The Effects of Warming Temperatures on Biomonitoring Metrics in California, 2000-2050

Jo-an Chen

ABSTRACT

Climate change is predicted to negatively affect freshwater benthic macroinvertebrates as a result of temperature preferences. Recent warming temperatures and a persistent drought threaten the habitats of these species, which may result in changes in distribution and range. I randomly selected 174 sites and modeled the current and future distribution of Ephemeroptera, Trichoptera, and Plectopera species in California from 2000 to 2050 using publicly-available biomonitoring datasets from the California Environmental Data Exchange Network. Based on changes in EPT richness and genus-level tolerance values from a sampled site, I calculated the difference in biomonitoring metrics of benthic macroinvertebrate communities. I constructed species distribution models using four WorldClim's projected annual climatic variables within MaxEnt. Overall, the models predicted general trends of decreasing species diversity and northward shifting towards cooler temperatures under projected climate change. Biomonitoring metrics, in terms of EPT richness and genus-level tolerance values, decreased in overall richness and reflected decreasing sensitivity to changing climatic conditions because tolerance values were higher. Despite the limitations and uncertainties involved in modeling, the projected changes in species distribution highlight the vulnerability of sensitive macroinvertebrates and the need to implement measures to protect freshwater resources against projected climate change.

KEYWORDS

species distribution modeling, EPT species, water quality, Maxent, climate change

INTRODUCTION

Climate change is a global phenomenon that has impacted California especially through increasing average annual temperatures and irregular precipitation patterns. Cal-Adapt estimates that California's 2015 average temperature has increased 1.36% (a total of almost 1◦C) compared to historic 1960 average temperature (California Energy Commission, 2015) and predicts that California will experience an increase in frequency and magnitude of extreme warm temperatures from June to September. These changes in temperature and precipitation lead to multiple hot days in succession and a potential for longer durations of heat waves. Moreover, frequent heat waves can potentially lead to declines in precipitation events, depleting spring snowpacks and increasing summer dryness (Cayan et al. 2009). All these predicted scenarios explain the current California drought and endanger the quantity and quality of our freshwater systems. Thus, climate change severely threatens freshwater resources, reducing habitat availability, diversity, and available oxygen (Combes, 2003) – all of which affect many sensitive species, such as benthic macroinvertebrates. Therefore, with increasing temperatures, low precipitation, and threatened water resources, freshwater species benthic macroinvertebrates will be severely affected due to their temperature sensitivity.

The presence of certain freshwater benthic macroinvertebrates towards physical and anthropogenic factors can reflect sensitivity to the conditions of their surrounding environments. For example, macroinvertebrate communities can indicate the presence of pollutants and the magnitude of pollution over time in a freshwater system (Mandaville, 2002). Using species to understand ecosystem health is known as biomonitoring, a method of surveying the environment by observing the presence, abundance, or behavior of an indicator (Bonada et al. 2006). Benthic macroinvertebrates are ideal indicators for biomonitoring as they vary greatly in life history and make up a diverse 39% of all freshwater species in California (Ball et al. 2013). Of the benthic macroinvertebrates, the three most sensitive orders are Ephemeroptera, Plectoptera, and Trichoptera (EPT). Families within these three orders have the lowest tolerance values to pollution (Mandaville, 2002). EPT species also represent a broad range of trophic levels in the food web, hence changes in their population and distribution will impact other species within the ecosystem (Bonada et al. 2006). These physical features make EPT species ideal indicators for their freshwater environment, which we can census them to understand the conditions of freshwater systems and larger environmental systems.

A majority of EPT species are expected to lose climatically suitable areas and experience decreases in population numbers, richness, and biodiversity. Past studies by Domisch et al. (2013) and Shah et al. (2015) incorporated the use of bioclimatic envelope models on EPT species in North America and projected that climatically suitable areas would shift on average 1°N latitude after 2080 (Shah et al, 2015). Although species may gradually adapt, there will be a general decrease in general richness and biodiversity (Domisch et al, 2013). EPT species are especially temperature sensitive, as increasing temperatures lower hatching time and rates. For example, for only an increase in temperature by 0.20°C, the hatching success percentage for *Ephemerella ignita*, an Ephemeroptera species, dropped from 90% to 10% (Elliot, 1978). With EPT species shifting and disappearing in terms of diversity and abundance, the quality of our current freshwater biomonitoring metrics will be severely impacted. Although studies have examined EPT distributions in response to climate change, none have addressed the implications of macroinvertebrate community changes on biomonitoring metrics. It is critical to bridge this knowledge gap so we can project future changes in how we assess the health of our ecosystems for better freshwater management.

