Title

Binational Climate Vulnerability Assessmentfor Cross-Border Adaptation Planning in theSan Diego-Tijuana Region

Author

Rosa, Melissa

Publication Date

2020-06-01

Binational Climate Vulnerability Assessment for Cross-Border Adaptation Planning in the San Diego-Tijuana Region

By Melissa Rosa

Masters of Advanced Studies (MAS) in Climate Science and Policy (CSP)
Scripps Institution of Oceanography
June 2020

Capstone Advisory Committee

Dr. Kyle Haines (Chair) - Lead Field Coordinator, UCSD Center on Global Justice

Signature: KHS

Dr. Fonna Forman - Associate Professor of Political Science and Founding Director of the UCSD Center on Global Justice

Signature:

Dr. Kristen Goodrich - Coastal Training Program Coordinator, Tijuana River National Estuarine Research Reserve

Signature: Kristen Goodrich

Abstract

Climate change is a global concern that requires international strategies for both mitigation and adaptation. Despite sharing a regional ecosystem and economy, the San Diego-Tijuana border region will face the same challenges without a common framework that addresses the collective social and ecological risk posed by climate change. Environmental issues, such as flooding, erosion, and pollution resulting from a long history of rapid urbanization in the region already impact both sides of the border, particularly disadvantaged communities. This project involved a binational climate vulnerability assessment that evaluated ecological and socioeconomic impacts beyond geopolitical boundaries to address the need for binational collaboration and cooperation in climate action planning. Results from the binational climate assessment were used to create a Binational Climate Vulnerability Atlas containing maps and narratives as a visual representation of social-ecological vulnerability and risk in the region.

The binational climate vulnerability assessment is an evolving deliverable and the first iteration of binational maps and data packaged in the context of climate change and in similar terms for San Diego-Tijuana. Information synthesized in the Atlas provides a novel composition of resources available along with recommendations for cross-border climate adaptation planning that can be used to inform policy from a binational perspective in the future. The recommendations focused on several themes, including natural climate solutions, partnerships and collaboration, governance, and science data and sharing. Collectively, this work provides a foundation for a more robust, detailed assessment that would involve cross-border collaboration between planners, resources managers, scientists, and other binational stakeholders.

Keywords: Binational, climate change, social vulnerability, U.S.-Mexico border, social-ecological systems, climate adaptation planning

Introduction

Population growth trends, urban development patterns, and socioeconomic factors are major stressors to climate-related vulnerability. The removal of native vegetation and soil due to urbanization disrupts hydrological patterns within major watersheds and alters ambient air temperature and precipitation patterns, which will influence how climate change affects both human and natural systems (GNEB 2016, Ochoa González & Ojeda-Revah 2017). The impact of these changes can be dire for communities living in dry subtropical regions, such as along the U.S.-Mexico border, where large urban populations are already challenged by water shortages and highly variable precipitation. Since 2007, the greater San Diego-Tijuana area has maintained roughly 5 million people, making it the largest transborder agglomeration shared between the U.S. and Mexico (Saxod et al. 2007). Over 19 million tourists cross the US-Mexican border at Tijuana annually on an average of over 50,000 people daily (González et al. 2012). The "double exposure" of accelerated global economic growth and climate change experienced in the region will only worsen existing environmental problems and expose larger populations to natural hazards, such as flooding and erosion.

Over the last fifty years, the San Diego-Tijuana border has been an area of concentrated population growth at a rate much faster than the national average for the U.S. or Mexico. In San Diego County alone, population growth increased rapidly at rates of 30%-90% in every decade of the 20th century and over 10% in each of the first two decades of the 21st century (CCCA4-SD 2018). This growth has been attributed by some to the Border Industrialization Program in 1965 that ignited the *maquiladora* industry and cheap labor markets, the Mexican economic crisis in the early 1980s, and the signing of the North American Free Trade Agreement (NAFTA) in 1993 (Dedina 1995, Anderson 2003, Kopinak 2003, Ojeda-Revah et al. 2008, Ríos Patrón et al. 2019). In recent years, changing weather patterns have been a major force driving intensifying migration from the Northern Triangle of Central America to the U.S.-Mexico border due to crop failure and malnutrition (Blitzer 2019). These population booms accompanied by rapid urban expansion have contributed to significant environmental hazards and waste on both sides of the border.

Urban expansion is expected to continue along with population growth, however the capacity for climate resilience continues to decline, particularly in disadvantaged communities, which make the border region highly vulnerable to climate variability and acute impacts of climate change. In San Diego County, cities struggle to provide affordable housing and urban areas have expanded far from city centers into wildland areas, degrading natural ecosystems and increasing wildfire risk. In Tijuana, the lack of sufficient government services has resulted in inadequate infrastructure to capture stormwater in areas susceptible to flooding, causing trash and sediment to clog stream channels. Homes are built on high-risk and unstable terrain, such as in river basins or on steep slopes inside canyons, and many buildings do not have proper infrastructure for removing wastewater, so runoff is disposed directly into the ground and weakens the soil. Current U.S. border policies have created a manufactured bottleneck in Tijuana, which allows border agents to only accept around 20 to 60 migrants seeking U.S. asylum per day while thousands are left waiting and more continue to arrive from countries all over the world (Kao and Lu 2019, Herrera 2020). Closing the border to asylum seekers will further contribute to Tijuana's unsustainable population explosion, bearing stress on the city's vulnerable infrastructure and amplifying the social justice implications of climate change.

Observed changes in the Earth's hydrological cycle indicate it is already responding to a warmer climate and shifts in precipitation regimes and climate extremes are expected to occur more frequently. Rainfall and fast-moving pluvial flooding that can develop within hours is an additional emerging challenge to public and health safety, particularly in Tijuana, which will only intensify with climate change (Goodrich et al. 2020). While climate adaptation planning has taken place at various scales, strategies to reduce emissions and adapt to climate impacts often are confined to jurisdictional boundaries. However, urban areas extend beyond political boundaries creating a complex social and ecological system that will face the challenge of climate change collectively. Currently, there is no comprehensive climate change vulnerability assessment that focuses on the San Diego-Tijuana section of the U.S.-Mexico border. Cross-border climate adaptation planning has the potential to address asymmetries in governance and land use planning in order to build resilience on both sides of the border.

Motivation & Objective

The goal of this project is to provide a framework for a binational climate vulnerability assessment in the form of an atlas for the San Diego-Tijuana region that takes into account transborder social-ecological systems. The Binational Climate Vulnerability Atlas is intended to serve as a public resource for policy outreach and climate adaptation planning from a binational perspective to increase cross-border collaboration. To address climate mitigation and adaptation simultaneously, this project provides recommendations for green infrastructure and nature-based climate solutions, such as land conservation and incorporating ecological functions into urban design, which can help restore degraded natural systems and their ability to sequester carbon while increasing urban resilience and environmental sustainability in the region. Outcomes of the project will enhance the availability of resources for policymakers, expose data gaps, and serve as a foundation for impactful future research that incorporates additional indicators of binational climate vulnerability.

Objectives:

1. *Conduct a binational climate vulnerability assessment for San Diego and Tijuana* that considers the region as one social-ecological system.
2. *Create a Binational Climate Vulnerability Atlas* that includes maps and narratives on climate change impacts and risks for public and policy outreach.
3. *Provide climate adaptation recommendations* to support public and policy outreach for cross-border climate adaptation planning in the future, drawing upon local examples from both sides of the border.

The project also explores the following research questions:

- How can the Binational Climate Vulnerability Atlas advance relevant climate solutions described in existing climate vulnerability assessments and climate-related reports?
- What's the relationship between social and ecological vulnerability?
- Where would communities (e.g. urban neighborhoods, micro basins) benefit from green infrastructure and urban tree canopy restoration?
- Which communities will be most negatively affected and in what aspects by current climate change projections?

Methodology and Data

Study Area

For this study, the binational region was defined geographically to include southwest San Diego County, California and northwestern portion of Baja California (Figure 1). This area captures the social and ecological variability of the region to include coastal urban landscapes, inland rural areas as well as wealthy and disadvantaged communities. The region covers the hydrological systems and sub-basins of several major watersheds, including Tijuana River, Otay, Sweetwater, Pueblo San Diego, San Diego River, and Penasquitos. The international border runs through the Tijuana River Watershed, making it a binational watershed that is approximately 1,750 square miles with roughly 75% of the area located in Mexico (Wilder et al. 2013).

The region is characterized by a Mediterranean climate that has highly variable precipitation and seasonality with warm, dry summers and relatively cool, wet winters (Eaton-Gonzalez and Mellink 2015). Total annual precipitation ranges between 5 inches (120 mm) and 35 inches (900 mm) (CCCA4-SD 2018). Temperatures range considerably (8°C to 18°C) between coastal and interior valleys, foothills, and mountains due to ocean cooling and marine fog. During the summer, average daily maximum temperatures are on average 10-20°F warmer inland than at the coast. In the winter, average coastal and inland temperatures are more similar, however there is still significant day-to-day variability.

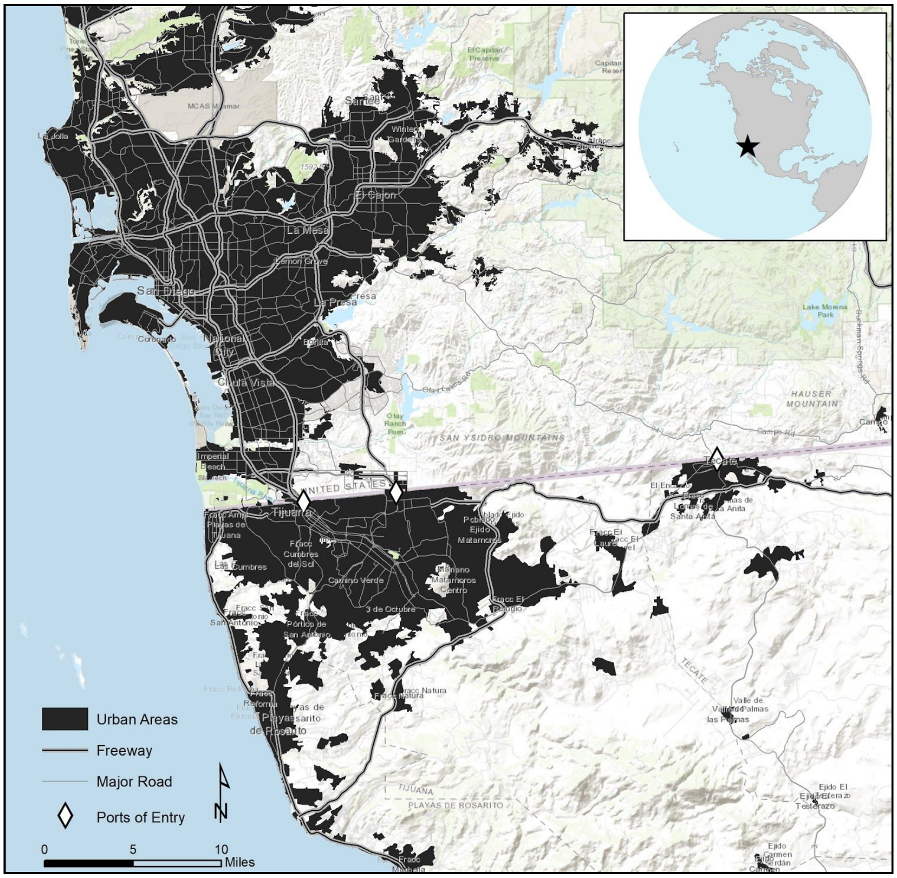

Figure 1: Binational study area of the San Diego-Tijuana region.

San Diego County and northwestern Baja California are within the California Floristic Province, one of the world's biodiversity hotspots. The mediterranean-type ecosystems contain high rates of species richness and diversity among both plants and animals. The dominant vegetation types are chaparral, coastal sage scrub, mixed conifer forest, mountain meadows, grasslands and riparian forest (Figure 2). The study area contains complex topography that spans from low hills to steep slopes with altitude ranges from sea level to almost 2000 m above sea level (Eaton-Gonzalez and Mellink 2015). Northern Baja California and southern California are located in a tectonically active area called the Baja California Shear Zone.

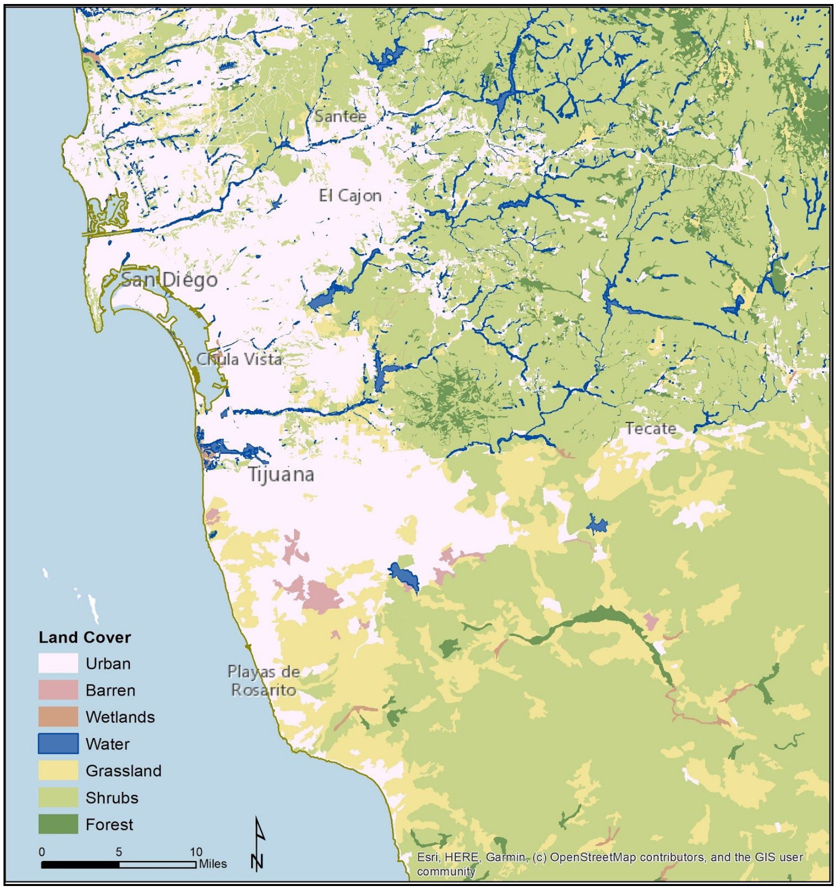

Figure 2: Land cover and dominant vegetation types in the San Diego-Tijuana region[1].

Approach to the Binational Climate Vulnerability Assessment

The binational climate vulnerability assessment for San Diego-Tijuana was conducted by reviewing existing climate change vulnerability assessments at global, regional, and local scales and synthesizing social, structural, ecological, and climate information (Figure 3). Content was primarily derived from the *Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)*, *4th California Climate Change Assessment - San Diego Region Report* (CCCA4-SD 2018), relevant scientific publications, and climate-related documents, including *Bending the Curve (2015)*, a report developed by over 50 researchers from the University of California that outlines ten scalable solutions for carbon neutrality and climate stability[2].

---

[1] 'Water' in San Diego consists of water bodies and riparian corridors based on the classification scheme for SANDAG's vegetation GIS layer.

