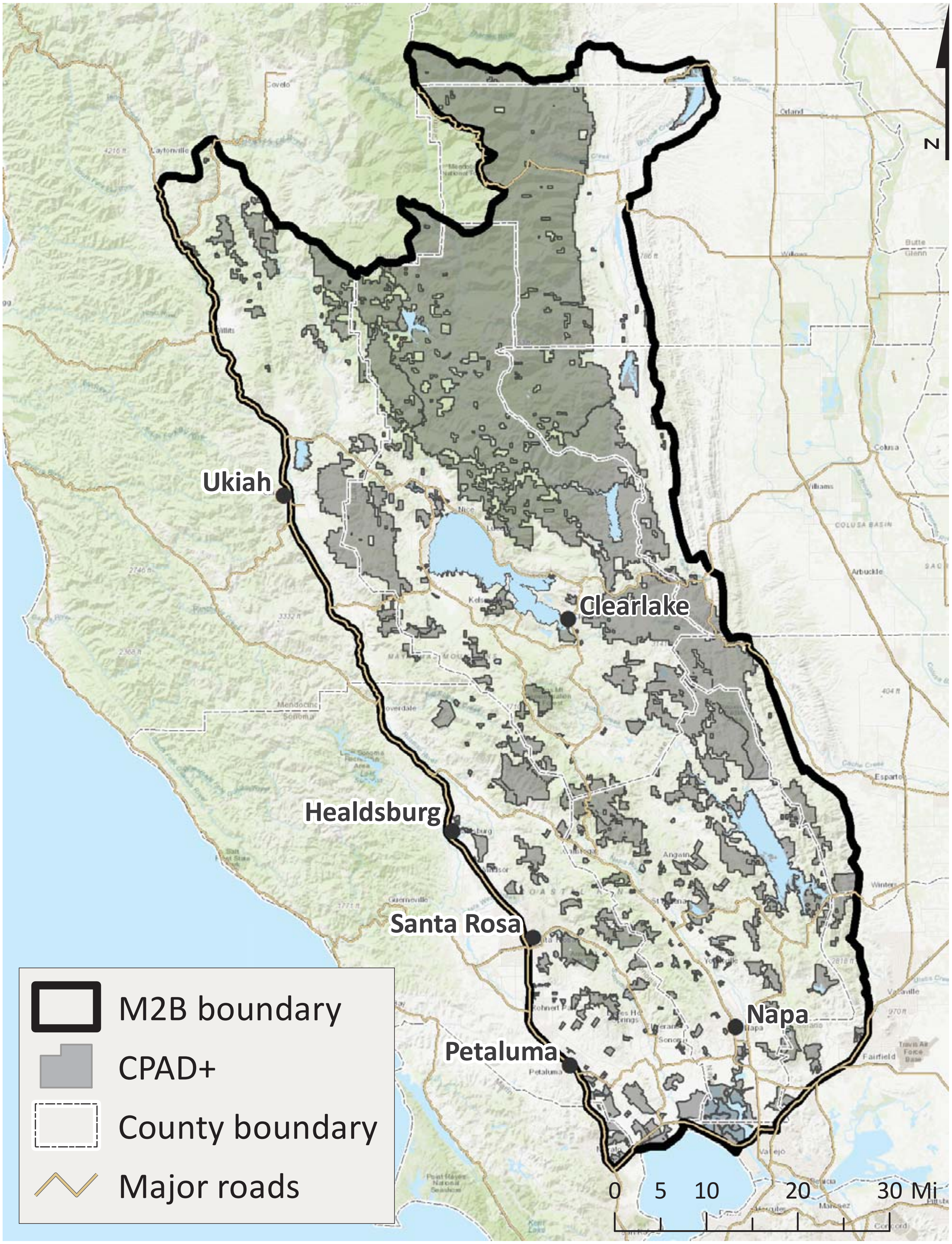


Figure 1. Mayacamas to Berryessa Connectivity Network (M2B) study area overlaid with protected area nodes (n=302).

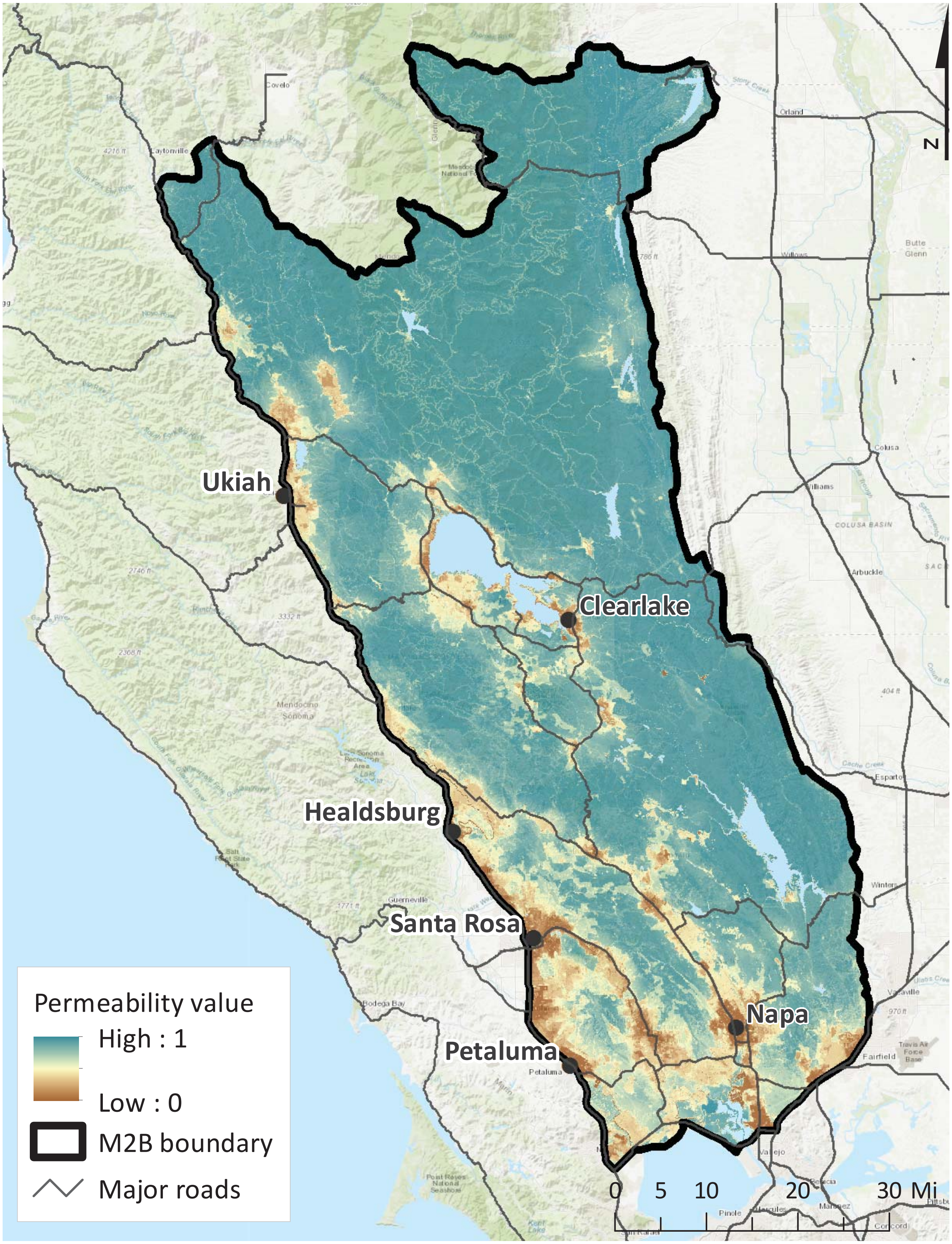


Figure 2. Permeability surface – ecological integrity index (naturalness).

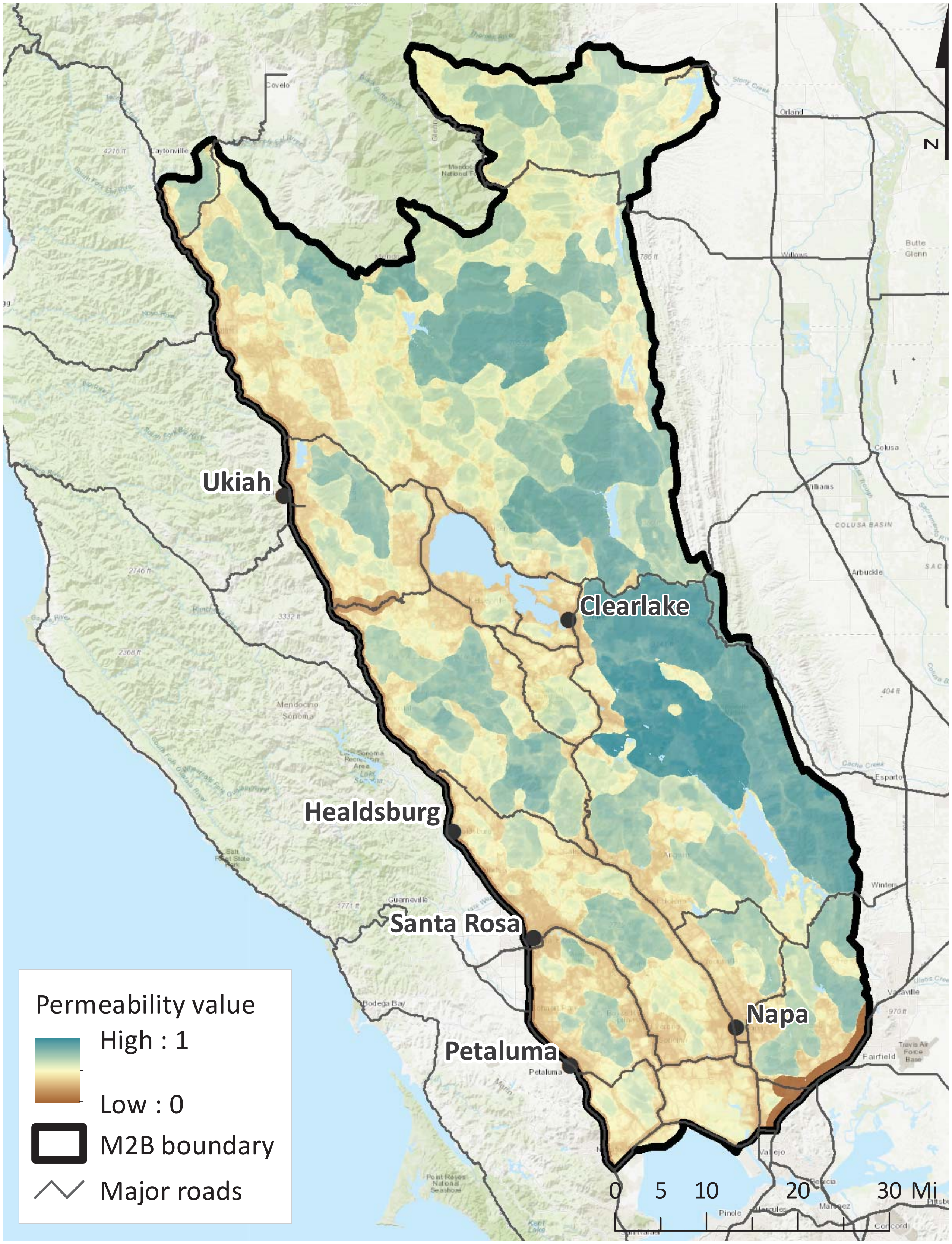


Figure 3. Permeability surface – combined model using parcel size, patch size, and road effect.