[2] http://climatechampions.ucop.edu/2016/05/22/bending-the-curve/

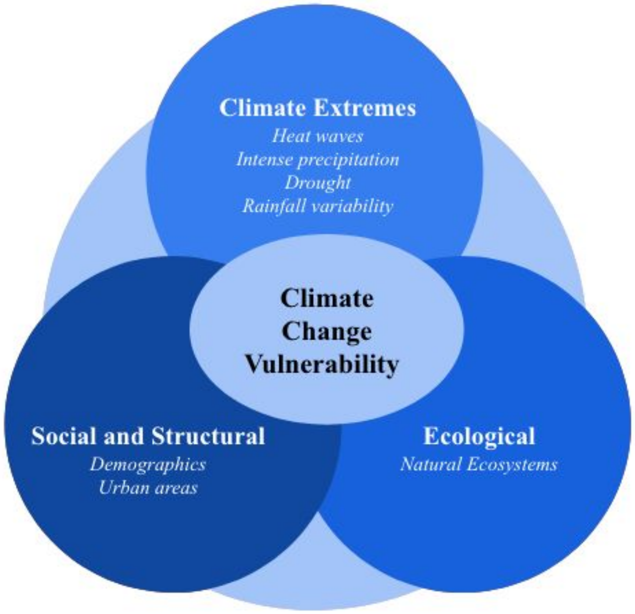

Figure 3: Conceptual integration of social, structural, ecological, and climate systems that served as the framework for the binational climate change vulnerability assessment.

To be consistent with the IPCC framework, this project defines “vulnerability” as an indicator of *sensitivity* (the degree of dependence on resources and activities that are impacted by climate change), *exposure* (the probability of experiencing change), and *adaptive capacity* (demographic, socioeconomic, institutional and technological characteristics that enable an entity to cope or reduce vulnerability) to a climate-related risk (IPCC 2007). Social vulnerability is defined as the “susceptibility of a given population to harm from exposure to a hazard” and is a “function of diverse demographic and socioeconomic factors that influence a community’s sensitivity to climate change” (CCCA4-SD 2018). Structural vulnerability refers to infrastructure within a social system, such as roads, urban areas, and other engineered assets of a community. Vulnerability can also be applied to ecosystems where the adaptive capacity of natural systems influence their ability to provide natural protection from climate change impacts in urban areas (Jennings et al. 2018). The project also refers to scenario-based planning, which is a type of adaptation planning that addresses uncertainty by considering a range of climate projections and scenarios (OPC 2018).

Climate science topics focused on global observed trends and attribution, regional observed trends and model projections, which included temperature, precipitation, and climate extremes (e.g. heat waves, rainfall, drought). Climate impacts reviewed were flooding, erosion, water supply and availability, sea level rise, and wildfire risk. Social, structural and ecological vulnerability were evaluated along with climate solutions and recommendations that were provided by *Bending the Curve (2015)* and the *4th California Climate Change Assessment - San Diego Region Report (2018)*.

Spatial Data Sources

To create the Binational Climate Vulnerability Atlas that accompanied the assessment, geospatial and other ancillary GIS datasets from various sources were acquired for the San Diego and Tijuana region. Datasets included demographic, ecological, and climate information to characterize the region into similar units to assess key variables of climate vulnerability and risk as one social-ecological system rather than separate jurisdictions, municipalities, or countries (Table 1). Once these datasets were gathered, they were converted to the same mapping unit and coordinate system/projection.

Table 1: Compilation of GIS data and sources for the San Diego - Tijuana region.

Climate Trends/Projections	**GIS Data Source**	
Precipitation (Wettest Days)	4th California Climate Assessment	
Temperature (Hottest Days)	4th California Climate Assessment	
Climate Impacts	**U.S. GIS Data Source**	**Mexico GIS Data Source**
Sea Level Rise	NOAA Office for Coastal Management (OCM)[3]	MarFishEco[4]
Wildfire (Burned Areas)	San Diego Association of Governments (SANDAG)	The National Commission for the Knowledge and Use of Biodiversity (CONABIO)
Flooding	FloodRISE[5] (Tijuana River Valley and Los Laureles Canyon sites only)	FloodRISE (Tijuana River Valley and Los Laureles Canyon sites only)
Social and Structural	**U.S. GIS Data Source**	**Mexico GIS Data Source**
Demographics	U.S. Census[6]	Instituto Municipal de Planeación (IMPLAN)
Roads	SANDAG	Instituto Nacional de Estadística y Geografía (INEGI)
Urban extent and expansion	NOAA CCAP[7] and USGS[8]	UN-HABITAT[9]
Biophysical	**U.S. GIS Data Source**	**Mexico GIS Data Source**
Elevation (DEM)	SANDAG	SANDAG
Watersheds	SANDAG	SANDAG
Hydrology (Rivers, Water Bodies)	SANDAG	INEGI
Vegetation	SANDAG	INEGI

---

[3] https://coast.noaa.gov/digitalcoast/data/slr.html

[4] Sea level rise inundation GIS layers for northern Baja California were created by MarFishEco using NOAA's methodology at 1-foot increments up to 7 feet. This ensured the sea level rise inundation spatial datasets for northern Baja California are comparable to sea level rise GIS layers made available by NOAA for San Diego County.

[5] http://floodrise.uci.edu/

[6] https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-data.2010.html

[7] https://coast.noaa.gov/digitalcoast/data/ccapregional.html

[8] https://www.sciencebase.gov/catalog/item/59ee2ea2e4b0220bbd975a5e

[9] http://www.atlasofurbanexpansion.org/cities/view/Tijuana

Binational Social Vulnerability Index

To examine the geographic variation in social vulnerability, a binational social vulnerability index (BSVI) was created as a comparative metric using census tract databases for the U.S. and Mexico. A geodatabase of TIGER/Line shapefiles for U.S. Census tracts and a subset of detailed tables for five years (2006-2010) of the U.S. Census's American Community Survey (ACS) data was cross referenced with Mexico INEGI's census urban and rural databases to harmonize socioeconomic and demographic information across the region. Socioeconomic and demographic variable selection was based on variables included the 2006-2010 Social Vulnerability Index (SoVI) developed by the Hazards and Vulnerability Research Institute at the University of South Carolina[10]. SoVI measures the social vulnerability of U.S. counties to environmental hazards and synthesizes 27 socioeconomic variables that literature suggests contribute to reduction in a community's ability to prepare for, respond to, and recover from hazards (Cutter et al. 2003). Table 2 contains a list of the 12 out of possible 27 SoVI variables that both censuses shared and were used in the BSVI calculation.

In order to calculate the BSVI, socioeconomic variables were individually ranked and combined following the methodology described in Arkema et al. 2013. First, each variable was ranked 1 to 5 where 1=lowest and 5=high vulnerability. Then, the 12 variable ranks were averaged across seven factors (or categories) by calculating the mean of variable ranks for each factor (Table 2). Some census tracts in Mexico contained an insufficient amount of data, so tracts that had less than four variables were not considered in the index. This resulted in 10 tracts omitted out of ~1300 total. Lastly, all variables were weighted equally and the geometric mean was calculated by multiplying across factor ranks, then divided by the nth root (or number of factors considered for each census tract).

$$\mathrm{BSVI} = (R_{\mathrm{Poverty}} R_{\mathrm{Wealth}}\ R_{\mathrm{Households}}\ R_{\mathrm{Age}}\ R_{\mathrm{ForeignBorn}}\ R_{\mathrm{Education}}\ R_{\mathrm{Employment}}\ )_{1/7}$$

---

[10] http://artsandsciences.sc.edu/geog/hvri/sovi%C2%AE-0

Table 2: Demographic and socioeconomic variables and factors that were included in the BSVI.

Factor	Mexico 2010 Census	U.S. 2010 Census/ACS
Poverty	Marginality score (1-5)	% Poverty
Wealth	% Households a car	% Households without a vehicle
	% Without piped water	% Lack complete plumbing facilities
Households	Average household size	Average household size
	Percent female head of household	Percent female head of household
Age	% Population over age 65	% Population over age 65
	% Population older than 5	% Population under age 5
Foreign Born	% Born in other country	% Foreign born
Education	% Population 15+ with incomplete basic education	% High school graduate
Employment	% Active in labor force	% Population in labor force
	% Women active in labor force	% Females in labor force
	% Unemployed	% Unemployed

Social Vulnerability and Natural Land Cover

This project looks at the relationship between green space and social vulnerability at the census tract scale because of the multiple benefits that green spaces provide in the process of climate adaptation. In San Diego County, many sustainability and climate actions plans include initiatives to increase urban tree canopy and green space as a strategy to improve public health and reduce risk of climate impacts such as flooding and heat waves. Green space is often measured by “greenness”, which accounts for natural land cover at various scales, from private yards to large national parks, and is an indicator of vulnerability that does not rely on juristical boundaries or proprietary access because it can be acquired from remotely sensed data.

Vegetation greenness was derived from the U.S. Geological Survey (USGS) Normalized Difference Vegetation Index (NDVI) and accessed from ClimateEngine[11] for the 2019 wet season. NDVI is the most widely used proxy for greenness in land management (e.g. drought impact monitoring, assessing land degradation, crop yield estimation and prediction) because it represents photosynthetic activity across the landscape (Ruiz-Gibert et al. 2019). Sparse vegetation such as shrubs and grasslands may result in moderate NDVI values (approximately 0.2–0.5), areas of barren rock, sand, or snow usually show very low NDVI values (e.g. 0.1 or less), and high NDVI values (approximately 0.6–0.9) correspond to dense vegetation such as that found in temperate and tropical forests or crops at their peak growth stage (USGS 2020).

---

[11] http://climateengine.org/

Green space was defined as having a NDVI value of 0.2 or higher, as recommended by USGS[12]. NDVI rasters were reclassified so each pixel had a binary value of 1 if green (greater than or equal to 0.2 raw NDVI score) or 0 if not green (less than 0.2 raw NDVI score). The NDVI binary raster was then used to calculate the percentage of greenness in each census tract. Bivariate choropleth maps (i.e. maps that depict two variables at once) were created to compare BSVI and NDVI to one another as an indicator of social-ecological vulnerability. This provided a visual tool that illuminates areas where high social vulnerability and low vegetation cover intersects, which can help prioritize climate action and aid policy decisions around green infrastructure.

Results

Global Climate Trends, Attribution, and Projections

From 1951-2010, contributions from natural forcings, internal variability, and anthropogenic forcings together are consistent with the observed global warming of approximately 0.6°C to 0.7°C, therefore it is likely that anthropogenic influences have affected the Earth's climate (Rhein et al. 2013). It is also likely that changes in large-scale circulation patterns have influenced climate extremes globally (Hartmann et al. 2013). While global observations show an increase in heavy precipitation, which is an expected response to anthropogenic forcing, a direct cause-and-effect relationship in hydrologic variables is challenging (Stott et al. 2010, Bindoff et al. 2013). Uncertainties in observational data and climate models limit confidence in the attribution of precipitation changes. Newer models with improved simulations of natural variability provide stronger detection and attribution at the global scale, but remain difficult to produce at the local level (Bindoff et al. 2013). Still, there have been more statistically significant increases than decreases in extreme precipitation events with satellite measurements showing an increase in frequency of heavy rainfall during warmer El Niño years (Hartmann et al. 2013). It is not possible to attribute changes in drought, flood, and extratropical cyclones frequency to anthropogenic climate change because there is not enough evidence to support trend detection and other mechanisms due to lack of direct observations, geographical inconsistencies, and discrepancies in "extreme" definitions (Hartmann et al. 2013). In western North America, recent droughts have not been definitively shown to fall outside of the range of natural precipitation variability (Cayan et al. 2010, Seager and Vecchi 2010). Human activity has altered many watersheds, making climate attribution of changes observed in streamflow difficult.

Climate modeling reported in IPCC AR5 refers to Atmosphere–Ocean General Circulation Models (AOGCMs) and Earth System Models (ESMs) participating in Coupled Model Intercomparison Project Phase 3 (CMIP3) and Phase 5 (CMIP5) (Flato et al. 2013). Near-term projected changes for the global water cycle (2016–2035, relative to 1986–2005) indicate the contrast between seasonal mean precipitation in wet and dry regions will increase (Figure 2). Soil moisture and relative humidity are projected to decrease while specific humidity is shown to increase in southwest North America, suggesting overall moisture loss that could generate drier

---

[12] https://www.usgs.gov/land-resources/eros/phenology/science/ndvi-foundation-remote-sensing-phenology?qt-science_center_objects=0#qt-science_center_objects

conditions and exacerbate future droughts. Wilder et al. (2013) projected moisture deficit to increase across California and top level soil moisture to decrease, particularly in southern California. Climate models show the magnitude of these projected changes will be small compared to internal variability; however, regional mean precipitation in the subtropics is likely to decrease due to anthropogenic aerosol emissions and natural variability (Kirtman et al. 2013). Considering the projected increase in atmospheric moisture content, El Niño–Southern Oscillation (ENSO)-related precipitation events will likely intensify on regional scales, but large natural variations in the magnitude and spatial patterns of ENSO events yield low confidence (Kirtman et al. 2013).

Long-term projected changes for the global water cycle (2100 and beyond, relative to 1986–2005) show high confidence in the increasing contrast between seasonal mean precipitation between dry and wet regions (Collins et al. 2013). This contrast is due to wet regions bringing moisture from dry regions, which will be accelerated by a warmer climate. Furthermore, well-mixed greenhouse gas concentrations that tend to reduce troposphere cooling coupled with non-uniform surface warming will impact atmospheric overturning circulation and precipitation trends (Takahashi 2009). As a result, the subtropics could experience up to 30% decrease rainfall, increasing the aridity of dry areas and expanding desert regions. CMIP3 and CMIP5 models show ‘extreme’ drought becoming a normal climatological condition in semi-arid regions of the mid-latitudes and subtropics, such as the Mediterranean and southwest U.S. (Collins et al. 2013). Under the RCP8.5 scenario, there is medium confidence that an increase in drought frequency by 2100 due to anthropogenic climate change will be larger than natural variability associated with ENSO and other climate modes in southwestern North America.

Regional Climate Variability and Change - San Diego/Tijuana Border

The San Diego-Tijuana border is an arid region with significant interannual and multidecadal variability that already challenges water management and planning. Streamflow in major rivers has dwindled, unprecedented “mega-droughts” have occured, and extreme storm events that cause flooding in the Tijuana River Watershed impact both Tijuana and San Diego (Nakaegawa et al. 2013, Pierce et al. 2018). In the coming decades, San Diego County and northern Baja California will very likely endure substantial increases in temperature, sea level rise, greater precipitation variability and increasing dryness, and heightened wildfire risk (CCCA4-SD 2018).

This binational climate vulnerability assessment primarily focused on mid-century (2040-2069) projections and considered the Representative Concentration Pathway (RCP) 8.5, a business as usual future scenario. Many decision-makers in urban planning do not look beyond mid-century and the RCP 4.5 and 8.5 scenarios are relatively similar through the middle of the century. Climate projections described in this section are based on regional projections from the *4th California Climate Change Assessment - San Diego Region Report*, which were derived from global climate models (GCMs) that have been downscaled using the Localized Constructed Analogs (LOCA) statistical downscaling method (Pierce et al. 2014). Since most GCM outputs are coarse, typically 60-120 mi (100-200 km) grid cells, the “downscaling” technique offers a better way to represent detailed variability of an area in order to make results compatible with regional planning and decision-making. These projections have also been “bias corrected” to consider how different methods alter the climate change signal of the GCM (Pierce et al. 2014).