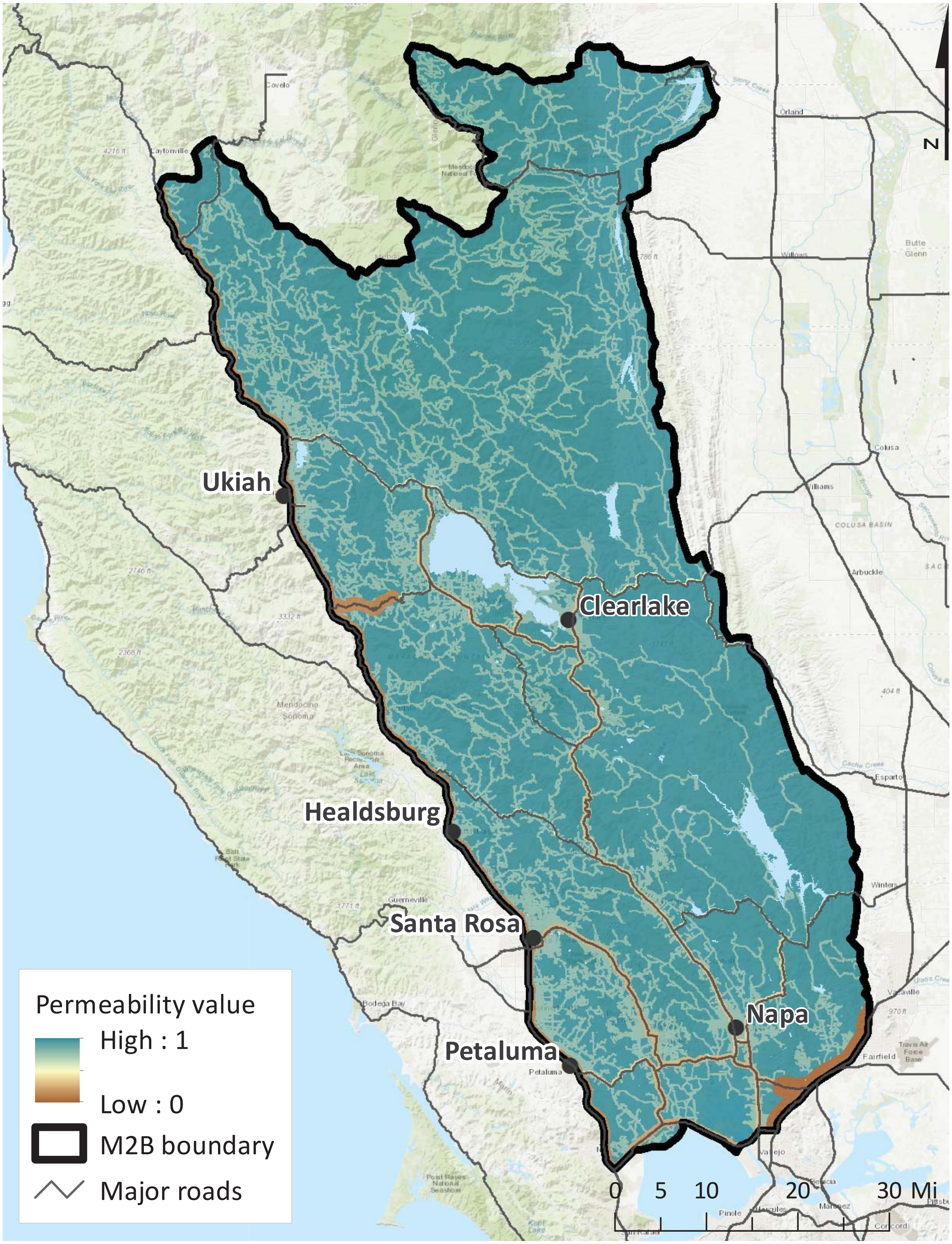


Figure 4. Permeability surface – road effect.

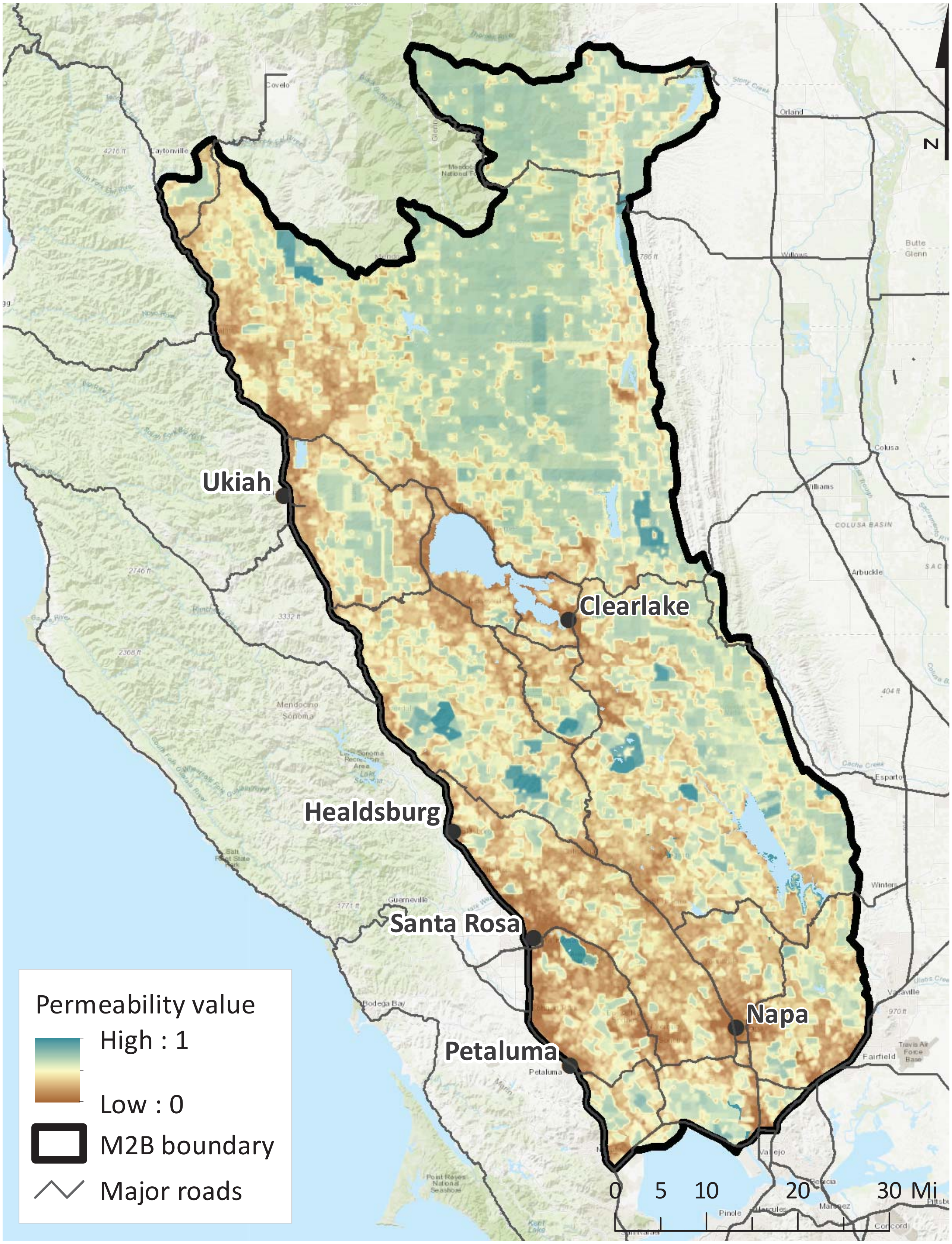


Figure 5. Permeability surface – mean parcel size effect.

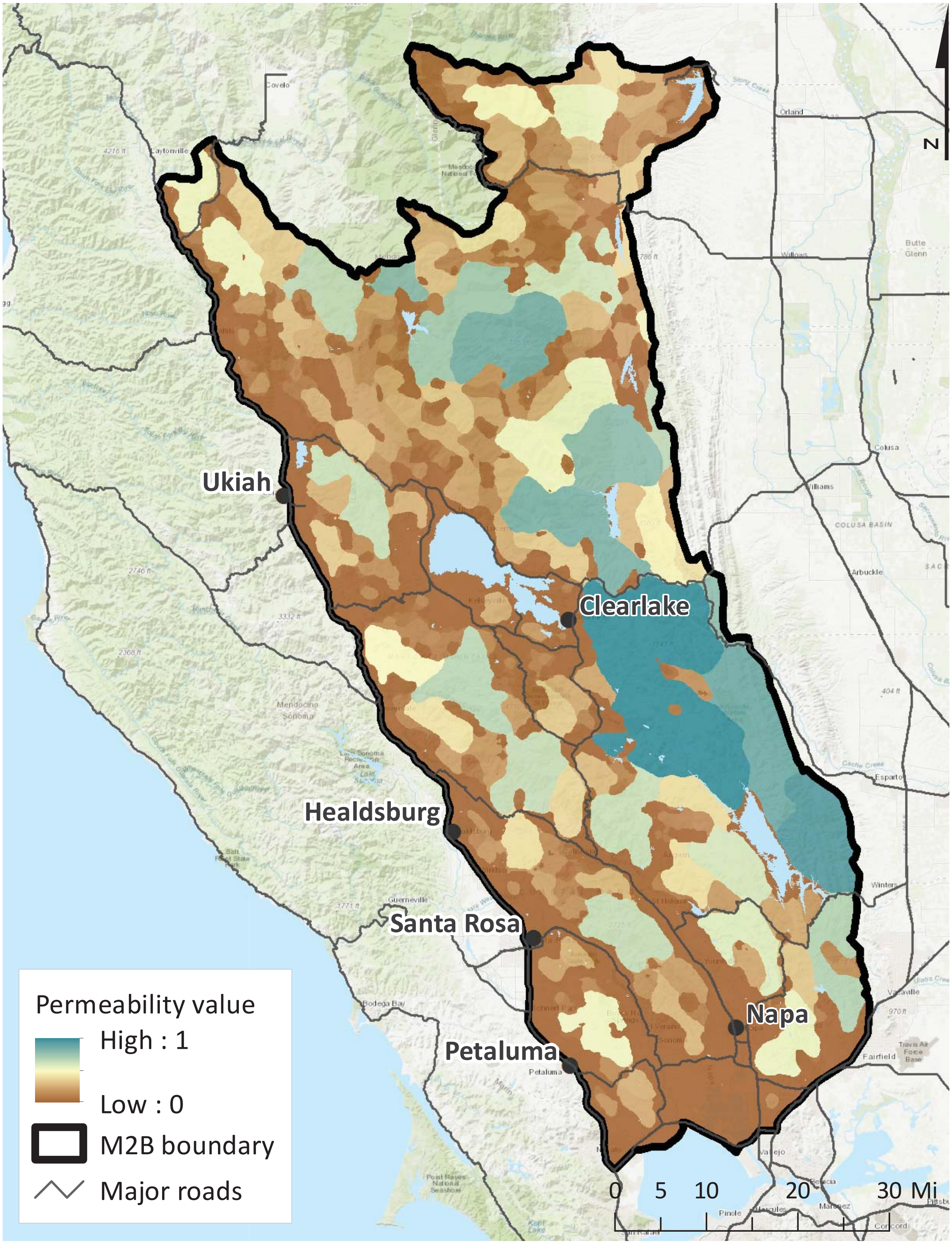


Figure 6. Permeability surface – median patch size effect.