Temperature

In the San Diego-Tijuana border region, average annual temperatures are projected to increase by 5˚F to 10˚F by the end of the 21st century. The spatial pattern of temperature change varies throughout the region, with the coastal zone projected to experience less warming due to the cooling effect of marine layer clouds as compared to inland areas, although the sensitivity of coastal clouds to climate change is uncertain at present (CCCA4-SD 2018). Background warming due to the anticipated increase in average annual temperature is expected to increase the intensity and frequency of temperature extremes with the number of heat wave days projected to increase between 20-50% under a 6˚F temperature increase (CCCA4-SD 2018). Historically, the average hottest day per year was in the range of 90-100˚F (32-38˚C) at the coast, but by mid-century under RCP 8.5, the average hottest day per year is projected to increase to 96-115˚F (36-46˚C) in the border region. Figure 4 shows the spatial distribution of projections for the average hottest day per year during 2040-2060 under the RCP 8.5 scenario. Temperatures are noticeably higher in Tijuana (> 100 ˚F) as compared to San Diego, which may be due to relative land cover or the higher heat capacity of the San Diego Bay. Heat waves in the region have become more humid as well, which can exacerbate health impacts of heat. In California, the strongest health impacts from recent heat waves have been found at the coast, where residents are used to relatively mild temperatures and are not acclimated to heat (Gershunov et al. 2011). Increased heat waves will also worsen urban heat island effects, air pollution, and energy demand for air conditioning (Revi et al. 2014).

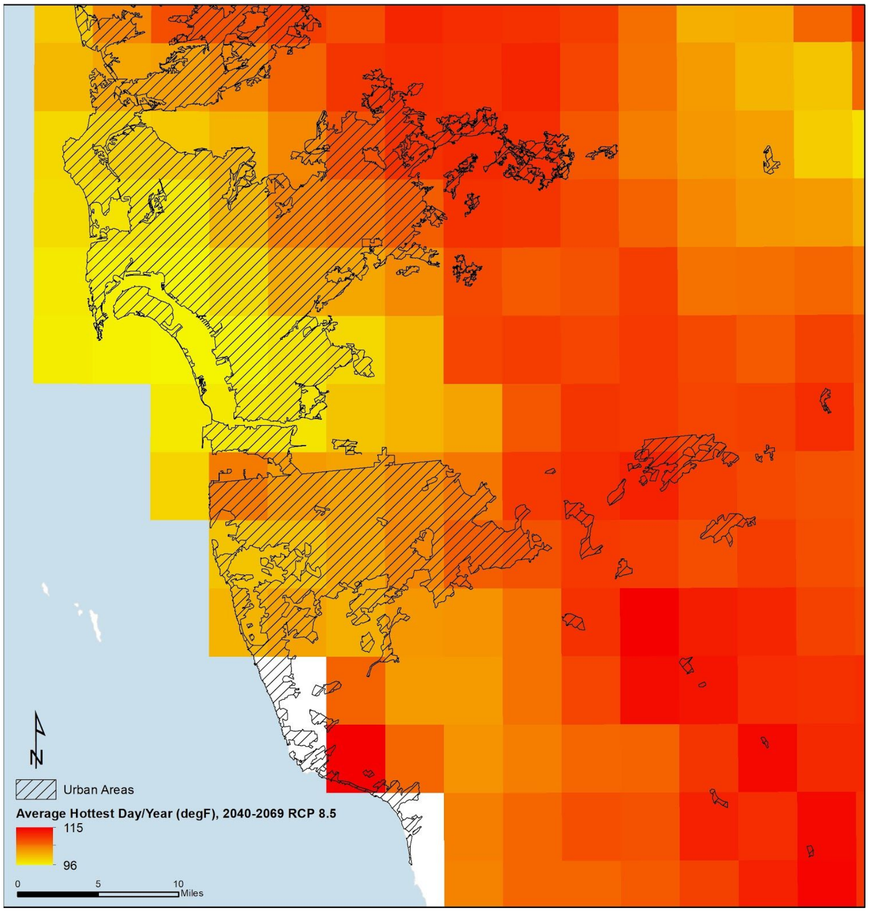

Figure 4: Average hottest day/year (˚F) for mid-century (2040-2069), RCP 8.5 scenario (Pierce et al. 2018)

Precipitation

The inter-annual and multi-decadal variability in precipitation in the San Diego-Tijuana region is often associated with ENSO, which has driven droughts and floods in the past, challenging water management and hydrological planning. Long-term changes in annual total precipitation are still uncertain (CCCA4-SD 2018), but Mexican scientists have shown high confidence through downscaled climate models under RCP 8.5 scenarios in annual precipitation decreases of more than 20% by mid-century in the border region (Wilder et al. 2013). As the climate warms, models show precipitation patterns will shift to wetter winters and drier springs (Pierce et al. 2018). The decrease in spring precipitation will lengthen the driest season (summer) and expose areas already prone to low precipitation to more consecutive dry days[13].

Despite climate models showing fewer wet days, they indicate that precipitation volatility will intensify in the future as the climate continues to warm (CCCA4-SD 2018). Daily extreme precipitation values are projected to increase up to 20% under RCP 8.5, which will subsequently

---

[13] CMIP5 projects a decrease in winter precipitation over the southwestern U.S. and Mexico due to Hadley Cell expansion and poleward shift of storm tracks, extending subtropical arid regions (Seager and Vecchi 2010).

increase flooding due to dry soils unable to quickly absorb floodwaters (Pierce et al. 2018). By mid-century, the average wettest day every year, which indicates an extreme precipitation event, is projected to increase by up to 23% under RCP 8.5. Figure 5 indicates that projections show urban areas will experience a lower increase (< 20%) compared to rural areas, which highlights the influence land cover has on precipitation.

CMIP5 projections show anthropogenic effects on thermodynamic moistening and orographic uplift will increase extreme precipitation events related to atmospheric rivers (ARs). These "rivers in the sky" are elongated, horizontal warm conveyor belts of tropical moisture that account for over 90% of the poleward water vapor transport across the mid-latitudes (Espinoza et al. 2018). Along the West Coast, ARs can produce more than 50% of total annual precipitation and are often associated with flooding and landslides (Gershunov et al. 2019). CMIP5 historical simulations and future projections indicate ~10% less ARs in the future, but ~50% increase in the frequency of ~25% longer and wider ARs under RCP8.5 (Espinoza et al. 2018). The greatest increases (>20%) are projected for southern California and Northern Baja California, emphasizing ARs crucial role in future changes to water resources in this region (Gershunov et al. 2019).

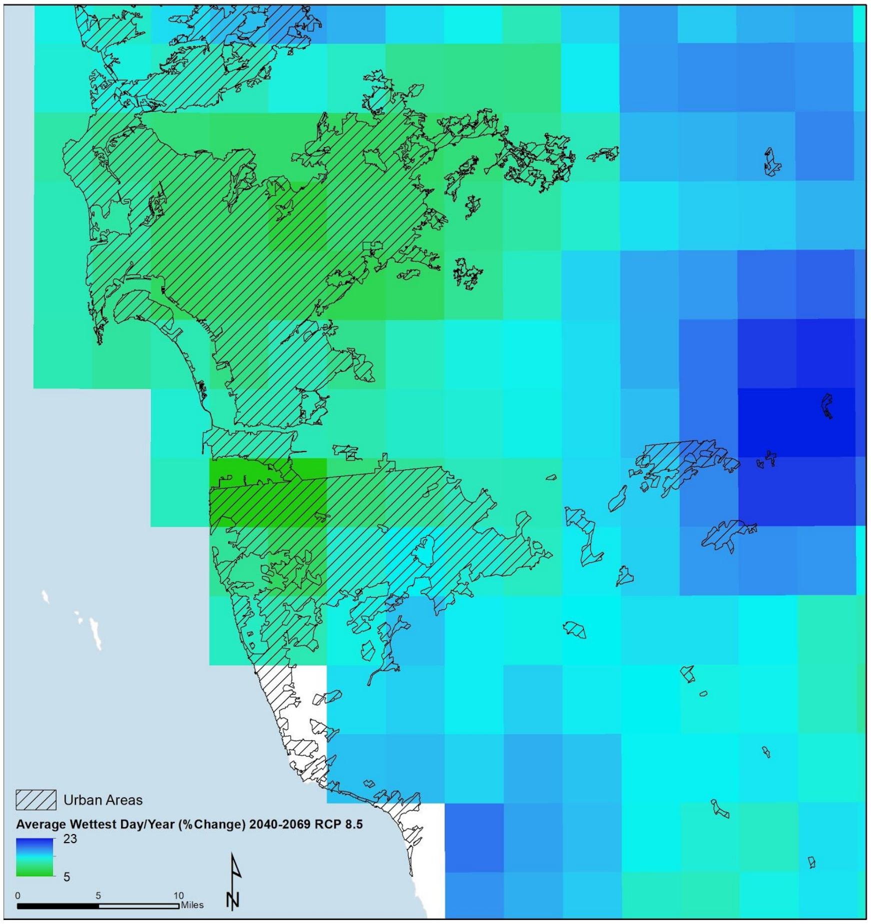

Figure 5: Average wettest day/year (% change) for mid-century (2040-2069), RCP 8.5 scenario (Pierce et al. 2018).

Extreme Drought and Rainfall Variability

The unusually wet years of 2005, 2011, and 2017 and the droughts of 2001-2004, 2007-2010 and 2012-2015 exemplify the highly variable climate of the region (CCCA4-SD 2018). For instance, the stark contrast between the 2011 wet year and 2014 dry year across the region caused large areas, particularly in northern Baja California, Mexico, to experience significant shifts in precipitation amounts from around 50mm above average to 100mm below average within several years. Over the past ten years, there has been an increase in extreme dry years and decrease in extreme wet years indicating an overall heightened trend of drying in the region. Downscaled climate model projections show droughts becoming more frequent and intense, which will likely be amplified by higher temperatures (Wilder et al. 2010). La Niña periods are also projected to become warmer and drier in the future (Romero-Lankao et al. 2014, Wang et al. 2018). Extended meteorological droughts tend to cause hydrological droughts. Model projections indicate decreasing streamflow for transboundary rivers, including the Colorado River and Rio Grande, which are expected to experience lower flow extremes during drought (Wang et al. 2018).

Droughts can impact urban areas through water or electricity shortages, water-related diseases, and food insecurity or inflated food prices. These may contribute to negative economic impacts and increased rural to urban migration (Farley et al. 2011). The 2014–2015 drought was the most intense and severe that California had faced since 1895, reducing surface water availability, increasing groundwater extraction, and costing a total statewide economic loss of $2.7 billion (Ruiz-Gibert et al. 2019). In Mexico, drought impacts both small and large scale agriculture, which are main sources of employment and income. From 2011-2012, Mexico experienced its most severe drought in 70 years that caused economic losses in the agricultural sector to exceed $1.2 billions (Neri and Magaña 2016).

Social and Structural Vulnerability

Many residents within border communities live in low-income areas with substandard housing that are commonly located in environmentally hazardous areas (GNEB 2016). Urban areas have also expanded into hazard prone regions that are particularly susceptible to climate risks, such as drought, heat waves, wildfires, and floods. Certain characteristics of the built environment can amplify these risks at the site-level, which are often correlated with neighborhood socioeconomic characteristics.

Binational Social Vulnerability Index (BSVI)

When visually comparing the U.S. side of the BSVI to existing indices, such as SoVI[14] and the Center for Disease Control (CDC) Social Vulnerability Index (SVI)[15], overall spatial patterns of census tracts with low and high vulnerability are mostly similar (Figure 6). However, discrepancies between the BSVI and these indices are present, such as areas east of La Jolla and I-5 (e.g. Sorrento Valley, Mira Mesa, Kerney Mesa) and parts of Chula Vista just south of

---

[14] Social Vulnerability Index for the United States - 2010-2014

[15] https://svi.cdc.gov/

downtown San Diego. The BSVI results[16] generally align with known socioeconomic characteristics of the region and highlight the different development patterns of urban areas in each country (Figure 7). In San Diego, the downtown center and affluent coastal neighborhoods, such as Coronado and La Jolla, indicate low vulnerability while El Cajon, areas south of downtown, and cities extending southward towards the border show high vulnerability. In developing countries, the "inner ring" is typically the hub of the city that consists of a more wealthy population, which are usually less vulnerable and captured by the BSVI. However, BSVI results for areas in southeast Tijuana are not consistent with known characteristics of those neighborhoods. The BSVI shows medium vulnerability, but these census tracts consist of poor, disadvantaged communities that are relatively young and live in substandard housing. Variables such as households with dirt floors and households unconnected to sewer were not included because either they were not available in the U.S. census or it did not make sense to include for the U.S. because these basic services are often available despite socioeconomic class. This underscores the challenge of combining census surveys for two countries with different definitions of vulnerability or poverty and suggests the BSVI calculation requires further refinement and consultation, which is elaborated on in the *Research Gaps and Uncertainties* and *Discussion* sections.

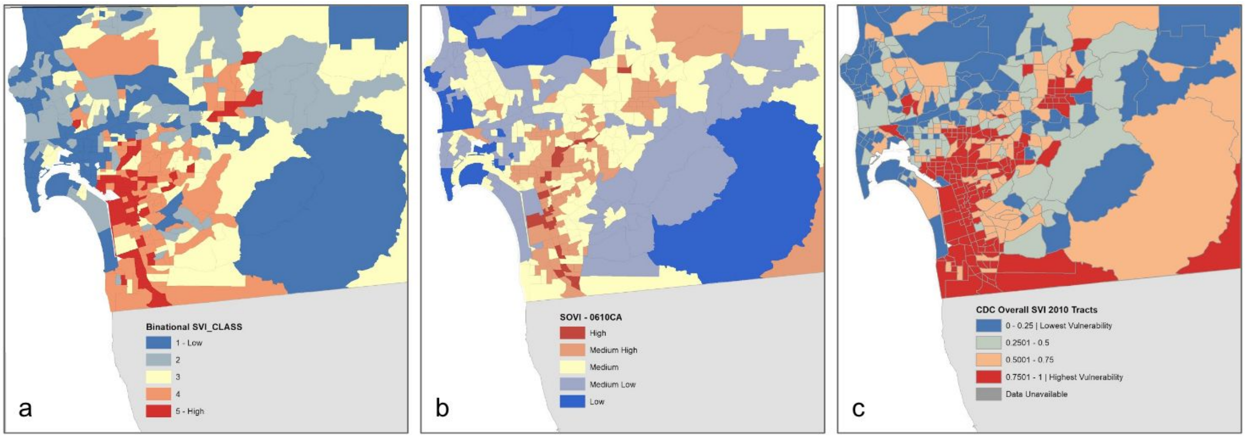

Figure 6: Comparison of social vulnerability indices: a) binational social vulnerability index, b) SoVI, and c) CDC's SVI. All are calculated using 2010 U.S. Census data.

---

[16] The BSVI was originally calculated from one table that contained both the U.S. and Mexico census data, however results showed a significant amount of high vulnerability in San Diego as compared to existing U.S. indices. Therefore, the BSVI was calculated for each country separately, then joined into one final table and shapefile.

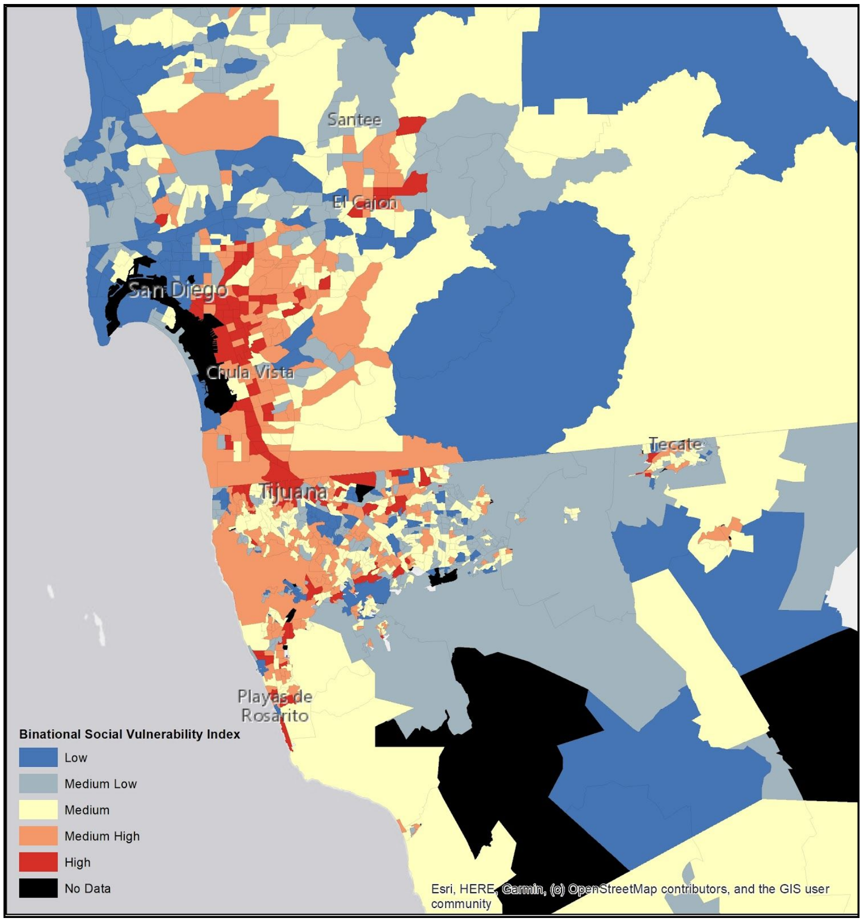

Figure 7: Binational Social Vulnerability Index based on 2010 U.S. Census and Mexico Census data.

Ecological Vulnerability

Ecological systems are mainly threatened by changes in land use and vegetation cover due to urbanization and climate change. Urban expansion significantly reduces the amount of ecologically intact land and increases habitat fragmentation, which further increases the likelihood of environmental degradation and threatens the high diversity of communities and endemic species. Endangered species habitat, wetlands and other natural ecosystems in the San Diego-Tijuana region are sensitive to climate change variables, including temperature, precipitation, and wildfire. For instance, changes in temperature impact species distribution alter the timing of ecological phenomena, such as flowering (Jennings et al. 2018). Drought and extreme temperatures can lead to widespread forest-mortality (Romero-Lankao et al. 2014). These disturbances could have impacts on ecosystem structure and function, wildfire risk, bark beetle infestation, and forest carbon storage. In coastal ecosystems and wetlands, tidal dynamics and river flow play a primary role in shaping the landscape, so sea level rise, shifting precipitation patterns, and drought will likely alter these ecosystems as a result of climate change as well (TRNERR 2017).

Natural resources are particularly vulnerable along the San Diego-Tijuana border because the regional planning process stops at the border of each county and binational conservation and shared resources are rarely given consideration. The international border also acts as a physical barrier that blocks the movement of wildlife east of Tijuana and disrupts ecological processes, including fire, hydrological flow, soil erosion and deposition, species population dynamics, and species interactions (Jennings et al. 2018). Climate change-driven movement, such as range shifts to cooler habitats as the climate warms, are further impeded by the border wall. Binational coordination is critical to develop linkages that allow movement and access to suitable habitat. Instead, the border wall bypasses environmental laws further harming wildlife populations and disrupting migration and dispersal routes, which can drive genetic discontinuities over the long-term (Peters et al. 2018). Since 2006, construction of border infrastructure is exempt from adhering to environmental regulatory requirements to allow additional segments of border wall bisect the landscape without an environmental impact review (United States Library of Congress 2005).

Protected Areas at the U.S.-Mexico Border

Patterns of land use change and habitat fragmentation differ between Mexico and the United States, primarily due to different conservation policies and planning efforts of the two countries. For example, Eaton-Gonzalez & Mellink (2015) measured land cover changes between 1990 and 2011 from satellite imagery and found there was greater landscape fragmentation in the U.S. than in Mexico, and more in the early 1990s than in 2011. In San Diego, rapid urban development prompted conservation planners, natural resource managers, and developers to implement a regional habitat conservation plan, which resulted in a network of linked conserved areas through federal Habitat Conservation Plans (HCPs) and state Natural Community Conservation Plans (NCCPs) (Jennings et al. 2018). Since the mid-1990s, most conservation efforts in San Diego County have been tied to these plans. In Mexico, the lax enforcement of land use plans compared to the US is quite evident considering there are 388,750 acres (1,573 square km) of protected areas in San Diego while there are only 14,373 acres (5,819 ha) protected on the Mexican side of the border (CBI et al. 2004). These conserved lands can help offset climate impacts by reducing habitat fragmentation and fire ignitions that result from urban areas extending into wildlands.

Social-Ecological Vulnerability

Figure 8 shows the bivariate map that combines the binational social vulnerability index with percent green (or “greenness”) by census tract as an indicator of vegetation cover. Areas with high social vulnerability and low greenness would be of primary importance, while areas of low vulnerability and high greenness would be of lesser concern for green infrastructure interventions. In San Diego, areas with medium to high social vulnerability tracts and low vegetation are primarily in urban areas such as National City, Chula Vista, and Imperial Beach as well as inland in El Cajon. High impervious surface and low vegetation cover is often associated with low socioeconomic status in both developed and developing countries. However, low vegetation does not necessarily indicate low socioeconomic status in Tijuana (e.g. Las Playas) due to different land use planning practices. Biggs et al. (2015) examined the relationship between land cover, number of years urbanized, and other socioeconomic indicators in Tijuana and found that the fraction of vegetation cover was relatively similar across census tracts and there was a weak correlation between vegetation and marginality. Considering vegetation in urban areas can reduce air pollution and high temperatures, most Tijuana neighborhoods are exposed to environmental hazards as compared to San Diego and would benefit from green infrastructure and urban tree canopy restoration.

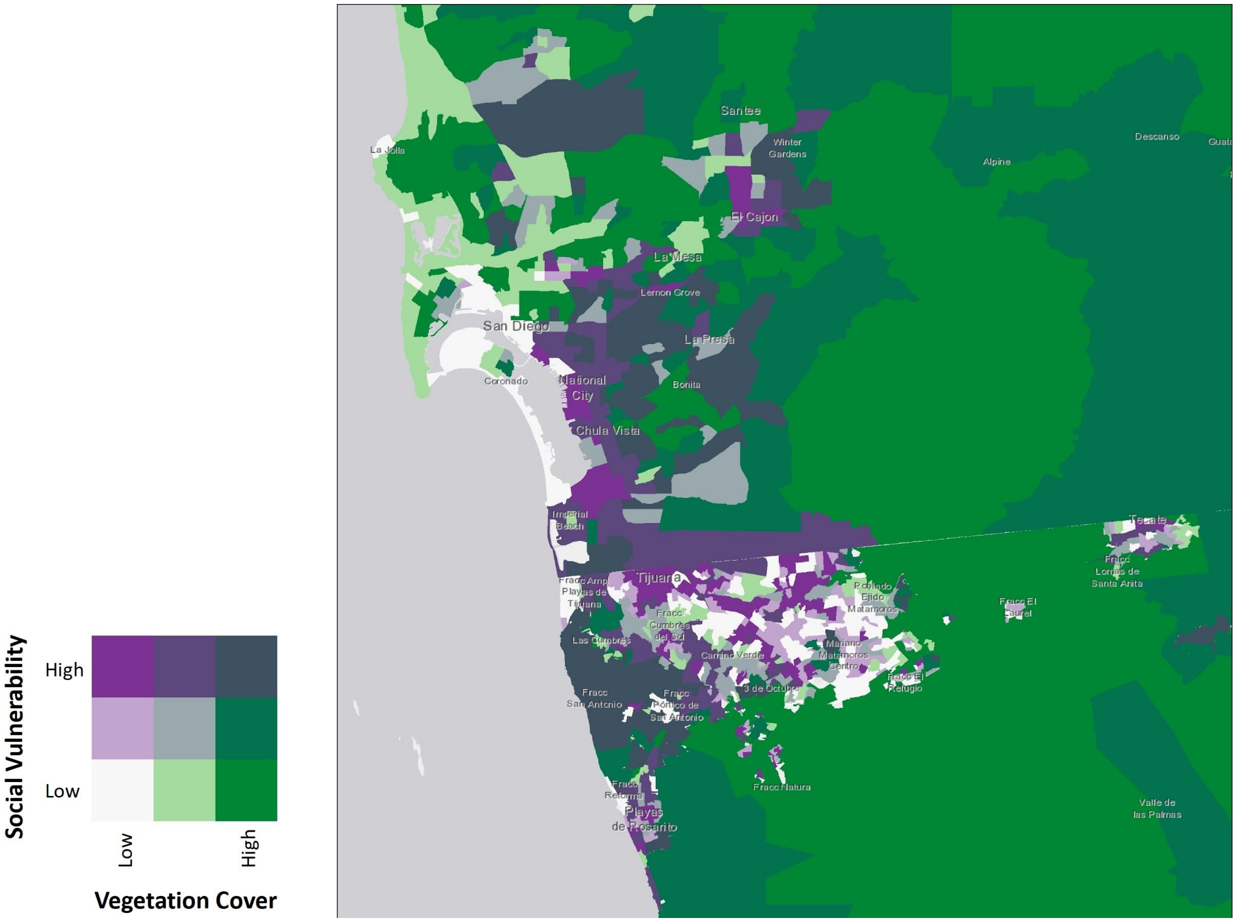

Figure 8: Bivariate map of the binational social vulnerability index combined with “greenness” by census tract.

Climate Impacts and Risk

Flooding and Erosion

The projected increases in extreme precipitation and storm events are expected to impact flooding in urban areas, which would damage homes, contaminate water resources, and increase exposure to water-borne diseases. Flooding and erosion often occurs in cities with inadequate drainage and sewer systems to cope with heavy rainfall over short periods of time. In Tijuana, over 30% of the population lives on unstable terrain, in riverbeds and on sharply sloping hillsides, which is exacerbated by the removal of natural vegetation due to construction of buildings and infrastructure that cut into the natural gradient of the slopes (González et al. 2012).

San Diego has also confronted flood control challenges in low lying areas with poor drainage and debris build-up in basins. Wastewater infrastructure is at risk, which was illustrated by large sewage spills in Tecolote Canyon and Los Coches Creek after a large storm (CCCA4-SD 2018). Storm water pipes can become submerged and cause flooding upstream during storm events that coincide with high tides, as was shown during the 2011 king-tide event (CCCA4-SD 2018). A local example that further illustrates social-ecological impacts of flooding and erosion is provided in the *Discussion* section.

Water Supply and Availability

Variable participation patterns and climate extremes due to climate change will place additional pressure on already stressed water systems in the San Diego-Tijuana border region. Many of San Diego's reservoirs import water from the Colorado River and coastal Baja California has two reservoirs that store water pumped over the mountains from the Colorado River to serve Tijuana, Playas de Rosarito, and Tecate (Wilder et al. 2013). Declines in total runoff have already been observed in the Colorado River watershed. A warmer climate is projected to significantly decrease Colorado River streamflow, with estimated reductions ranging from 10-45% by the mid-21st century (Vano et al. 2014, Udall and Overpeck, 2017). Combined with the region's existing natural variability and shifting precipitation regimes, these declines could amplify past extreme drought conditions.

In San Diego, total water demand is expected to increase by approximately 30 % by 2040 compared with demand in 2015 due to population and economic growth (CCCA4-SD 2018). A study of the Colorado River Basin concludes that by 2060, there will be an annual shortfall between water production and water demand ranging from 0 and 6.8 million acre-feet (8.4 billion cubic meters) leading to reductions in water service delivery. Water shortages may spark significant transaction costs, such as water rights and allocation, which would have severe socioeconomic and environmental impacts. Several California crops are projected to decline from 9 to 29% by 2097, and up to 30% in Mexico by 2040 (Romero-Lankao et al. 2014). Additional impacts of drought include emergency restrictions on outdoor water use, agricultural revenue losses, and impacts to hydro-generated electricity (Wilder et al. 2013).

Sea Level Rise

Sea level rise projections are similar until mid-century and all models show sea level rise accelerates significantly during the second half of the century (CCCA4-SD 2018). The 2018 Ocean Protection Council (OPC) Sea Level Rise Guidance provides projections for 12 tide gauges in California, including San Diego, which can be used for scenario-based planning (OPC 2018). This involves choosing a range of sea level rise projections to analyze best and worst case scenarios and identify the associated time period for when impacts may occur, which helps to address the uncertainty of sea level projections in planning decisions. The OPC guidance provides sea level rise projections for three scenarios: 1) low risk aversion (17% chance of being exceeded), medium-high risk aversion (0.5% probability of exceedance), and 3) extreme risk (accounts for extreme ice loss, which currently does not have an associated probability). The

California Coastal Commission[17] recommends that communities evaluate sea level rise impacts using the "medium-high risk aversion" scenario, therefore projected sea level rise inundation at 5ft are shown in Figure 9. This corresponds to the "medium-high" risk for 2080 and "extreme" risk scenarios for 2070 under OPC projections for the San Diego tide station. These projections do not include effects from storm surges and tidal action, which may cause these water levels to occur sooner during extreme events (e.g. king tides and strong storms or El Niño).

Vulnerability assessments have shown that higher sea levels coupled with extreme precipitation and/or tidal events have the potential to cause significant flooding in the region, particularly in the low lying or beachfront areas, such as San Diego Bay, Imperial Beach, La Jolla Shores in San Diego and Rosarito in Mexico (Figure 9) (CCCA4-SD 2018). Coastal estuaries and marshes may become inundated as sea level rises, but different estuary settings will determine their adaptability. Saltwater intrusion into coastal aquifers can also damage potable water sources. In Tijuana, high bluffs protect adjacent residential areas from widespread flooding, however as sea levels rise, beach dynamics and wave runup from high tides and intense storm activity will cause bluffs to erode and buildings close to the bluff edge will become vulnerable to landslides.