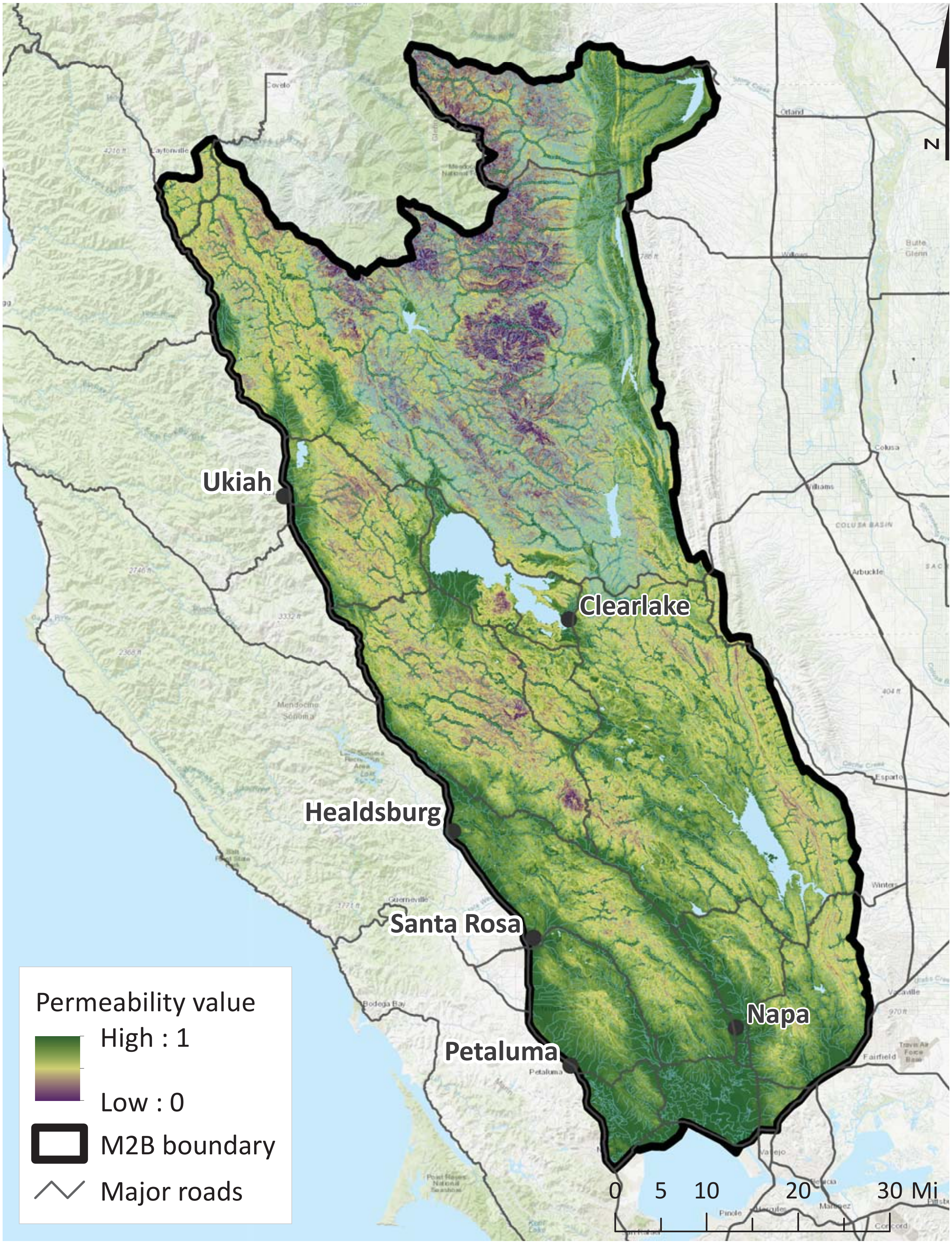


Figure 7. Permeability surface – riparian features.

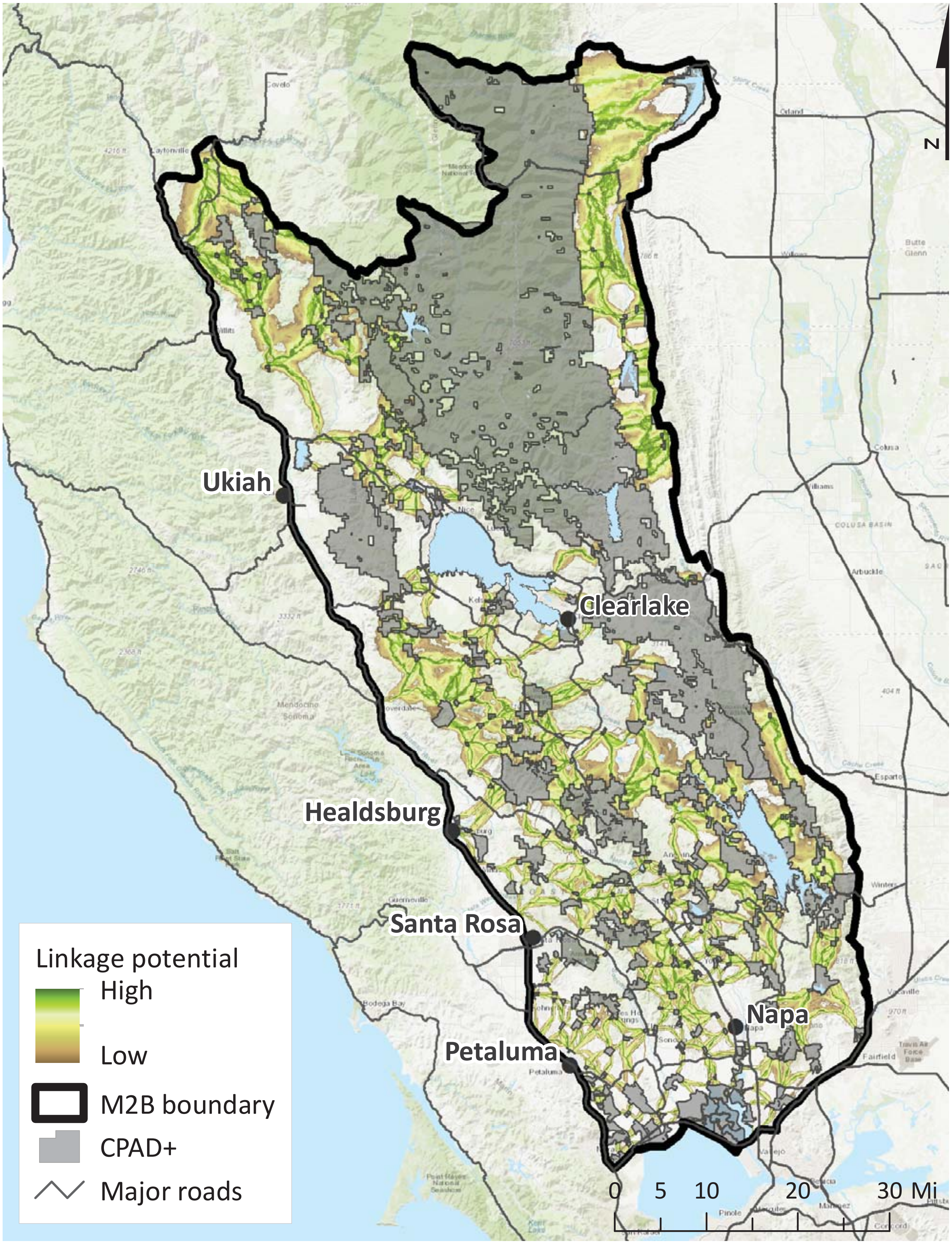


Figure 8. Structural (terrestrial) linkage potential.

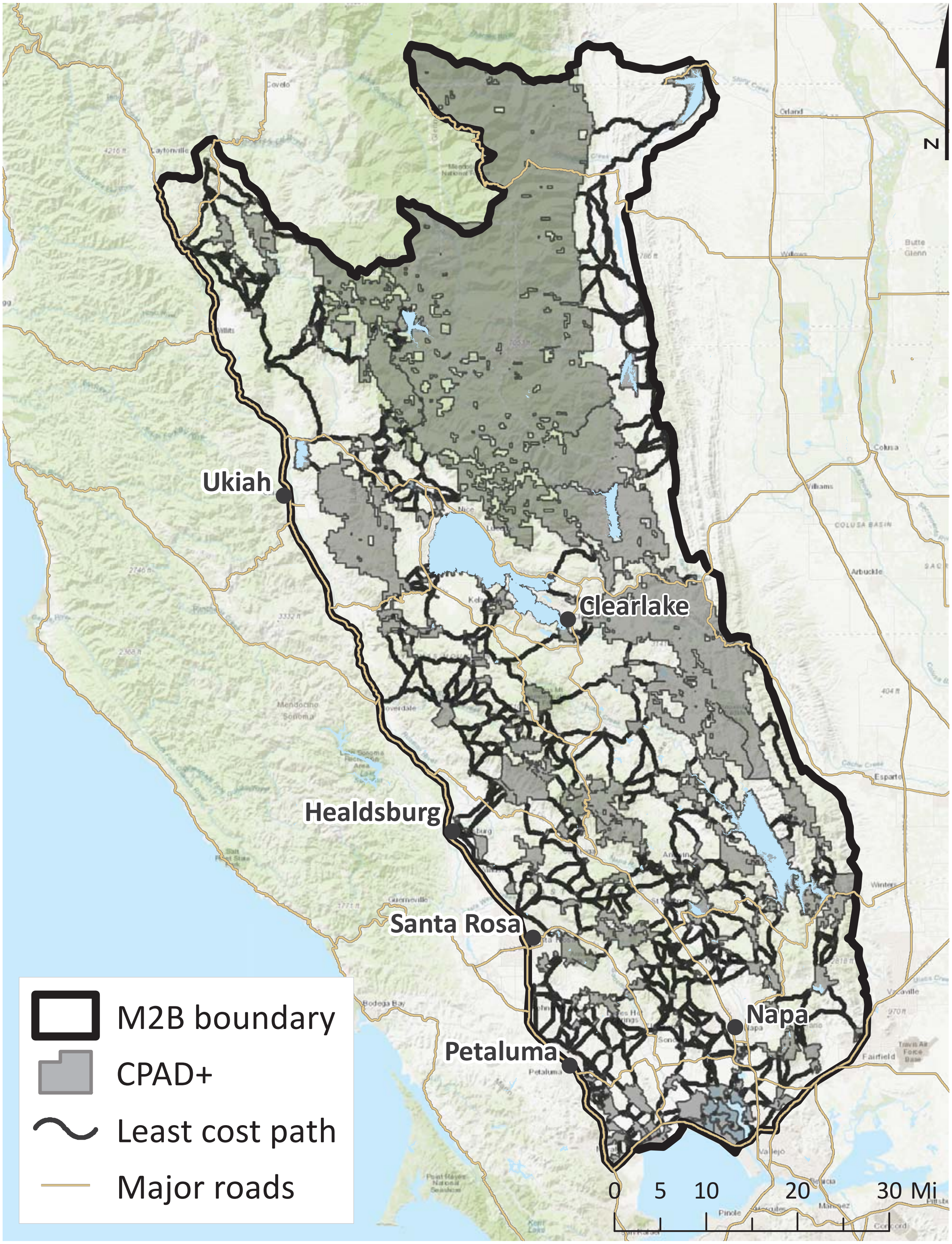


Figure 9. Structural (terrestrial) least cost paths.

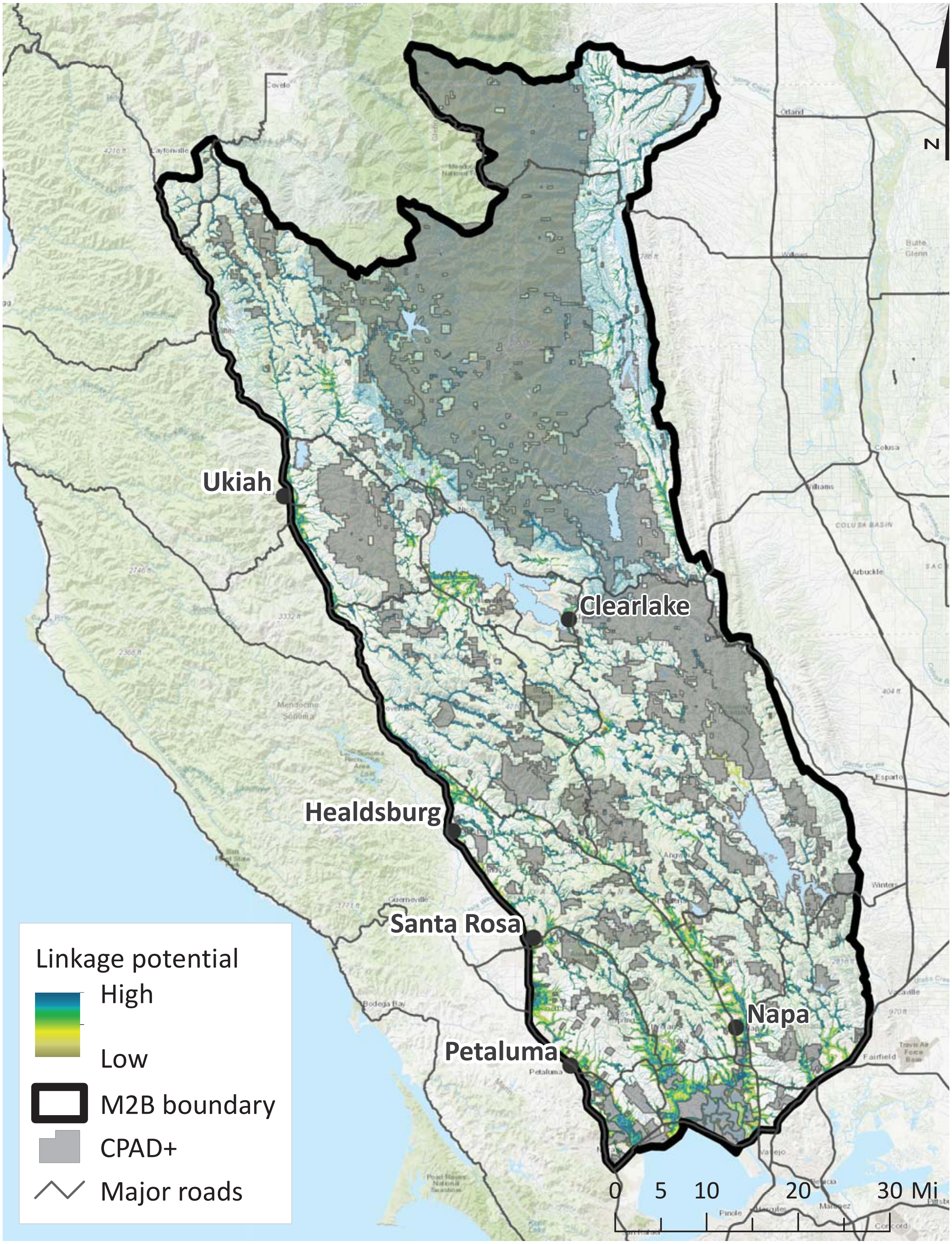


Figure 10. Riparian linkage potential.

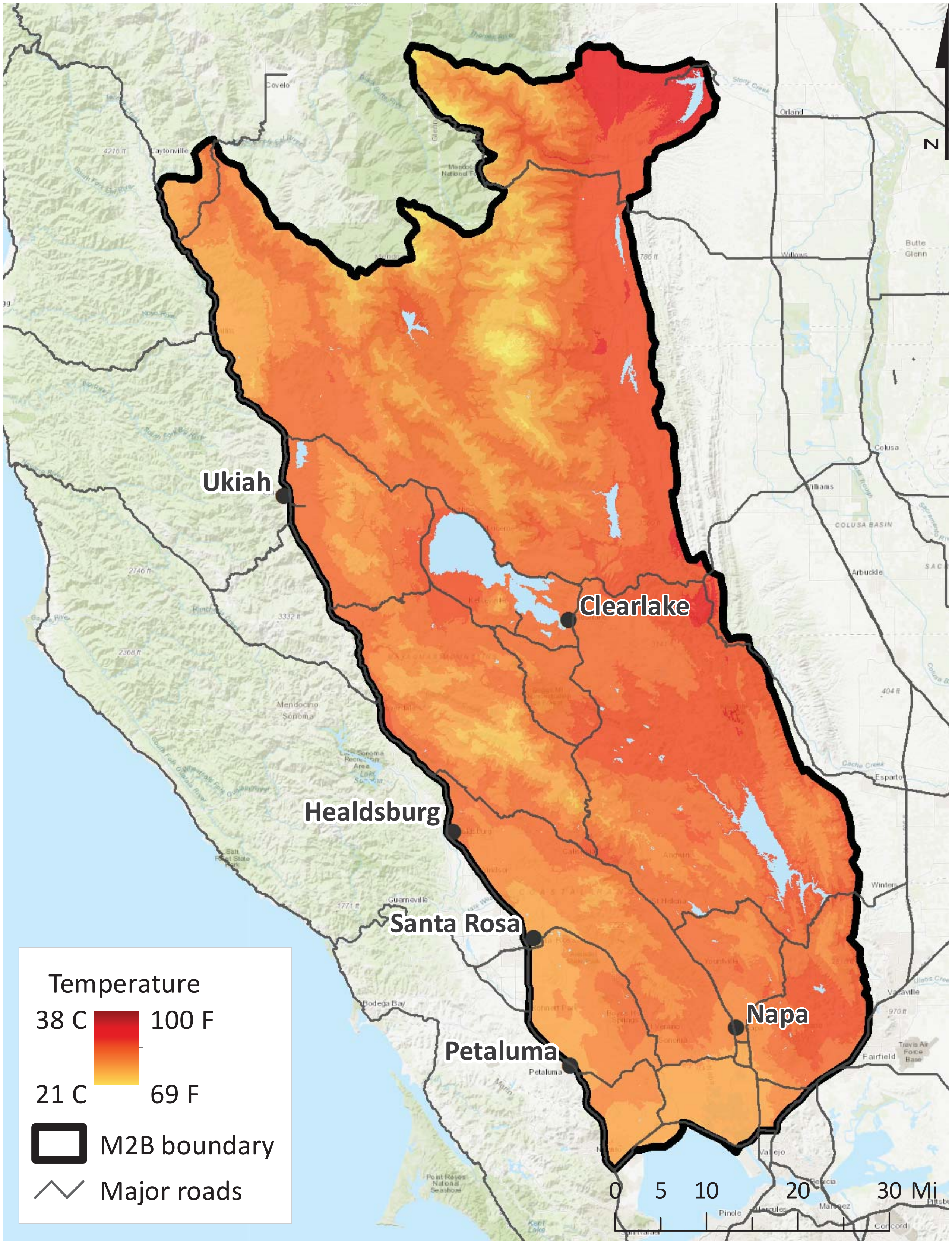


Figure 11. Recent distribution – mean summer maximum temperature.

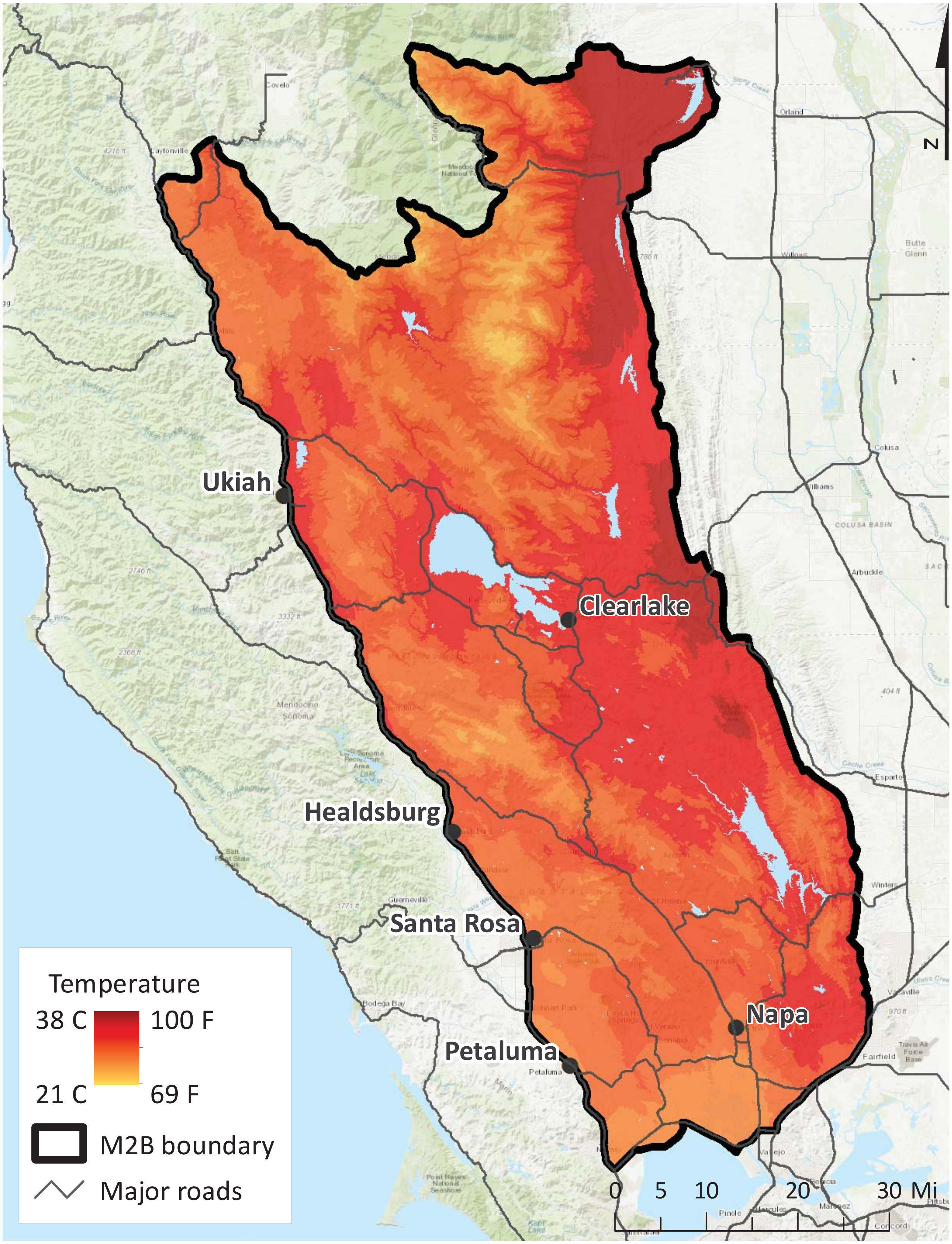


Figure 12. Future distribution – mean summer maximum temperature.