---

[17] https://www.coastal.ca.gov/climate/slrguidance.html

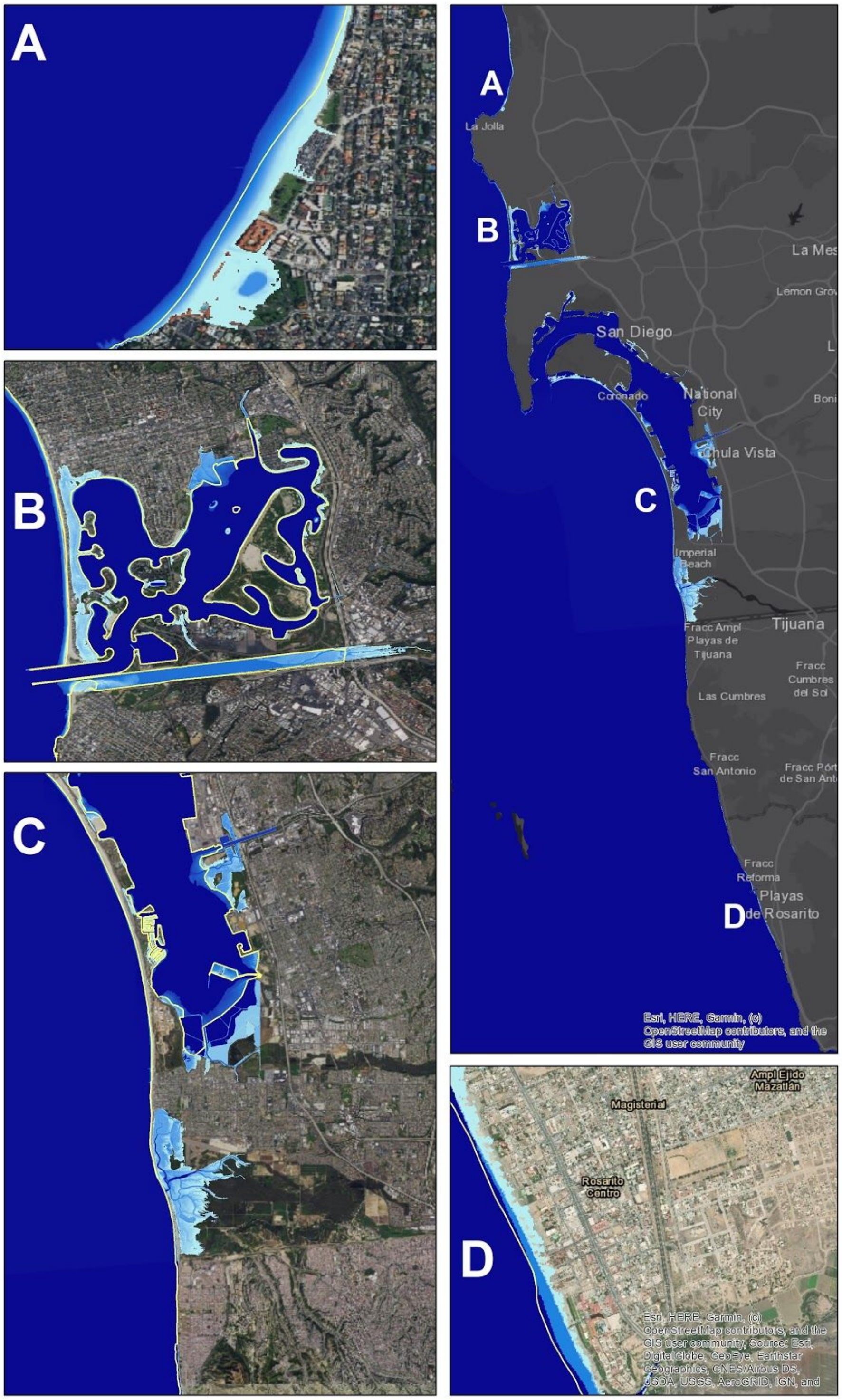

Figure 9: Projected sea level rise inundation for a) La Jolla Shores, b) Mission Bay (including Mission Beach and Pacific Beach), c) south San Diego Bay, Imperial Beach, and Tijuana River Estuary in San Diego County; and d) Rosarito, Mexico. Water levels are at 5ft, which is the approximate OPC projected sea level for the 2070 (extreme risk scenario) and 2080 (medium-high risk scenario) at the San Diego tide gauge.

Wildfires

Future wildfire risk on both sides of the border will depend on development patterns and climate factors, such as higher average temperature and extreme droughts. Projections of longer, hotter, and drier summers combined with precipitation changes will cause an increase in wildfire occurrences. A statistically based model shows an increase in area burned by up to 61 acres (0.25 square km), or up to 50%, under RCP 8.5 at the end of the century (2070-2100) as compared to the historical simulations (CCCA4-SD 2018). Increased temperatures, earlier spring warming, and decreased surface water will also contribute to a longer wildfire season, which now lasts all year in California (Wilder et al. 2013). While the start of fire season in Baja California is similar to San Diego, 90% of fire scars appear during the early summer (June-August) (Jennings et al. 2018). Wildfires have also occurred more frequently than historical wildfire return intervals (Wilder et al. 2013), which has negative implications for ecosystem evolution and the ability to regrow after a fire (Jennings et al. 2018). The impacts of increased wildfire frequency can lead to vegetation type conversation, particularly from shrub-dominated systems to non-native grasses, which is exacerbated by drought conditions (Jennings et al. 2018).

Santa Ana winds that occur during the early (May) or late (October) part of the warm season are known to fan the region's most catastrophic wildfires, such as those that occurred during 2003 and 2007 in San Diego (Figure 10). These winds will likely become hotter relative to background warming and contribute to higher wildfire risk (Pierce et al. 2018). While dry, hot, strong and gusty Santa Ana are a large factor in fire weather conditions, other factors such as urban expansion into wildlands are important when determining risk. In Baja California, which has one of the highest occurrences of wildfires in Mexico, most wildfires were close to urban areas between 2010-2015. Two large wildfires have occurred in the past several years that burned into urban areas, such as Tecate and the outskirts of Tijuana (Figure 10). The U.S. has a long history of fire suppression, but fire management in Mexico wasn't started until the 1970s, so Baja California could experience the same devastating wildfire effects that have recently been experienced in California by suppression practices (Jennings et al. 2018).

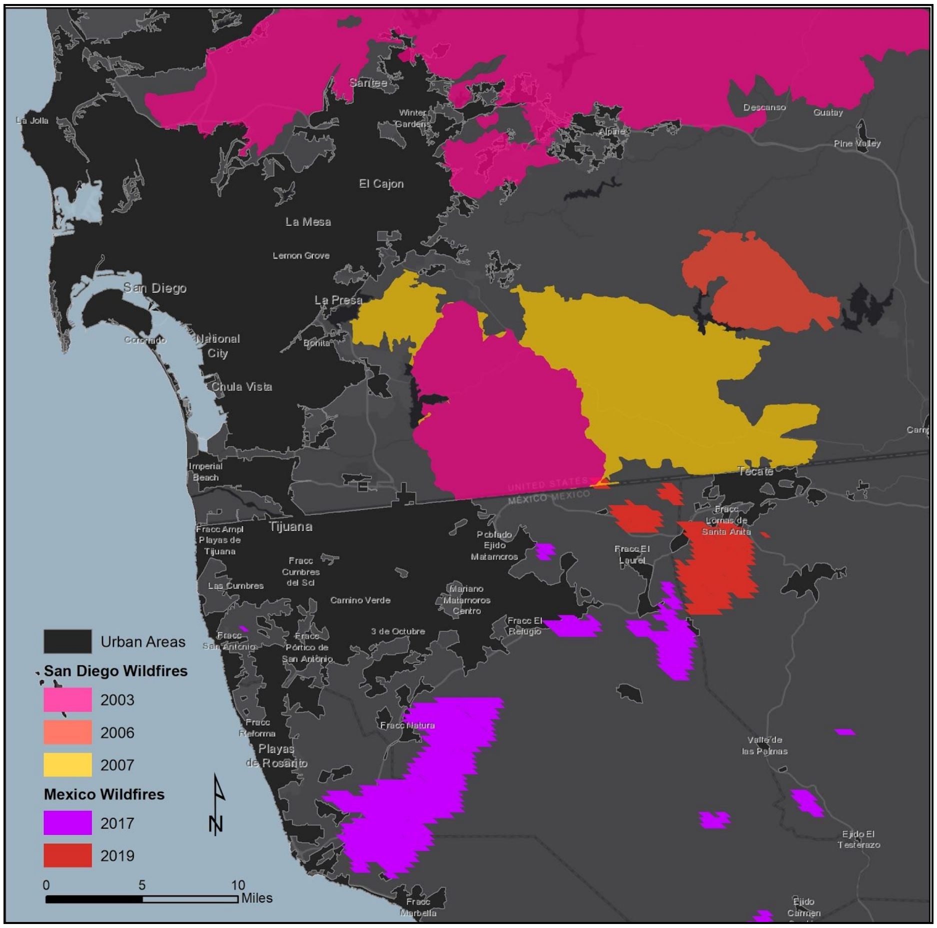

Figure 10: Extent of the largest wildfires (area burned) in San Diego and recent wildfires in northern Baja California. Future remote sensing research could investigate whether these wildfires stopped at the border to measure the extent of binational wildfires.

Research Gaps and Uncertainties

Varying data availability, methodologies, and model results account for the majority of uncertainties in the observed and projected global and regional climate trends. Observing climate extremes is also challenging because they are rare and occur with other disruptive conditions (Hartmann et al. 2013). Attribution research is limited by incomplete observational records and flawed climate models that lack processes and resolution needed to realistically simulate regional details (Stott et al. 2010, Trenberth et al. 2011). More literature is also available in the U.S. compared to Mexico making it difficult to dedicate equal space to observed and projected climate changes in the region (Romero-Lankao et al. 2013).

Despite a robust understanding of global climate changes, reducing the uncertainty in regional-scale projections remains a challenge due to the lack of direct long-term measurements that capture natural variability. In the border region, differences in the availability of high-quality, continuous meteorological and hydrological records over a long-period and lack of data sharing are a source of uncertainty in climate model projections (Flato et al. 2013). Most hydrological studies and drought predictive capabilities also require more research as they lack land-atmosphere coupling (e.g. evapotranspiration) and vegetation response information (Fisher et al. 2017). Additional research needs include improved climate predictions and understanding of the region's variable precipitation regime and hydrological balance to better support water management and better long-term observations to track changes of Santa Ana winds and relative humidity for more reliable wildfire season and heat wave predictions (CCCA4-SD 2018).

For the BSVI, this project found that there are two issues that need to be addressed in future work. First, there is already a large amount of error that is introduced when combining two datasets that were collected differently, (e.g. survey methods, question phrasing, etc.), so it is difficult to avoid comparing apples to oranges. The ACS margin of error was not considered when calculating U.S. ranks, so those errors were also not addressed in the analysis. For Mexico, urban and rural census tracts were separate shapefiles and the rural data was not included with the rural shapefiles, so they needed to be summarized from point data and joined to the shapefile, which may have also introduced errors. Secondly, and more importantly, there are important socioeconomic variables that were not considered on the Mexico side because those variables were not available in the U.S. census dataset and vice versa. Income is a significant indicator of wealth, but these data were not available or reliable for Mexico. As mentioned above, socioeconomic variables, such as households without electricity and households unconnected to sewer, were not included because it is very likely these services are available to communities of all socioeconomic classes in the U.S. Future research will require investigating the significance of the socioeconomic variables in each census dataset based on their range of values. Since variables were weighted equally, taking weighting into account may also help achieve a BSVI ranking that aligns with known socioeconomic characteristics of the region.

Discussion

The San Diego-Tijuana region has an extensive history of human settlement and population growth. The environmental impacts of this growth have been significant (e.g. species decline, vegetation conversion, erosion, sediment flow, slope instability), which have also disproportionately impacted vulnerable populations (e.g. flooding, health, landslides). In recent decades, the region has collectively endured extreme climate-related events, such as wildfires, droughts, strong storms, and high temperatures. Climate change will continue to accelerate existing environmental degradation and increase the severity and uncertainty of its impacts. Cross-border climate adaptation planning provides communities on both sides of the border an opportunity to rethink how cities are built and redesign urban landscapes in a way that works with nature, not against it. By understanding the social and ecological connections as well as the political history of a landscape, communities can seek to address chronic social issues, such as inequality and public health, through pursuing natural solutions in climate planning. Urban areas in the region can benefit from land management and planning strategies that improve substandard infrastructure and reduce climate risk by expanding urban green spaces in vulnerable areas. In the San Diego-Tijuana region, the challenges of different cultures, land use planning, and governance make this difficult. Through incorporating binational climate science information into government planning and operations, as well as better integration of agencies themselves, governance actors could be more responsive to climate change. Additionally, cross-border partnerships and local interventions could help build a binational community of stakeholders to identify where institutional priorities align, incentivize collaboration and create a more sustainable and equitable future for the region.

Recommendations for Cross-Border Climate Adaptation and Mitigation

The recommendations described in this section came from the *California 4th Climate Change Assessment* and *Bending the Curve* reports based on the relevant findings in this project. These recommendations were selected to elevate key strategies for climate adaptation planning from a binational perspective. The project addresses several solutions across three clusters from *Bending the Curve* (societal transformation, governance, and ecosystem management) as well as science and data sharing from the *California 4th Climate Change Assessment*.

Green Infrastructure and Nature-Based Solutions

"Accelerate the impact of cities on ***climate mitigation through … green infrastructure projects****, such as ... urban forestry to improve carbon sequestration and reduce the urban heat island effect"*

"Regenerate damaged ***natural ecosystems*** *and restore soil organic carbon to improve natural sinks for carbon (through afforestation, reducing deforestation and restoration of soil organic carbon)"*

These above recommendations from *Bending the Curve (2015)* underscore the importance of nature-based solutions, such as green infrastructure and conservation of natural ecosystems, to reduce climate risk. This requires identifying vital conservation areas for restoration of ecosystem functions and connectivity across the border to promote the understanding of co-benefits of natural climate solutions as a mitigation and adaptation strategy. For example, urban trees provide shading, moderate high temperatures, cool streets and buildings, reduce urban heat island effects and lower energy demand. Roots from vegetation also help anchor soil and minimize erosion during heavy rain events. Limiting the loss of vegetation cover and restoring vegetated areas can help with carbon capture and sequestration. Coastal wetlands are particularly efficient and store up to 10 times more carbon per equivalent area than tropical forests (GNEB 2016). Green areas also provide improved public health and air quality, expand recreation space, and increase property values of up to 30 percent in Mexico (GNEB 2016).

Green infrastructure provides a cost-effective alternative to gray infrastructure using urban design elements and constructed features that mimic nature and link the built environment to ecological functions, such as stormwater infiltration, reduced runoff, evaporative cooling, rainwater interception, and wildlife habitat (Voskamp and Van de Ven 2015). Table 3 summarizes common strategies for green infrastructure implementation and their typology. The built environment is constantly changing, especially in informal settlements in cities such as Tijuana, therefore urban planners have opportunities to implement green infrastructure projects and bring cities to life by bringing life back to the cities.