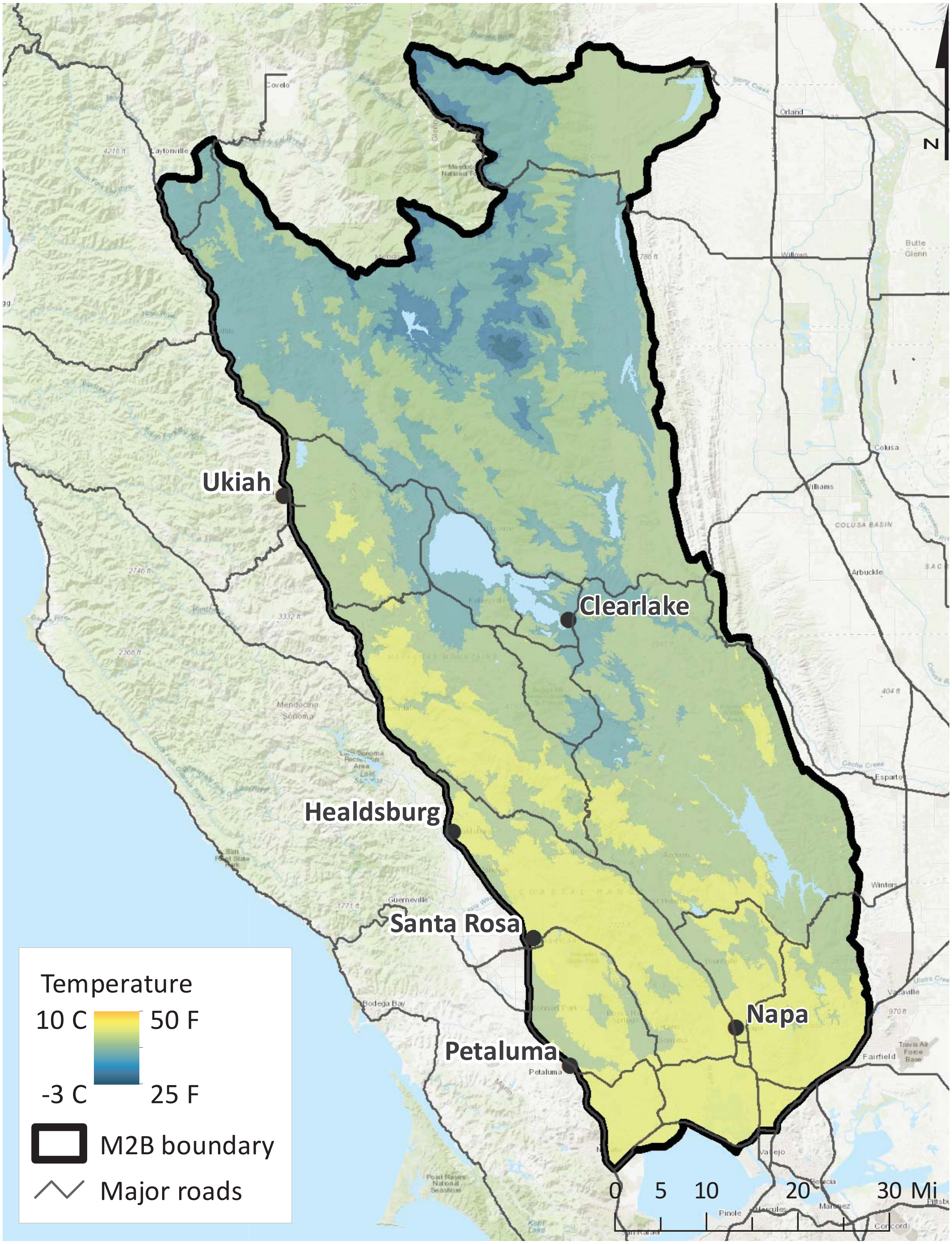


Figure 13. Recent distribution – mean winter minimum temperature.

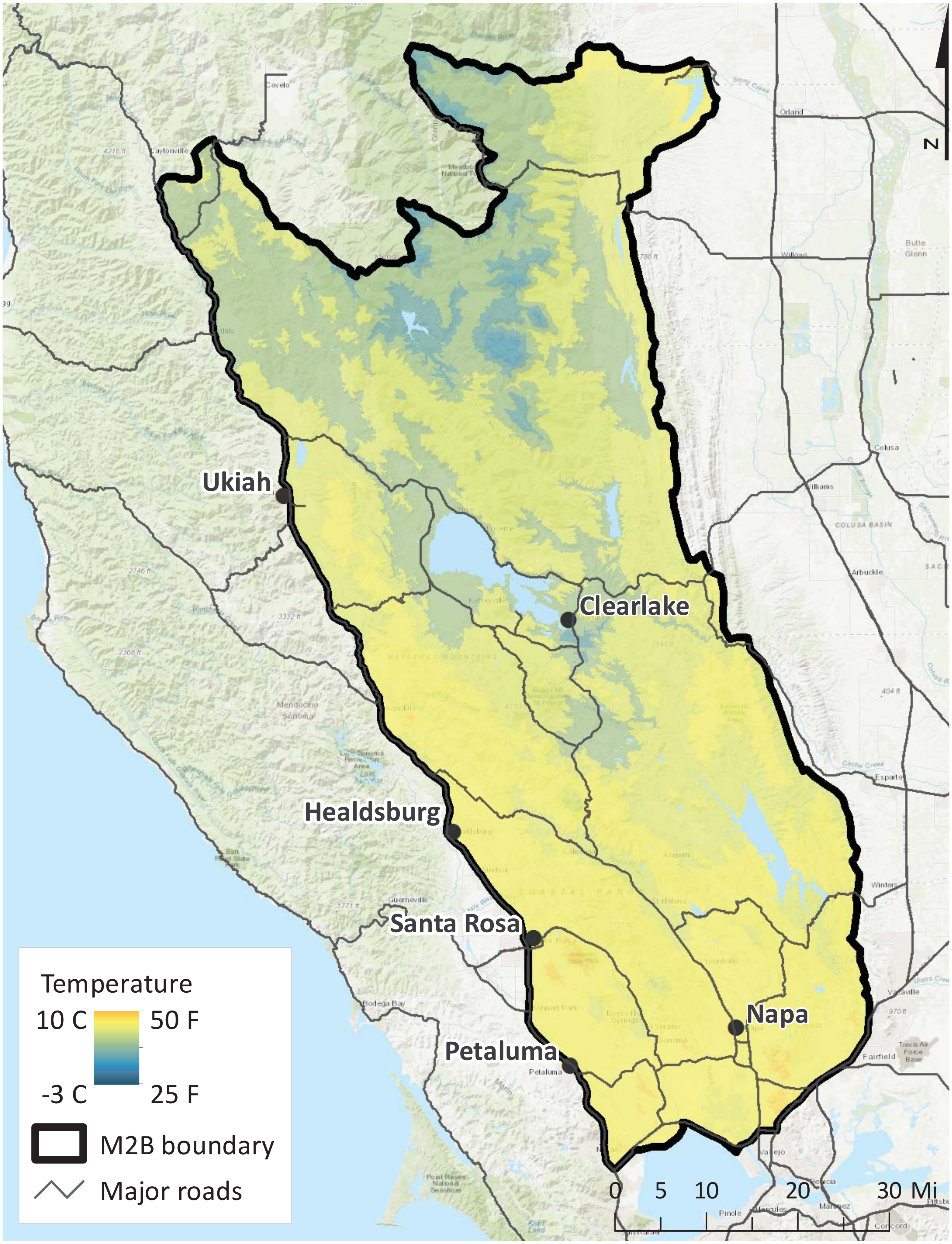


Figure 14. Future distribution – mean winter minimum temperature.

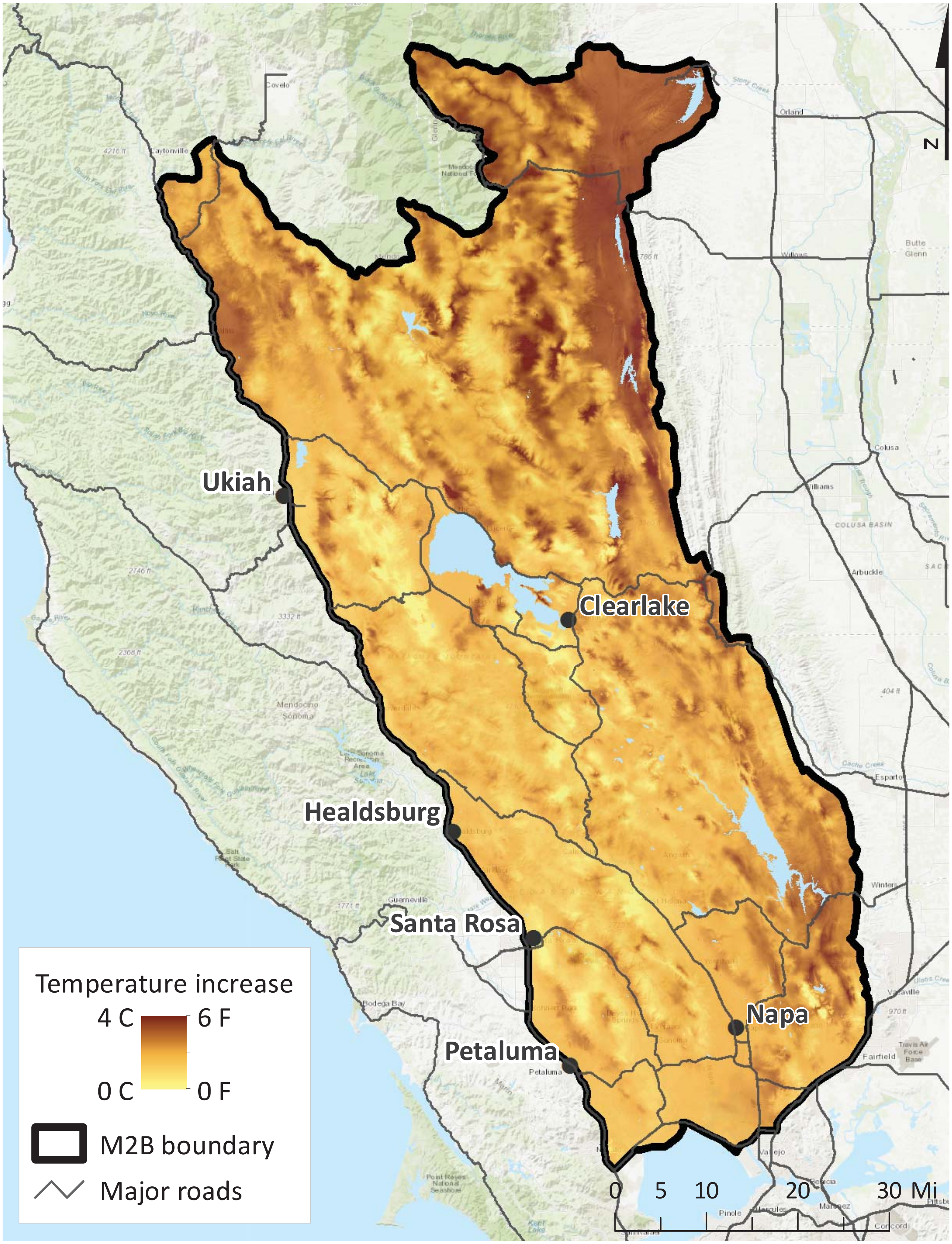


Figure 15. Increase by mid-century – mean summer maximum temperature.

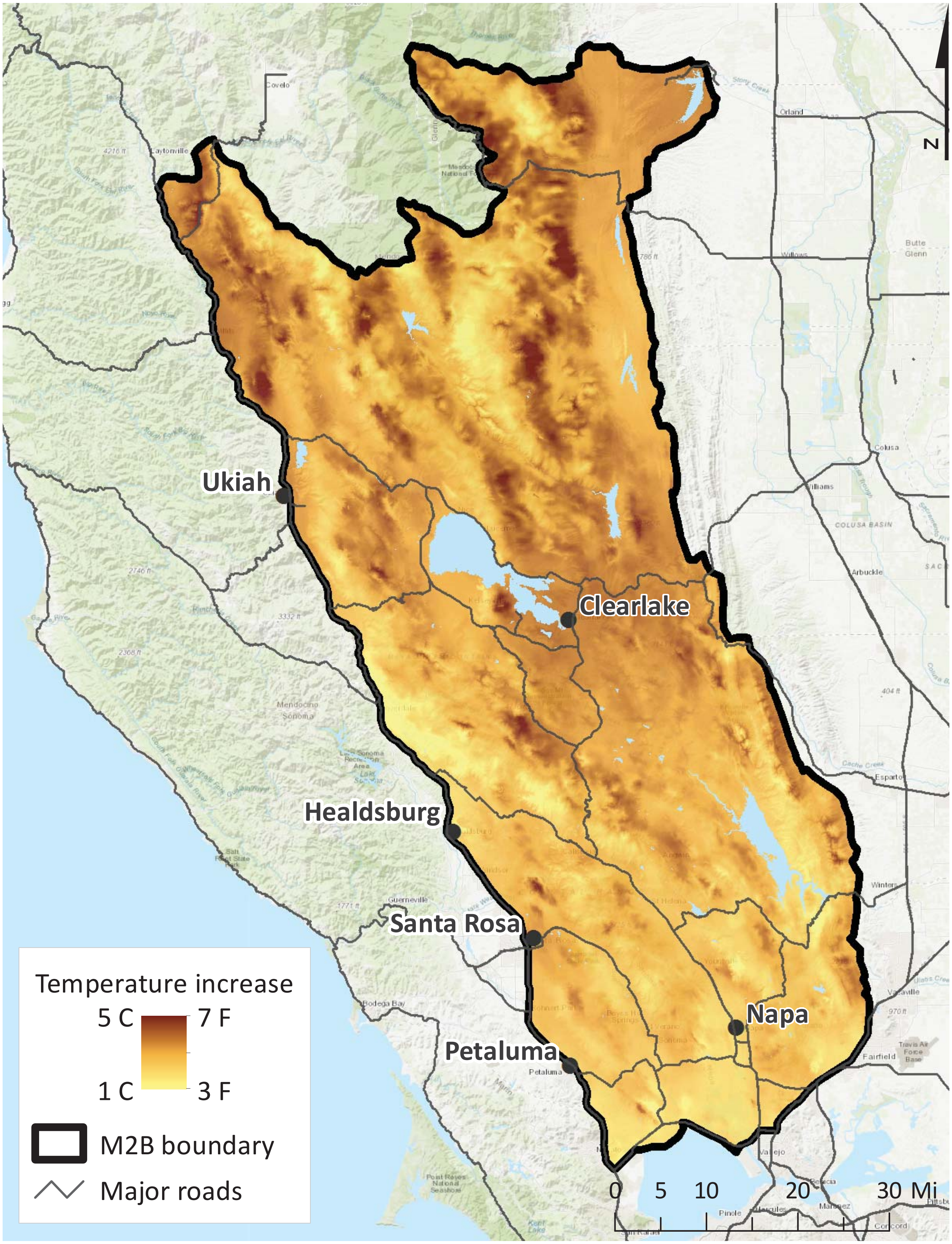


Figure 16. Increase by mid-century – mean winter minimum temperature.

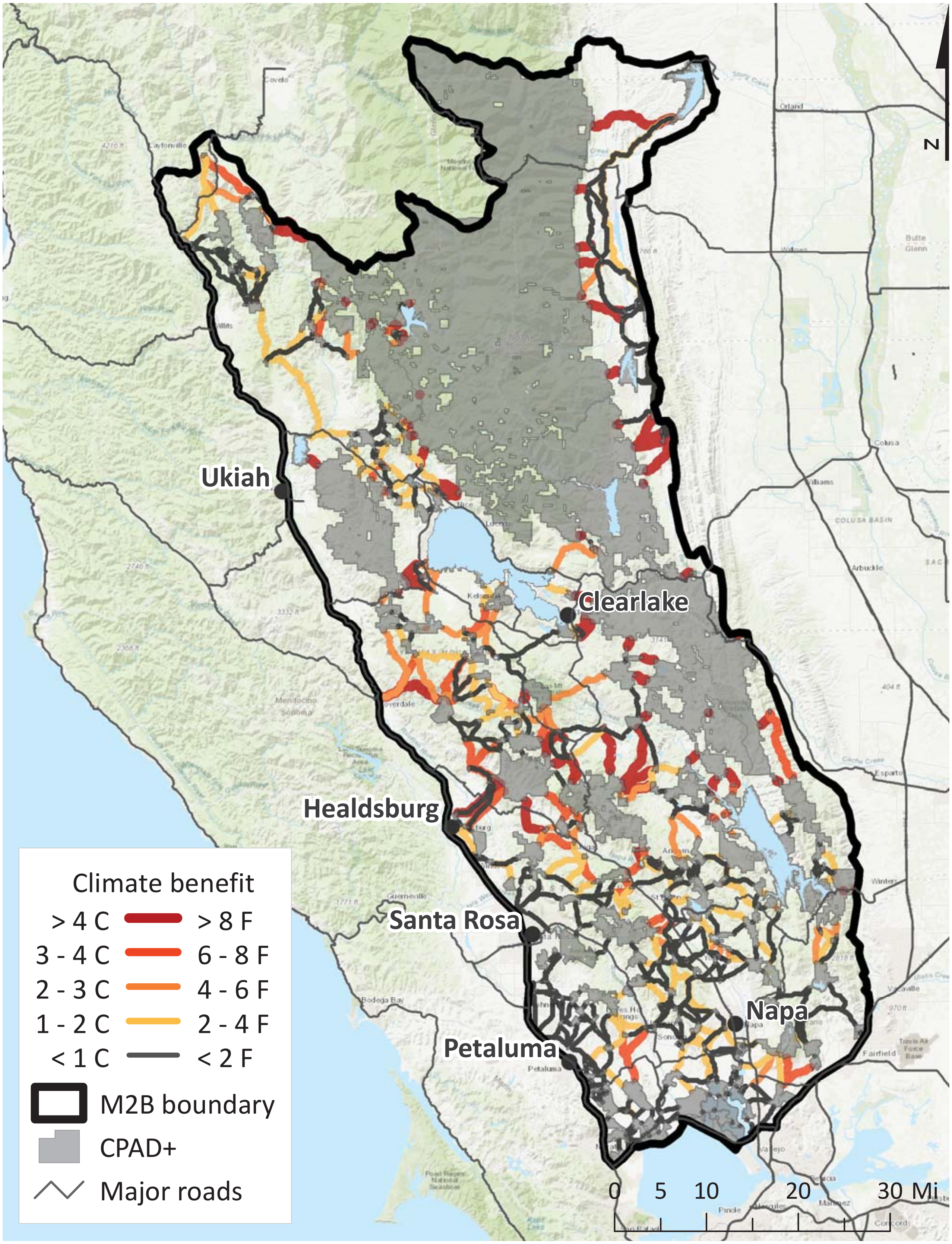


Figure 17. Climate benefit of each structural (terrestrial) LCP by mid-century – mean summer maximum temperature.