Table 3: Green infrastructure strategies for reducing climate risk (adapted from Voskamp and Van de Ven 2015)

Green Measure	**Description**	**Climate Risk Reduction Benefit**
Increase vegetation in medians and sidewalks	Replace paved surfaces with native vegetation	➔ Slows runoff during storm events ➔ Provides water infiltration and cooling ➔ Supports local biodiversity
Bioswales	Vegetated ditch for stormwater storage above ground with subsurface drainage and infiltration through drainpipe	Reduces surface runoff and erosion by capturing water aboveground and storing it in the soil
Permeable pavements	Pavements that allow rainfall runoff to quickly infiltrate into the soil	Reduces surface runoff during heavy precipitation events
Green roofs	Rooftop vegetation and soil	➔ Decrease solar heat gain ➔ Cools ambient air ➔ Retain water during storms ➔ Reduce runoff
Cool roofs	White/bright roof surfaces that reflect shortwave solar radiation	Lowers the surface temperature of buildings as compared to dark roofs
Green streets	Street design concept implemented in San Diego that combines stormwater management and transportation needs (.e.g bikes, buses, walking, etc)	➔ Porous pavement with biofilters or retention soils reduce runoff ➔ Widened sidewalks accommodate bike and pedestrian traffic ➔ Improved bike corridors and connectivity allow safe and efficient carless travel
Urban Agriculture	Growing fruit and/or vegetables on plot of land or rooftop within a city	➔ Provides healthy, local food to the community ➔ Reduces emissions due to transporting food from outside the city ➔ Roots from crops help stabilize the soil
Creation of green corridors	Large, continuous areas of open green space or collection of trees	➔ Provides cooling and shade ➔ Reduces air pollution ➔ Captures and stores carbon ➔ Increases habitat and recreation connectivity
Restoration of rivers, canals, wetlands	Revegetated banks of canals, rivers and within coastal areas	➔ Absorbs floodwaters ➔ Captures and stores carbon ➔ Filters air and water

Connected Systems - Los Laureles Canyon and Tijuana River Estuary

To provide a local example, Figure 11 highlights the hydrological connectivity and flood risk of a binational watershed. The Tijuana River Watershed (TRW) is a complex drainage system where the Tijuana River drains from forest-covered mountains in Mexico to a tidal saltwater estuary at its mouth in the U.S., the Tijuana River National Estuarine Research Reserve (TRNERR). TRNERR is the largest intact coastal wetland system in Southern California, making it a unique coastal ecosystem. Designated as a Ramsar Wetland of International Importance[18], TRNERR consists of several sensitive habitats for endangered species and nursery grounds for commercially important fish. Just south of the estuary, in the informal settlement of Los Laureles Canyon, Tijuana, unregulated urban growth on steep canyon slopes and variable enforcement of environmental regulations has significantly reduced green spaces. This has dramatically altered the landscape and excessive erosion has accelerated the rate of sedimentation, changing the natural ecosystem of the estuary through burial of habitat downstream in the TRNERR. During rainfall events, the Tijuana River Valley is also exposed to contaminants from sewage/urban runoff and illegal dumping, which has prompted beach closures at two proximate beaches to the border due to poor water quality (San Diego Water Board 2020).

Figure 11 depicts the location of Los Laureles Canyon and TRNERR, inflow locations, and flood depth for a 100-year storm event to highlight the hydrological connectivity and flood risk of the binational watershed. Two different types of flooding are experienced in each area with their own set of impacts - fluvial flooding in the Tijuana River Valley and pluvial flooding in Los Laureles Canyon. Lack of vegetation, a naturally erodible landscape, and unpaved roads contribute to erosion; heavy rainfall creates running rivers of mud and debris, erodes unpaved roads, destabilizes slopes, and destroys homes (Goodrich et al. 2018). Flood waters that carry debris that can block flood conveyance channels and contribute to flood risk (Goodrich et al. 2020). Flooding can also pose life-threatening situations for people who live adjacent to unstable stream channels or on steep, erodible slopes. The conversion from natural to built landscapes in Los Laureles along with extreme rainfall events due to climate change will have a significant impact on the estuarine system downstream.

Given the added uncertainty of climate change, two key variables - extreme river flow and tidal prism - are considered in planning for future climate scenarios (TRNERR 2017). These variables determine the amount of freshwater and sediment entering the system as well as the status of the river mouth. The Climate Understanding & Resilience in the River Valley (CURRV) initiative led by TRNERR identified four potential climate change outcomes, or scenarios, for adaptation planning based on changes in extreme river flow and tidal prism (Figure 12). Monitoring “triggers”, such as a closed river mouth during a year when El Niño conditions are not present, allows TRNERR managers to tackle uncertainty and determine when the estuary is being pushed into a future scenario that would require an adjustment to current management strategies. Land management decisions in Los Laureles Canyon and the ability to successfully protect the remaining natural areas and vegetation cover in the canyon will directly influence

---

[18] https://rsis.ramsar.org/ris/1452

extreme river flow events, sediment input in the Tijuana Estuary, and the future climate scenario that unfolds in the estuary (Boudreau et al. 2017).

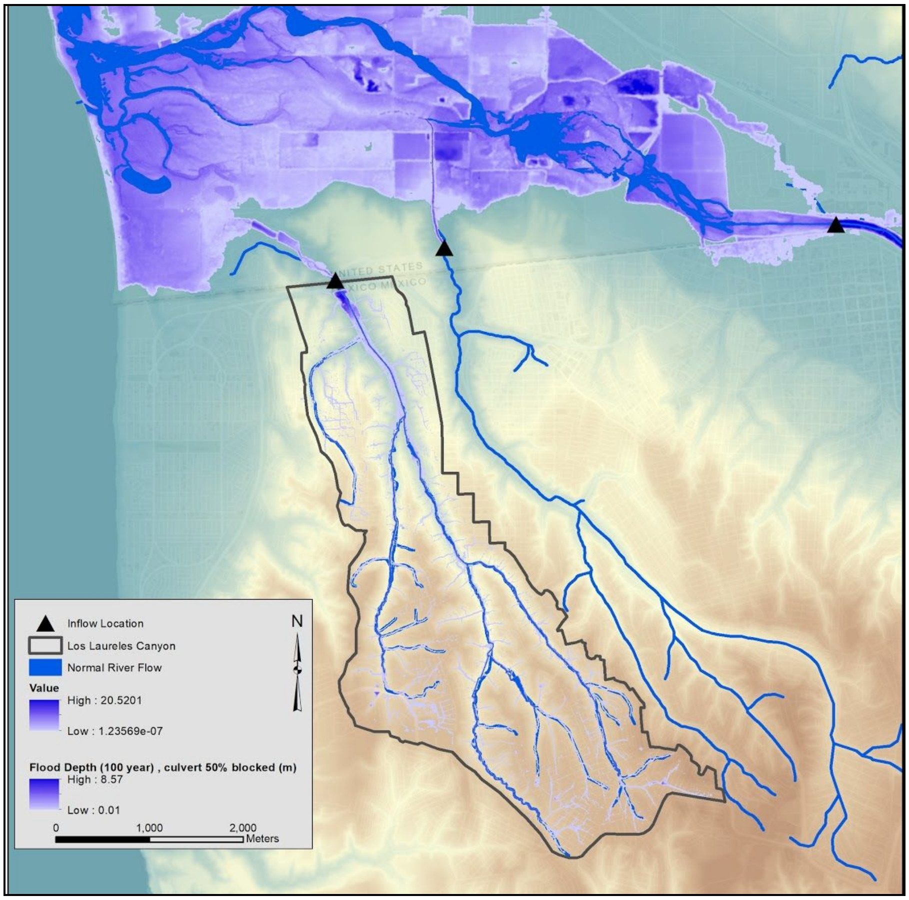

Figure 11: Flood layers for TRNERR and Los Laureles Canyon showing the hydrological connectivity of binational watersheds and flood depths during 100-year storm events (Source: FloodRISE)

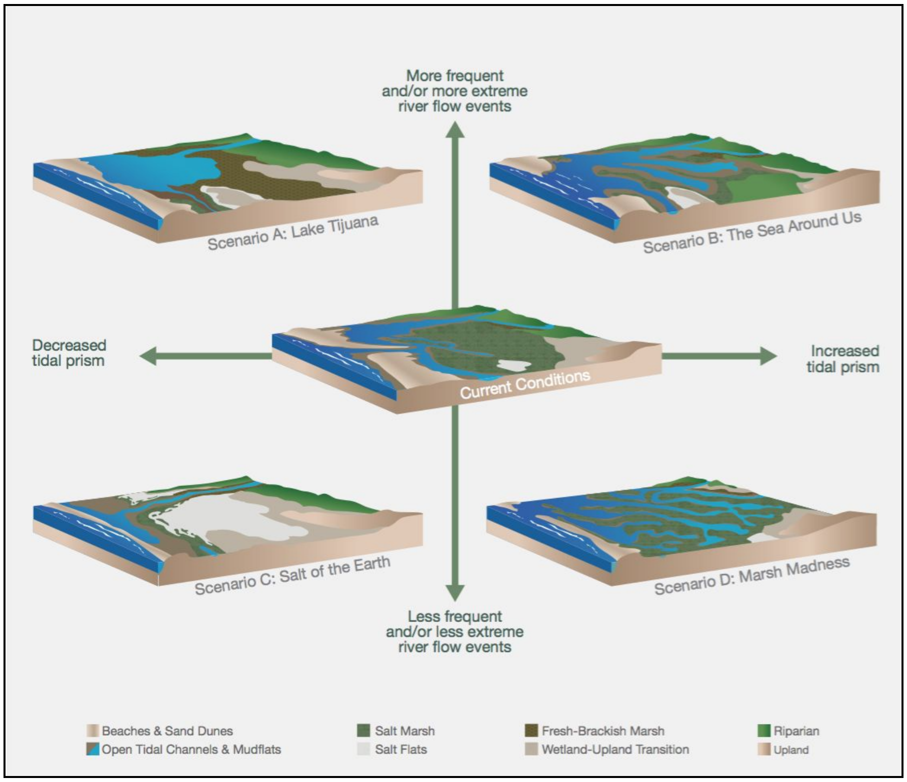

Figure 12: Four possible climate scenarios for the Tijuana River Estuary and River Valley based on the frequency of extreme river flow events and increases/decreases of the tidal prism (TRNERR, 2017).

Binational Conservation Assets

Green infrastructure measures such as restoration of river canals, increasing native vegetation cover, and conserving existing green spaces can help reduce environmental risk of flooding and sedimentation and climate impacts in the canyon, Tijuana River Valley, and inform climate adaptation strategies in TRNERR. Researchers at the X-Border Lab[19] of the Center on Global Justice (CGJ) at UC San Diego are dedicated to advancing work on equitable, green urban development in the San Diego-Tijuana border region. Through their Cross-Border Commons[20] project, a set of undeveloped parcels in Los Laureles Canyon have been identified as an "archipelago" of conservation (Figure 13), which could serve to further link the Tijuana River Estuary with Los Laureles Canyon, strengthen the topographic integrity of the canyon, and protect communities and the natural resources shared by San Diego and Tijuana.

Protected areas, or special zones, already exist in Los Laureles Canyon, which were established by law through the Plan Parcial 2004 (Instituto Municipal de Planeación de Tijuana). There are three types of special zones: preservation (strict, no development zones due to the ecological sensitivity of the area), conservation (mixed development with ecologically important factors) and protection (flood and erosion zones). Special zones in the Plan Parcial 2004 were largely focused on the upper basins (A, B, and C in Figure 13), which contained more intact native vegetation and ecosystems at the time and were more attractive for development because the slopes are less steep than areas near the border downstream. However, despite these special zone designations, rapid construction and expansion of building footprints still occurred throughout the canyon because environmental regulation was rarely enforced, which is particularly troubling in the protection zones that were designated to reduce social risk from landslides, flooding, and water contamination.

To address this issue, the Cross-Border initiative proposes to implement three types of demonstration projects to create a green space network and update the Plan Parcial 2004: 1) critical infrastructure, 2) pedagogical parks, and 3) urban conservation areas. All projects focus on building green infrastructure to protect communities from flood and erosion while providing public space simultaneously, particularly in microcuencas, or sub-basins, where special zones are not publicly owned or there are no conservation areas. The canyon is an ideal case study to support main recommendations throughout this project because it already has a binational council that represents communities in each microcuenca (governance), social and ecological institutions already exist (partnerships and collaboration) for the exchange of technical information (science and data sharing). The U.S. investment in the conservation of green spaces in the canyon can serve as a form of binational asset that will not only help increase climate resilience for the most vulnerable populations in Tijuana, but also protect the estuary from adverse environmental and climate impacts.

---

[19] http://gjustice.ucsd.edu/x-border-lab/

[20] http://gjustice.ucsd.edu/cross-border-commons/

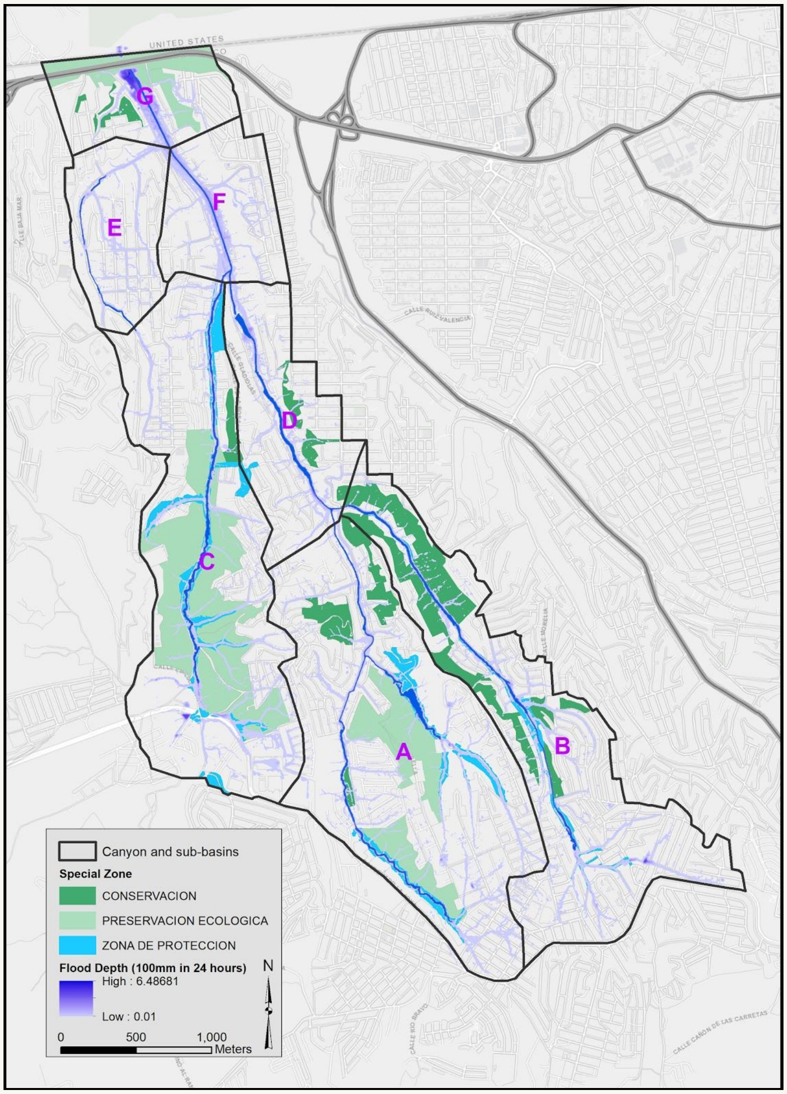

Figure 13: Special zones identified by the Plan Parcial 2004, Cross Border Commons proposed projects, and remaining open space in each microcuenca (sub-basin) of Los Laureles Canyon.