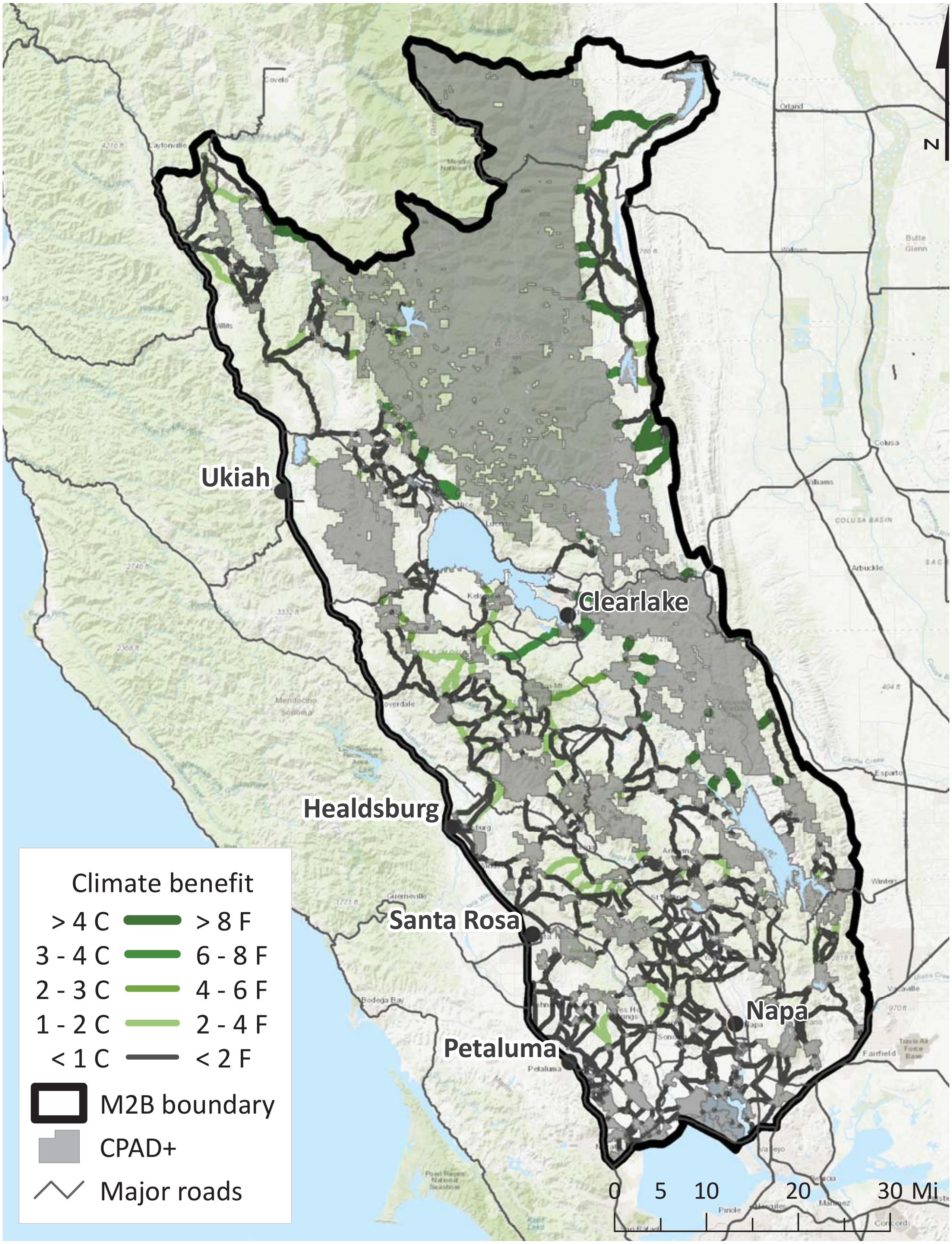


Figure 18. Climate benefit of each structural (terrestrial) LCP by mid-century – mean winter minimum temperature.

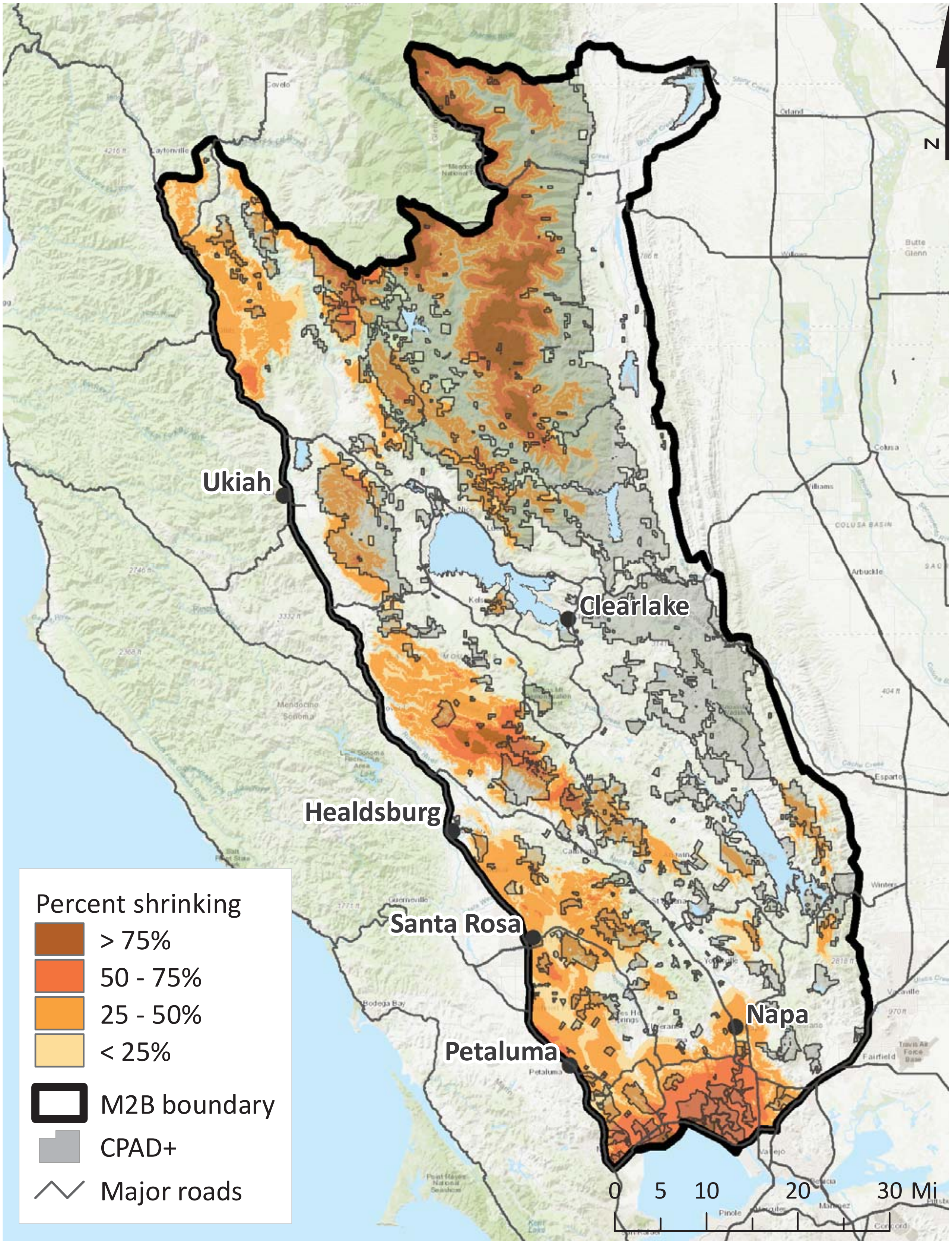


Figure 19. Location and severity of shrinking temperature space by mid-century – mean summer maximum temperature.

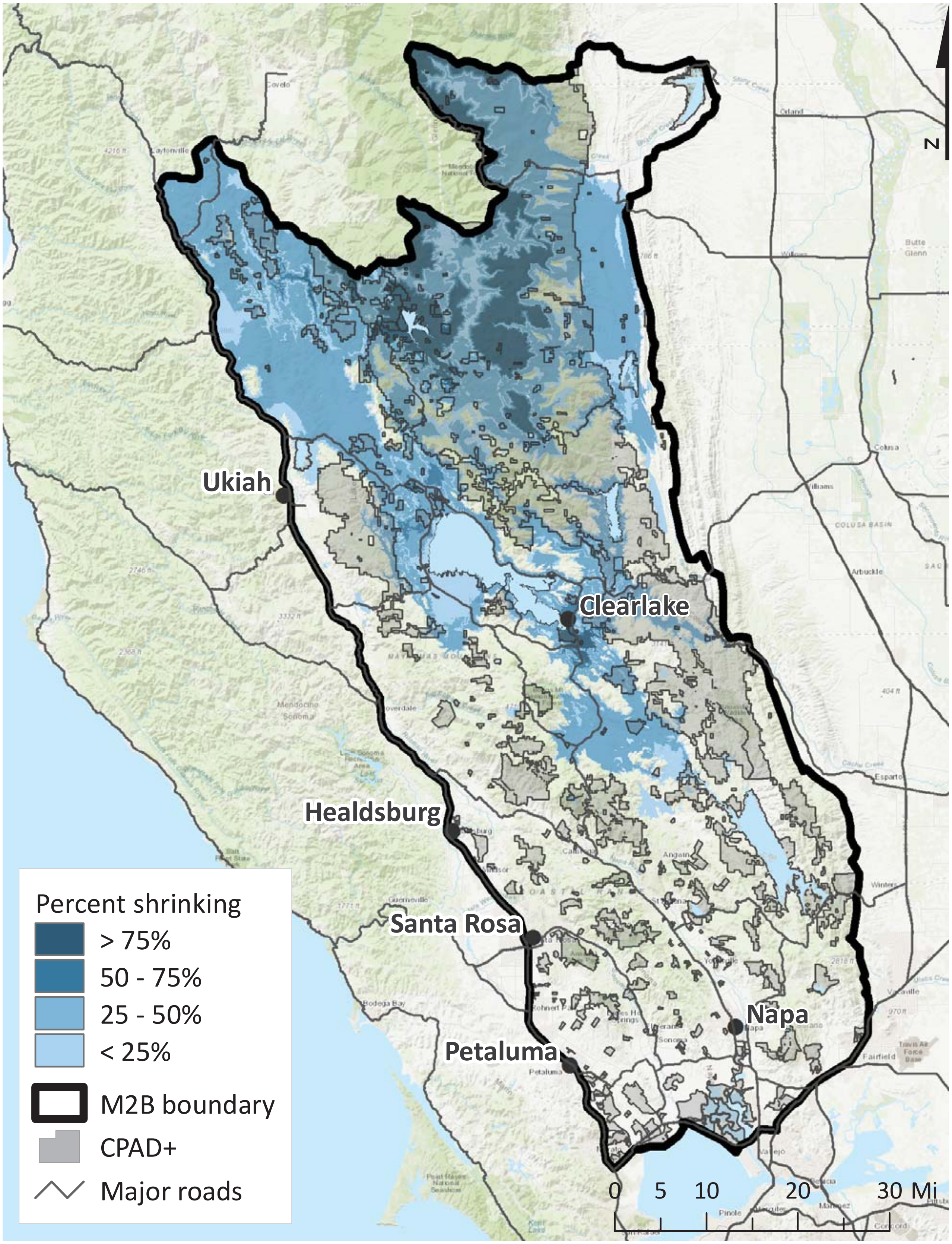


Figure 20. Location and severity of shrinking temperature space by mid-century – mean winter minimum temperature.