Partnerships and Collaboration

“Initiate a culture of climate action by ***localizing interventions****. Research shows that behavioral change and positive public opinion are more likely when the impacts of climate are recognized at a local scale and when barriers are lowered for people to participate in concrete actions to solve our climate crisis”*

This recommendation from *Bending the Curve (2015)* emphasizes the importance of influencing public attitudes as they experience climate impacts rather than learn about it in distant regions. People are at the center of climate adaptation decisions because they will be the most impacted, so a key element to successful implementation of climate strategies is to actively engage the communities to build relationships and trust. Pilot projects can serve as demonstrations to local communities and help strengthen buy-in for natural climate solutions and co-benefits. These projects can also increase public interest and establish political support for conservation of natural resources and biodiversity.

Robust environmental education strategies are also essential to any proposed solution to increase climate knowledge among all generations and socioeconomic classes. For example, the UCSD Center on Global Justice links communities and universities through their Community Stations, a network of field hubs designed to transform vacant parcels into environments for collaborative research, education, and climate action in disadvantaged neighborhoods on both sides of the San Diego-Tijuana border[21]. The Miramar Park project, known as "Parque Hidrológica Educativa", is the pilot project of the Cross-Border Commons initiative and serves as a public space in Los Laureles Canyon that educates communities on durable green infrastructure, best management practices for building on slopes, and native vegetation restoration. The location of the project is inside the scar of a major 2015 landslide where nineteen houses slid down the hillside during a rain event. Project plans include building a giant bioswale and an education plaza around the remaining skeletons of old buildings as a reminder of bad practices. The education and networking elements of these types of projects create a space for innovative cross-sector solutions and can help connect community groups to local government officials as well.

"Deepen the global culture of ***climate collaboration****. Design venues where stakeholders, community and religious leaders converge around concrete problems with researchers and scholars from all academic disciplines, with the overall goal of initiating collaborative actions to mitigate climate disruption."*

This recommendation from *Bending the Curve (2015)* underscores the importance for shared understanding of vulnerability and visioning as well as new binational, cross-sector platforms. Shared social learning in a transboundary setting develops common conceptual understandings of climate challenges over multiple institutional scales, from individuals to communities to organizations (Varady et al. 2013). Communities of practice also builds trust, lowers barriers to cross-border cooperation, and can be sustained over iterative interactions and political cycles. The Tijuana River National Estuarine Research Reserve (TRNERR) and the Climate Science Alliance (CSA) are examples of transborder organizations that work to address climate change adaptation across the border. TRNERR facilitates discussions about management of the Tijuana River watershed through the CURRV initiative and CSA is collaborating with educational programs in Mexico for their Climate Kids-Mexico program (CCCA4-SD 2018).

In regards to ecological vulnerability, there are several goals for sharing the responsibility of protecting transboundary ecosystems that have been identified through binational collaborations. For instance, the conservation of north-south and east-west linkages between core areas of high biodiversity could be established through a binational park system that connects Parque Nacional Constitución de 1857 in Baja California to the State Parks, National Forest lands, and Wilderness Areas in the Peninsular Ranges north of the border in California (Jennings et al. 2018). Border security and conservation goals can also align through border enforcement that simultaneously

---

[21] http://gjustice.ucsd.edu/ucsd-community-stations/

protects these open space linkages. Land use planning should not stop at the border and can promote partnerships and collaboration among organizations and institutions that have shared goals.

This project focused on natural climate solutions and the benefits of green infrastructure as a climate and mitigation adaptation strategy. However, a more detailed binational climate change vulnerability assessment that takes into account other highly vulnerable sectors, such as energy systems and agricultural land use, is needed. Therefore, this project recommends convening a workshop that brings stakeholders (e.g. Border Environment Cooperation Commission, Good Neighbor Environmental Board, International Boundary and Water Commission, UCSD Center for Mexican Studies, The Colegio de la Frontera Norte, etc.) together for a facilitated discussion with objectives to address data gaps and identify opportunities for increased collaboration in order to take the binational climate vulnerability assessment to the next level. The group could also collaborate with the UCSD Center on Global Justice to build a binational community of practice and offer a space for showcasing available data, visualization tools and other climate resources.

Governance

"Scale up subnational models of ***governance*** *and collaboration around the world to embolden and energize national and international action."*

In addition to rethinking urban design and development patterns, this recommendation from *Bending the Curve (2015)* emphasizes the need to reassess environmental governance in binational regions such as San Diego-Tijuana. Governance refers to the "set of regulatory processes, mechanisms, and organization through which political actors influence actions and outcomes" (Lemos and Agrawal 2006). Binational urban and conservation planning can only advance when local governments on both sides of the border work together to develop solutions, but different priorities make this challenging. In the U.S., immigration and terrorism is prioritized while Mexico focuses on public safety, unemployment, and attracting investment for bringing urban infrastructure to marginlized communities (Wilder et al. 2010). In the U.S. governance is decentralized while it is highly centralized in Mexico, which complicates binational cooperation and land use planning at the border. The Mexican federal government plays a central role in setting priorities and providing financial and technological resources needed for adoption of climate mitigation and adaptation measures, so political and administrative management decisions are achieved more readily in Mexico (Lara-Valencia et al. 2010). However, Mexican cities are slow to respond to climate change threats due to limited resources for implementing changes. Local governments are also overwhelmed by structural failures of rapidly urbanizing areas and climate action competes with other threats such as safe drinking water, sanitation, and safety (Lara-Valencia et al. 2010). Binational interactions need to move beyond centralization and decentralization to establish governance that shares the responsibility of managing adaptive social-ecological systems. U.S. collaboration could help fill gaps in scientific baselines and budget deficits for environmental issues.

Regulatory frameworks and planning legislation related to the environment and housing also operate through complex legal and political systems. When used effectively, legislative and regulatory frameworks can deter settlements from hazard areas through urban design techniques that reduce risk and are held to high construction standards. However, there are currently limited incentives to enforce environmental laws or sufficient building codes in Tijuana. Addressing this issue will require improved, strong leadership and societal transformation. Financial support can also go a long way to getting new ideas adopted; however, in both the U.S. and Mexico, it can take several budget cycles to integrate new concepts and practices into government agencies, so the presence of a strong, high-level champion, such as community representatives of the binational council, is required to sustain this process.

Policies and incentives that align across multiple levels of government can also improve the likelihood of agencies to take action and deliver effective climate adaptation. Binantional agencies, such as the Border Environment Cooperation Commission (BECC), and the North American Development Bank (NADB) have increased climate change action planning by aligning binational priorities among stakeholders along the northern border of Mexico, which has been vital to progressing climate mitigation and adaptation strategies. For example, BECC developed a four year initiative to help build adaptive capacity and strengthen natural ecosystems through green infrastructure projects within communities in Mexico. This initiative focused on community training, strengthening municipal codes, developing pilot projects, and restoring native vegetation. Binational collaboration was achieved by aligning objectives and agency mandates of The U.S. Environmental Protection Agency (EPA) and BECC, which both prioritized stormwater management and improved surface water quality. BECC also contracted a Mexican law firm to draft legal instruments that would allow Tijuana and other Mexican municipalities to incorporate green infrastructure concepts in their legal framework by updating state law and municipal codes (Giner et al. 2019). One shortcoming of the BECC initiative was the lack of a national stormwater permitting process, such as in the U.S., which could further help incentivize the adoption of green infrastructure. Regardless, the decentralized implementation and government assistance through transparency helped elevate green infrastructure projects.

Science and Data Sharing

*"**Transboundary data sharing between the U.S. and Mexico** is needed to enable vulnerability assessments and adaptation planning and to promote urban and economic development strategies, water conservation, and green infrastructure."*

This recommendation from the *California 4th Climate Change Assessment (2018)* emphasizes the need to improve the dissemination of climate data and information in order to advance coordination and adaptation goals in the context of binational planning. Collaborative development of science and policy relies on information flows and easily accessed information, which is challenging in a transboundary setting due to different languages and institutional structure (Varady et al. 2013). However, current climate information, new tools available, and scenarios are key to the usability of climate information that is provided to the public and government organizations.

This project is the first collection of maps and data that have been packaged for the study region in the context of climate change vulnerability. In addition to pooling together relevant spatial datasets, the data was packaged in similar units so that different social and ecological variables could be compared and analyzed concurrently. However, gathering GIS and remotely sensed data at the same level of detail on both sides of the border proved to be challenging, especially in Mexico, and the process of acquiring adequate datasets to complete a cross-broder climate vulnerability assessment was time consuming because it required reaching out to numerous partners and contacts in the region. For the BSVI, a substantial amount of time also went into preprocessing the census datasets so that the variables were in one shapefile attribute table. For example, subtle differences in question phrasing (e.g. percent without a car in the U.S. Census and percent with a car in the Mexico Census) would create large errors if the raw numbers were used in the analysis. The project provides a framework that enables future collaboration that would continue this work using the best data available, including the 2020 Census when it is released. The Binational Climate Vulnerability Atlas itself is a first iteration and was designed to be an ongoing effort. Leveraging existing partnerships is helpful, but creating a binational community described above would be more efficient. A binational exchange of climate data, land use information and adaptation strategies that focus on regionally shared climate change impacts and variability would help bridge the divide and strengthen transferability of ideas and climate solutions between San Diego and Tijuana.

"A ***regional social vulnerability study*** *that outlines impacts to communities on both sides of the border and also identifies opportunities for San Diego and Tijuana to work together to reduce socioeconomic vulnerabilities and increase local resilience to climate change."*

This project took the first step towards conducting a binational social vulnerability study, as recommended in the *California 4th Climate Change Assessment (2018)*, using both the U.S. and Mexico census tract data, which became a critical deliverable in the end. The BSVI calculation helped to begin answering questions regarding which communities will be most negatively affected and in what aspects by current climate change projections. For example, the most vulnerable communities were located in highly dense urban neighborhoods in both countries with climate projections showing urban areas in Tijuana experiencing higher extreme temperatures as compared to San Diego in the future. However, the true vulnerability of communities in poor neighborhoods of Tijuana that lack sewer, electricity, and other basic services was not captured, therefore the BSVI as it currently stands would not be appropriate for sound policy making. Robust indices that address socioeconomic vulnerability, climate change, and environmental justice exist for San Diego (e.g. San Diego Social Equity Index[22]). Lessons learned from calculating the BSVI highlight the need to bring together social scientists, statisticians, and other experts who have worked on such indices, understand how to work with the technical complexities of census datasets and can justify decisions when ranking certain socioeconomic variables.

---

[22] https://www.sandiego.gov/sustainability/social-equity-and-job-creation

Conclusion

Intense development pressure due to increased migration coupled with degradation of natural resources will amplify climate change impacts experienced along the border. Communities in San Diego and northern Mexico experience environmental impacts collectively and climate change will only amplify existing socioeconomic vulnerability. Precipitation in this region is dominated by a high amount of variability, which adds to uncertainty. Extreme rainfall, droughts, heat waves, wildfire risk as well as increased runoff and contamination of waterways in binational watersheds is expected to worsen with climate change as well. The binational climate vulnerability assessment and Atlas for the San Diego-Tijuana region developed through this project lays the foundation for a robust climate vulnerability assessment that requires cross-border collaboration to conduct a more thorough analysis of social, structural, and ecological vulnerability.

In the San Diego-Tijuana region, land management decisions have the potential to reduce carbon emission, strengthen resilience, and improve public health by investing in green infrastructure and conservation projects. This project also provided key recommendations that were drawn from existing climate reports to support binational policy and urban planning decisions in the future. Transborder collaboration among key U.S. and Mexican organizations, institutions, and agencies is critical for addressing climate change vulnerability and strengthening adaptive capacity. Shared understanding, data, priorities, and cooperation also have the potential to shape our landscape. Binational coordination and effective approaches to climate mitigation and adaptation measures must overcome varying governance, community, and urban development structures. The Atlas created through this project can begin that conversation and help resource managers and policy makers move past these barriers by showing the San Diego-Tijuana region as one social-ecological system and the interconnections between climate vulnerability, impacts, and risk.

Acknowledgements

First and foremost, I would like to thank my capstone advisory committee for their commitment and time advising me throughout this project: Dr. Kristen Goodrich who introduced me to the UCSD Center on Global Justice and strengthened the social-ecological connections throughout the project, Dr. Kyle Haines for his excellent idea to conduct the binational climate change vulnerability assessment and agreeing to be the Chair of my capstone committee, and Dr. Fonna Forman for her valuable feedback and all she does to advance climate justice for the world's most vulnerable populations. I would also like to thank Bridey Scully for her help with connecting this project to pathways and solutions outlined in the *Bending the Curve* report and feedback on draft project reports, as well as Brittany Dutton for her insight on U.S.-Mexico environmental law. In regards to climate science and impacts, I would like to acknowledge Dr. Julie Kalansky, lead author of the *4th California Climate Change Assessment - San Diego Report*, for her guidance on the climate content and helping me access the spatial data on temperature and precipitation. I would also like to thank Alexandria Warneke at Climate Science

Alliance - Baja Working Group for her recommendations on the ecological components of climate vulnerability. For the geospatial data used to create maps in the Binational Climate Vulnerability Atlas, I would like to thank Dr. Alejandro Hinojosa at the Ensenada Center for Scientific Research and Higher Education, Ensenada (CICESE) who provided the digital elevation dataset required to create the sea level rise GIS layers along the Mexican coastline in the study area, Dr. Charlotte Gonzalez-Abraham who helped me find the spatial data for wildfire burned areas in northern Baja California as well as IMPLAN Tijuana, Delia Castellanos, Ana Xochilt Eguiarte, TRNERR, SANDAG for various other GIS datasets used in this project.

References

Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R., & Rockström, J. (2005). Social-ecological resilience to coastal disasters. *Science*, *309*(5737), 1036-1039.

Anderson, J. B. (2003). The US-Mexico border: a half century of change. *The Social Science Journal*, *40*(4), 535-554.

Arkema, K. K., Guannel, G., Verutes, G., Wood, S. A., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M., & Silver, J. M. (2013). Coastal habitats shield people and property from sea-level rise and storms. *Nature climate change*, *3*(10), 913-918.

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A. Wood, T. Nozawa, A. Mirin, D. Cavan, and M.D. Dettinger, 2008: Human-induced changes in the hydrology of the western United States. *Science*, 319(5866), 1080-1083.

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, 2013: Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Blitzer, J. (2019, April 3) How Climate Change Is Fuelling the U.S. Border Crisis. *The New Yorker.* Retrieved from https://www.newyorker.com/news/dispatch/how-climate-change-is-fuelling-the-us-border-crisis?utm_campaign=aud-dev&utm_source=nl&utm_brand=tny&utm_mailing=TNY_Daily_040319&utm_medium=email&bxid=5be9fe813f92a404693a259c&user_id=53028941&esrc=&utm_term=TNY_Daily

Biggs, T. W., Anderson, W. G., & Pombo, O. A. (2015). Concrete and poverty, vegetation and wealth. A counterexample from remote sensing of socioeconomic indicators on the US–Mexico border. *The Professional Geographer*, *67*(2), 166-179.

Boudreau, D., Crooks, J., Goodrich, K., and Lorda, J. (2017) "Preparing for Climate Change in the Tijuana River Valley," Tijuana River National Estuarine Research Reserve, Imperial Beach, CA.

California Coastal Commission. (2018). California Coastal Commission sea level rise policy guidance: Interpretive guidelines for addressing sea level rise in local coastal programs and coastal development permits. *Adopted on November 7, 2018.*

Carruthers, D. V. (2008). The globalization of environmental justice: Lessons from the US-Mexico border. *Society and natural resources*, *21*(7), 556-568.

Cayan, D.R., T. Das, D.W. Pierce, T.P. Barnett, M. Tyree, and A. Gershunov, 2010: Future dryness in the southwest US and the hydrology of the early 21st century drought. *Proceedings of the National Academy of Sciences of the United States of America*, 107(50), 21271-21276.

Cavazos, T., & Arriaga-Ramírez, S. (2012). Downscaled climate change scenarios for Baja California and the North American monsoon during the twenty-first century. *Journal of Climate*, *25*(17), 5904-5915.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Conservation Biology Institute (CBI), Pronatura Noroeste, and T. N. C. (TNC). 2004. Las Californias binational conservation initiative—a vision for habitat conservation in the border region of California and Baja California.

Cutter, S.L., B.J. Boruff, and W.L. Shirley. 2003. "Social Vulnerability to Environmental Hazards." *Social Science Quarterly* 84(2): 242-261.

Das, T., M.D. Dettinger, D.R. Cayan, and H.G. Hidalgo, 2011: Potential increase in floods in California's Sierra Nevada under future climate projections. *Climatic Change*, 109(1), 71-94.

Dedina, S. (1995). The political ecology of transboundary development: land use, flood control and politics in the Tijuana River Valley. *Journal of Borderlands Studies*, *10*(1), 89-110.

Eaton-Gonzalez, R., & Mellink, E. (2015). One shared region and two different change patterns: Land use change in the binational Californian Mediterranean Region. Land, 4(4), 1138-1154.

Espinoza, V., Waliser, D. E., Guan, B., Lavers, D. A., & Ralph, F. M. (2018). Global analysis of climate change projection effects on atmospheric rivers. *Geophysical Research Letters*, *45*(9), 4299-4308.

Farley, K. A., Ojeda-Revah, L., Atkinson, E. E., & Eaton-González, B. R. (2012). Changes in land use, land tenure, and landscape fragmentation in the Tijuana River Watershed following reform of the ejido sector. *Land Use Policy*, *29*(1), 187-197.

Fisher, J. B., et al. (2017), The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources, Water Resour. Res., 53, 2618–2626.

Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason and M. Rummukainen, 2013: Evaluation of Climate Models. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Gershunov, A., Johnston, Z., Margolis, H. G., & Guirguis, K. (2011). The California heat wave 2006 with impacts on statewide medical emergency: A space-time analysis. *Geography Research Forum*, *31*, 53–59.

Gershunov, A., Shulgina, T., Clemesha, R. E., Guirguis, K., Pierce, D. W., Dettinger, M. D., & Ralph, F. M. (2019). Precipitation regime change in Western North America: the role of Atmospheric Rivers. *Scientific reports*, *9*(1), 1-11.

Giner, M. E., Córdova, A., Vázquez-Gálvez, F. A., & Marruffo, J. (2019). Promoting green infrastructure in Mexico's northern border: The Border Environment Cooperation Commission's experience and lessons learned. Journal of environmental management, 248, 109104.

González, A. O. O., Navarro, A. R., Salgado, R. M., Nicieza, C. G., & Fernández, M. I. Á. (2012). Urban development and human activity as factors in terrain instability in Tijuana. Engineering Failure Analysis, 19, 51-62.

Goodrich, K. A., Boudreau, D., Crooks, J. A., Eguiarte, A., & Lorda, J. (2018). The Role Of Community Capitals in Climate Change Adaptation in a Binational Setting. *Addressing climate change at the community level in the United States*, 243-258.

Goodrich, K. A., Basolo, V., Feldman, D. L., Matthew, R. A., Schubert, J. E., Luke, A., Eguiarte, A., Boudreau, D., Serrano, K., Reyes, A.S.,Contreras, S., Houston, D., Cheung, W., AghaKouchak, A., & Sanders, B.F. (2020). Addressing Pluvial Flash Flooding through Community-Based Collaborative Research in Tijuana, Mexico. *Water*, *12*(5), 1257.

GNEB (2016). Good Neighbor Environmental Board 17th Report: Climate Change and Resilient Communities Along the US-Mexico Border: The Role of the Federal Agencies. *Washington, DC. https://www.epa.gov/sites/production/files/2016-12/documents/17th_gneb_report_publication_120516_final_508.pdf*.

Gudino-Elizondo, N., Biggs, T. W., Bingner, R. L., Langendoen, E. J., Kretzschmar, T., Taguas, E. V., ... & Yuan, Y. (2019). Modelling runoff and sediment loads in a developing coastal watershed of the US-Mexico Border. Water, 11(5), 1024.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Herrera, J. (2020, January 5). How Trump Created a New Global Capital of Exiles. *Politico.* Retrieved from https://www.politico.com/news/magazine/2020/01/05/trump-tijuana-extracontinentales-immigrants-093223

Instituto Municipal de Planeación de Tijuana. *Programa Parcial de Majoramiento Urbano de la Subcuenca los Laureles (2007-2015)*.

Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007: Impacts, adapta- tion and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson. Cambridge: Cambridge University Press.

Jennings, Megan K., Dan Cayan, Julie Kalansky, Amber D. Paris, Dawn M. Lawson, Alexandra D. Syphard, Udara Abeysekera, Rachel E.S. Clemesha, Alexander Gershunov, Kristen Guirguis, John M. Randall, Eric D. Stein, and Sula Vanderplank. (San Diego State University). 2018. San Diego County ecosystems: ecological impacts of climate change on a biodiversity hotspot. California's Fourth Climate Change Assessment, California Energy Commission. Publication number: CCCA4-EXT-2018-010.

Kalansky, Julie, Dan Cayan, Kate Barba, Laura Walsh, Kimberly Brouwer, Dani Boudreau. (University of California, San Diego). 2018. San Diego Summary Report. California's Fourth Climate Change Assessment. Publication number: SUM-CCCA4-2018-009.

Kao, J and Lu, D. (2019, August 18). How Trump's Policies Are Leaving Thousands of Asylum Seekers Waiting in Mexico. *The New York Times*. Retrieved from https://www.nytimes.com/interactive/2019/08/18/us/mexico-immigration-asylum.html

Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi and H.J. Wang, 2013: Near-term Climate Change: Projections and Predictability. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M.

Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kopinak, K., & Barajas, M. D. R. (2002). Too close for comfort? The proximity of industrial hazardous wastes to local populations in Tijuana, Baja California. *The Journal of Environment & Development*, *11*(3), 215-246.

Kopinak, K. (2003). Maquiladora industrialization of the Baja California Peninsula: the coexistence of thick and thin globalization with economic regionalism. *International Journal of Urban and Regional Research*, *27*(2), 319-336.

Lara-Valencia, F., Brazel, A. J., Mahoney, E., Raja, R., & Quintero, M. (2010). The response of US–Mexico border cities to climate change: current practices and urgent needs. *Southwest Consortium for Environmental Research and Policy*.

Lemos, M. C., and A. Agrawal. 2006. Environmental governance. *Annual Review of Environment and Resources* 31:297–325.

Nakaegawa, T., Kitoh, A., & Hosaka, M. (2013). Discharge of major global rivers in the late 21st century climate projected with the high horizontal resolution MRI‐AGCMs. *Hydrological Processes*, *27*(23), 3301-3318.

Neri, C., & Magaña, V. (2016). Estimation of vulnerability and risk to meteorological drought in Mexico. *Weather, Climate, and Society*, *8*(2), 95-110.

Ocean Protection Council (2018). State of California Sea Level Rise Guidance, 2018 Update. *Ocean Protection Council: Sacramento, CA, USA*, 84.

Ochoa González, Y., & Ojeda-Revah, L. (2017). Conservación de vegetación para reducir riesgos hidrometereológicos en una metrópoli fronteriza. *Estudios fronterizos*, *18*(35), 47-69.

Ojeda‐Revah, L., Bocco, G., Ezcurra, E., & Espejel, I. (2008). Land‐cover/use transitions in the binational Tijuana River watershed during a period of rapid industrialization. Applied Vegetation Science, 11(1), 107-116.

Peters, R., Ripple, W. J., Wolf, C., Moskwik, M., Carreón-Arroyo, G., Ceballos, G., & List, R. (2018). Nature divided, scientists united: US–Mexico border wall threatens biodiversity and binational conservation. BioScience, 68(10), 740-743.

Pierce, D. W., Cayan, D. R., & Thrasher, B. L. (2014). Statistical downscaling using localized constructed analogs (LOCA). *Journal of Hydrometeorology*, *15*(6), 2558-2585.

Pierce, D. W., J. F. Kalansky, and D. R. Cayan (Scripps Institution of Oceanography) (2018). *Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment.* California's Fourth Climate Change Assessment, California Energy Commission. Publication Number: CNRA-CEC-2018-006.

Rempel, R. S., & Hornseth, M. L. (2017). Binational climate change vulnerability assessment of migratory birds in the Great Lakes Basins: Tools and impediments. *PloS one*, *12*(2).

Revi, A., D.E. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R.B.R. Kiunsi, M. Pelling, D.C. Roberts, and W. Solecki, 2014: Urban areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang, 2013: Observations: Ocean. In: *Climate Change 2013: The Physical Scien*ce Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D.

Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ríos Patrón E., González Terrazas D.I., González Mora I.D. (2019) Climate Change and Vulnerability of Water Resources in Mexico: Challenges for Basin Management. In: Guerrero García Rojas H. (eds) Water Policy in Mexico. Global Issues in Water Policy, vol 20. Springer.

Romero-Lankao, P., J.B. Smith, D.J. Davidson, N.S. Diffenbaugh, P.L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz, 2014: North America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1439-1498.

Ruiz-Gibert, J. M., Hallack-Alegría, M., Robles-Morua, A., & Molina-Navarro, E. (2019). Using an integrated hydrological model to estimate the impacts of droughts in a semiarid transboundary river basin: the case of study of the Tijuana River Basin. *International Journal of River Basin Management*, 1-16.

Saxod, E., Castro, J. L., Silvan, L., & Reyna, M. A. (2007). A Binational Planning Approach for the Development of the Tijuana River Watershed: Policy Options from Rhetoric to Action. Retrieved from Internet site of Southwest Consortium for Environmental Research and Policy (SCERP).

Sánchez Rodríguez, R. A., & Morales Santos, A. E. (2018). Vulnerability assessment to climate variability and climate change in Tijuana, Mexico. Sustainability, 10(7), 2352.

Seager, R. and G.A. Vecchi, 2010: Greenhouse warming and the 21st century hydroclimate of southwestern North America. *Proceedings of the National Academy of Sciences of the United States of America*, 107(50), 21277-21282.

Stott, P. A., Gillett, N. P., Hegerl, G. C., Karoly, D. J., Stone, D. A., Zhang, X., & Zwiers, F. (2010). Detection and attribution of climate change: a regional perspective. Wiley Interdisciplinary Reviews: Climate Change, 1(2), 192-211.

Takahashi, K. (2009). The global hydrological cycle and atmospheric shortwave absorption in climate models under CO2 forcing. *J. Clim.*, 22, 5667–5675.

Taniguchi, K. T., Biggs, T. W., Langendoen, E. J., Castillo, C., Gudino-Elizondo, N., Yuan, Y., & Liden, D. 2018. Stream channel erosion in a rapidly urbanizing region of the US-Mexico border: documenting the importance of channel hardpoints with Structure-from-Motion photogrammetry. Earth Surface Processes and Landforms.

Trenberth, K. E., Fasullo, J. T., & Shepherd, T. G. (2015). Attribution of climate extreme events. *Nature Climate Change*, *5*(8), 725-730.

TRNERR. (2017). *Climate Understanding & Resilience in the River Valley*. Imperial Beach, CA. Retrieved from https://trnerr.org/currv/

United States Library of Congress (USLOC). 2005. REAL ID act of 2005.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, *53*(3), 2404–2418. https://doi.org/10.1002/2016WR019638

USGS. NDVI, The Foundation for Remote Sensing Phenology. Accessed 15 May 2020. https://www.usgs.gov/land-resources/eros/phenology/science/ndvi-foundation-remote-sensing-phenology?qt-science_center_objects=0#qt-science_center_objects

Vano, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., et al. (2014). Understanding Uncertainties in Future Colorado River Streamflow. *Bulletin of the American Meteorological Society*, *95*(1), 59–78. https://doi.org/10.1175/BAMS-D-12-00228.1

Varady, R. G., Scott, C. A., Wilder, M., Morehouse, B., Pablos, N. P., & Garfin, G. M. (2013). Transboundary adaptive management to reduce climate-change vulnerability in the western US–Mexico border region. *Environmental Science & Policy*, *26*, 102-112.

Voskamp, I. M., & Van de Ven, F. H. (2015). Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events. *Building and Environment*, *83*, 159-167.

Veerabhadran Ramanathan, Juliann E. Allison, Maximilian Auffhammer, David Auston, Anthony D. Barnosky, Lifang Chiang, William D. Collins, Steven J. Davis, Fonna Forman, Susanna B. Hecht, Daniel Kammen, C.-Y. Cynthia Lin Lawell, Teenie Matlock, Daniel Press, Douglas Rotman, Scott Samuelsen, Gina Solomon, David G. Victor, Byron Washom, 2015: Executive Summary of the Report, Bending the Curve: 10 scalable solutions for carbon neutrality and climate stability. Published by the University of California, October 27, 2015.

Wang, J., Yin, H., Reyes, E., Smith, T., Chung, F. (2018). Mean and Extreme Climate Change Impacts on the State Water Project. California's Fourth Climate Change Assessment. Publication number: CCCA4-EXT-2018-004.

Wilder, M., Scott, C. A., Pablos, N. P., Varady, R. G., Garfin, G. M., & McEvoy, J. (2010). Adapting across boundaries: climate change, social learning, and resilience in the US–Mexico border region. *Annals of the Association of American Geographers*, *100*(4), 917-928.

Wilder, M., G. Garfin, P. Ganster, H. Eakin, P. Romero-Lankao, F. Lara-Valencia, A. A. Cortez-Lara, S. Mumme, C. Neri, and F. Muñoz-Arriola. 2013. "Climate Change and U.S.- Mexico Border Communities." In Assessment of Climate Change in the Southwest United States: A Re- port Prepared for the National Climate Assessment, edited by G. Garfin, A. Jardine, R. Merideth, M. Black, and S. LeRoy, 340–384. A report by the Southwest Climate Alliance. Washington, DC: Island Press.