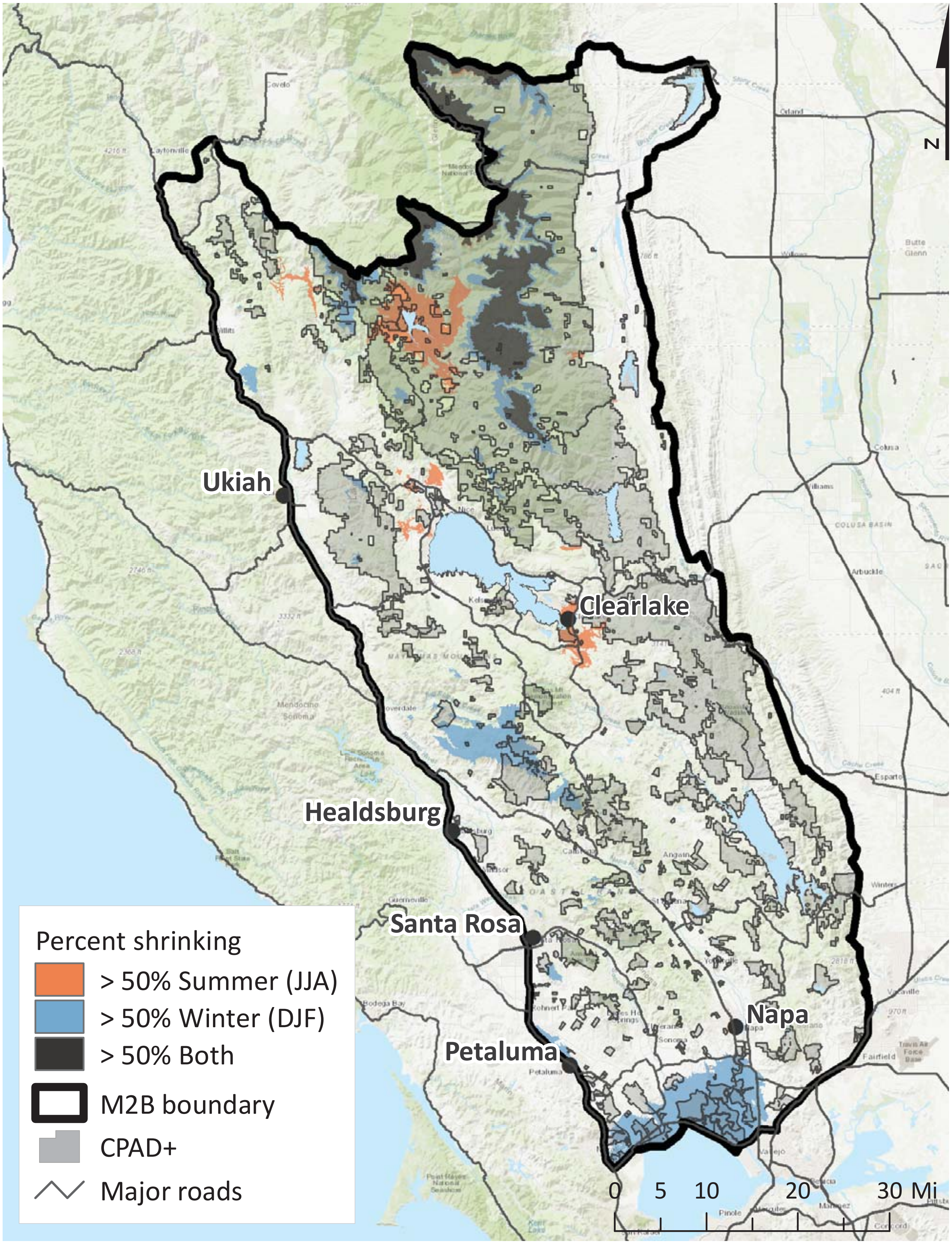


Figure 21. Locations projected to experience greater than 50% shrinking temperature space by mid-century – mean summer maximum temperature, mean winter minimum temperature, and both variables.

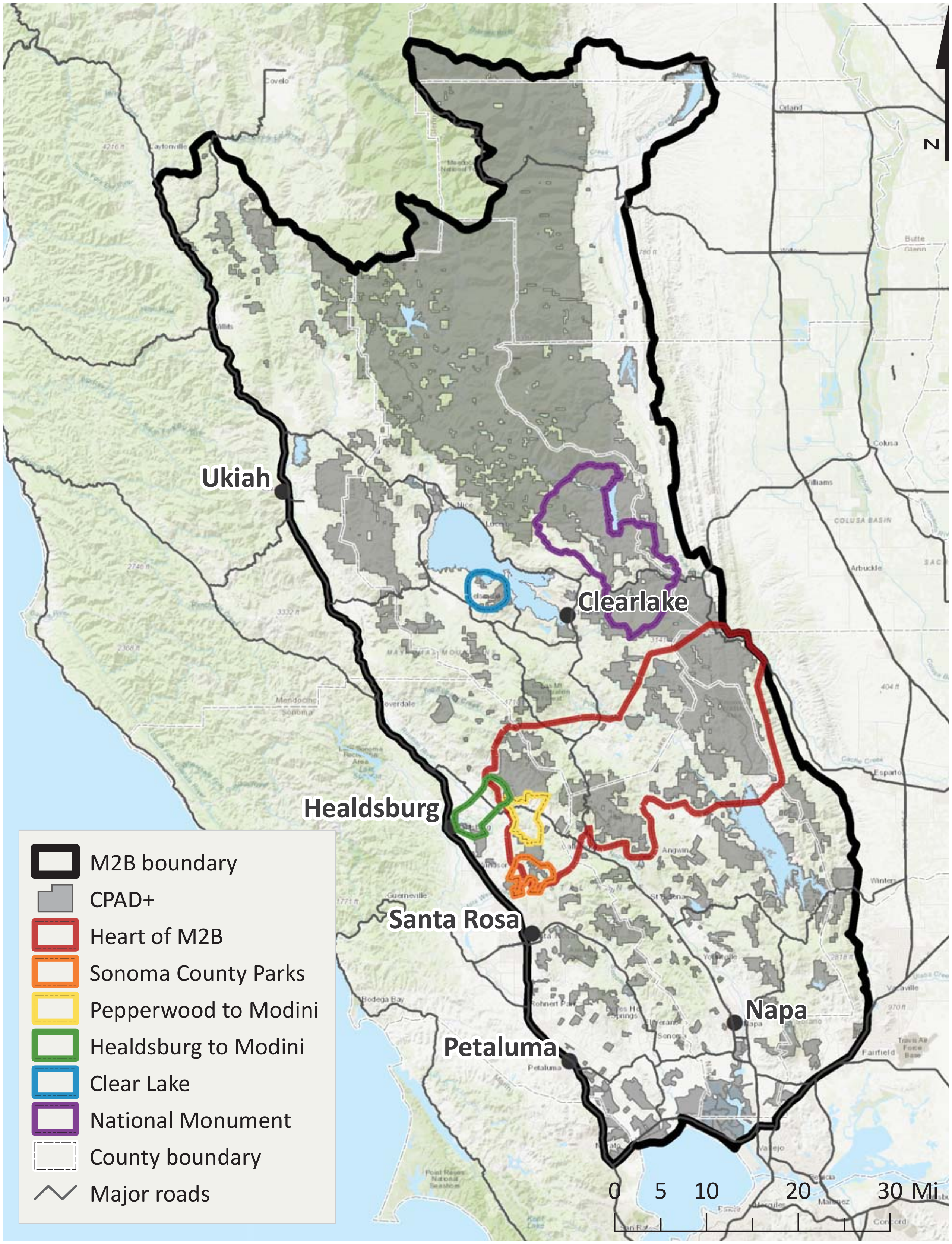


Figure 22. Six regional corridor projects within the M2B study area.

APPENDICES

Appendix 1. Table of routes used to calculate the road effect

We assigned an effect distance to all highways and streets based on their traffic volume (derived from primary/secondary roads, streets, AADT) using the following equation:

$$x_{ED} = 0.0126 w_{TV} + 178.75$$

where w_{TV} is the average traffic volume of the road, and x_{ED} is the road effect-distance (Forman 2000).

Route	**wTV**	**xED**
1	2291.18	207.62
12	28367.86	536.19
16	5256.92	244.99
20	7473.53	272.92
29	21499.55	449.64
37	37107.14	646.30
53	11225.00	320.19
80	136750.00	1901.80
101	72136.00	1087.66
116	12944.17	341.85
121	16592.39	387.81
128	3233.87	219.50
162	532.86	185.46
175	2630.00	211.89
221	24437.50	486.66
222	4400.00	234.19
253	1450.00	197.02
281	3400.00	221.59
505	19350.00	422.56
680	53250.00	849.70
780	47285.71	774.55

Appendix 2. R code to calculate mean parcel size effect

```
### Calculate mean parcel size using 480m radius
### Formatted for R Studio on MacBook Pro
### Author: Morgan Gray
### Date: 6 September 2017

#LOAD LIBRARIES AND SET WORKING DIRECTORY
library(raster)
library(rgdal)
setwd("~/Dropbox/R/M2BS/parcel")

#LOAD AND PREVIEW DATA
parcel <- raster("M2BS10_UTM10_parcel_ras30.tif")
plot(parcel, main = "Parcel values")

#CALCULATE THE MEAN PARCEL SIZE
#GENERATE A MATRIX FOR THE AREA TO BE CALCULATED AROUND EACH PIXEL (HERE USING 17 TO APPROX 500M)
m17 <- matrix(1/289, nrow = 17, ncol = 17)

#CALCULATE THE MEAN PARCEL SIZE USING THE MATRIX
parcel1 <- focal(parcel, w = m17, fun = mean, na.rm = TRUE)

#RASTER MATH FOR MODEL
#CALCULATE THE CUBE ROOT OF MEAN PARCEL SIZE
parcel2 <- (parcel1)^(1/3)

#MULTIPLY THE CUBE ROOT OF MEAN PARCEL SIZE BY 0.0211
parcel3 <- (0.0211)*(parcel2)

#ADD 0.0155 TO THE PRODUCT
parcel4 <- parcel3 + 0.0155

#DETERMINE THE MAXIMUM AND MINIMUM PARCEL EFFECT VALUES
parcel5 <- cellStats(parcel4, max)
parcel6 <- cellStats(parcel4, min)

#NORMALIZE DATA TO SCALE MEAN PARCEL SIZE FROM 0 TO 1
#THIS IS THE FINAL MEAN PARCEL SIZE MODEL
```

```
#(VALUE-MIN)/(MAX-MIN)
yPARCEL <- (parcel4-parcel6)/(parcel5-parcel6)
plot(yPARCEL, main="yPARCEL model (510m)" )

#EXPORT FINAL MODEL BACK INTO GIS
writeRaster(yPARCEL, "yPARCEL_20170912", format = "GTiff")
```

Appendix 3. R code to calculate median patch size effect

```
### Calculate median patch size using 2500m radius
### Formatted for R Studio on MacBook Pro
### Author: Morgan Gray
### Date: 6 September 2017

#LOAD LIBRARIES
library(raster)
library(rgdal)
setwd("~/Dropbox/R/M2BS/patch")

#LOAD RASTER OF PATCH
patch <- raster("patch.tif")

#PLOT THE RASTER TO CONFIRM DATA
plot(patch)

#CALCULATE THE MEDIAN PATCH SIZE
#GENERATE A MATRIX FOR THE AREA TO BE CALCULATED AROUND EACH PIXEL (HERE USING 83 TO APPROX 2500M)
m83 <- matrix(1/6889, nrow = 83, ncol = 83)

#CALCULATE THE MEDIAN PATCH SIZE USING THE MATRIX
patch1 <- focal(patch, w = m83, fun = median, na.rm = TRUE)
#started at 6:17pm

#RASTER MATH TO CALCULATE THE PATCH-BASED HABITAT INTEGRITY METRIC
#SQUARE ROOT OF MEDIAN PATCH SIZE
patch2 <- (patch1)^(1/2)

#MULIPLY THE SQUARE ROOT OF MEDIAN PATCH SIZE BY 0.2356
patch3 <- (0.2356)*(patch2)

#ADD 1.385 TO PRODUCT
patch4 <- patch3 + 1.385
summary(patch4)

#DETERMINE THE MAXIMUM NUMERATOR VALUE
patch5 <- cellStats(patch4, max)
```

```
patch6 <- cellStats(patch4, min)

#NORMALIZE DATA TO SCALE MEDIAN PATCH SIZE EFFECT MODEL FROM 0 TO 1
#THIS IS THE FINAL MEDIAN PATCH SIZE EFFECT MODEL
#(VALUE-MIN)/(MAX-MIN)
yPATCH <- (patch4-patch6)/(patch5-patch6)
plot(yPATCH, main="yPATCH model (2500m)" )

#EXPORT THE FINAL MODEL BACK INTO GIS
writeRaster(yPATCH, "yPATCH_20170912", format = "GTiff")
```