This study aims to answer the central question: how will warming temperatures affect richness and tolerance of benthic macroinvertebrate communities in California. I examined the effects on current EPT species distribution, which in turn will suggest ways that our biomonitoring metrics will be impacted. Using past and present data, I will incorporate them into my species distribution model to determine potential outcomes of EPT species, to see if their populations will shift with future predicted temperatures. I hypothesized that: (1) EPT species diversity will decrease overall, (2) EPT species will shift northward where temperatures are cooler, (3) biomonitoring metrics (such as EPT richness and mean tolerance values) will decline in richness and sensitivity as less sensitive EPT species will be less affected by climate change and persist in replacement of more sensitive EPT species.

METHODS

Benthic Macroinvertebrate Data

To obtain data for species distribution modeling, I downloaded information regarding the spatial locations of sampled EPT species from the California Environment Data Exchange Network (CEDEN) (http://ceden.waterboards.ca.gov/AdvancedQueryTool), under the Benthic Results Category. CEDEN is an online collaborative public data source, created by the State Water Resources Control Board to aggregate statewide surface water quality data in California. From CEDEN's database, 70,927 individuals were collected from January 2000 to December 2015. To build the database, I used R package 'readr' and 'stringr' data cleaning and vetting. I vetted data by deleting incomplete records to reduce potential errors. Relevant columns that contributed to my database included information regarding latitude, longitude, and final identifications to create a presence-absence dataset. Records without geographical coordinates and final identification were removed from the database. For each of the Ephemeroptera, Trichoptera, and Plecoptera order, I categorized and accumulated presence data from 2000-2015, for a 15 year resolution into separate databases. This assumed that if EPT species have been found once in a site, they would be found in that same site preceding the following years for this 15 year window. Through accumulating 15 years of species records, my databases amounted to a total of 30,699 Ephemeroptera points, 27,268 Trichoptera points, and 12,960 Plecoptera points within the California boundary.

Climate Data

To observe and project California's past, present, and future climatic conditions, I obtained tabular climate data from WorldClim (www.worldclim.org/). WorldClim is one of the most referenced and downloaded data source for obtaining current and predicted climatic raster data. I chose to represent climate change using four main environmental parameters: annual average temperature (◦C), annual minimum temperature (◦C), annual maximum temperature (◦C), and annual average sum of precipitation (mm). These parameters are the most commonly used, along with the 19 bioclimatic parameters (Shah et al, 2014). To represent current climatic conditions, I downloaded 30-second resolution (~1km spatial resolution) ESRI grids for the climatic variables in addition to 19 bioclimatic data. For future data, I obtained 2050 annual climate data of the same four variables and bioclimatic variables. I selected 30-second resolution under the GFDL-CM3 with RCP-26 (Representative Concentration Pathways). This climate model was developed by the Geophysical Fluids Dynamic Laboratory (GFDL), has high climate sensitivity, and projects a 4.5◦C rise in annual temperature by 2070-2099 (Cal-Adapt, 2016).

Species Distribution Modeling

To build the species distribution models, I overlaid the previously collected specimen records using MaxEnt and R with environmental data. Maximum Entropy of Information (MaxEnt) is a species distribution modeling program, often used by government and non-government organizations to map biodiversity and forecast distributions. MaxEnt assumes that the best approximation of the unknown distribution is the one that has uniform distribution, subjected to the constraints, agreeing with everything known and assuming little of the unknown. MaxEnt also assumes a pseudo-absence approach, using presence data and background environmental data of the entire area (Phillips et al. 2006). I ran all EPT genera under MaxEnt to observe percentage contribution of the four climatic variables representing climate change. Percentage contribution depicts variations of the degree of how the four climatic variables impacted each genus's spatial distribution. This therefore leads to differently weighted climatic variables in the species distribution models. MaxEnt also generated ASCII maps depicting probabilities of each genus' presence throughout California.

Using MaxEnt to compare richness measures between current and future climatic conditions, I used predicted 2050 conditions into MaxEnt to generate future probabilities. 174 sites were randomly chosen throughout California by creating random points through stratified sampling in ArcMap and recording the sampled sites (Appendix A). Three random points were generated within each county. To determine genus presence, I obtained binary values: 1 or 0 for each species that had a probability of 0.65 or higher appearing at the site. These were totaled for each site for current and future climatic conditions and compared to determine richness changes (e.g Figure 1) within each of the sampled sites.

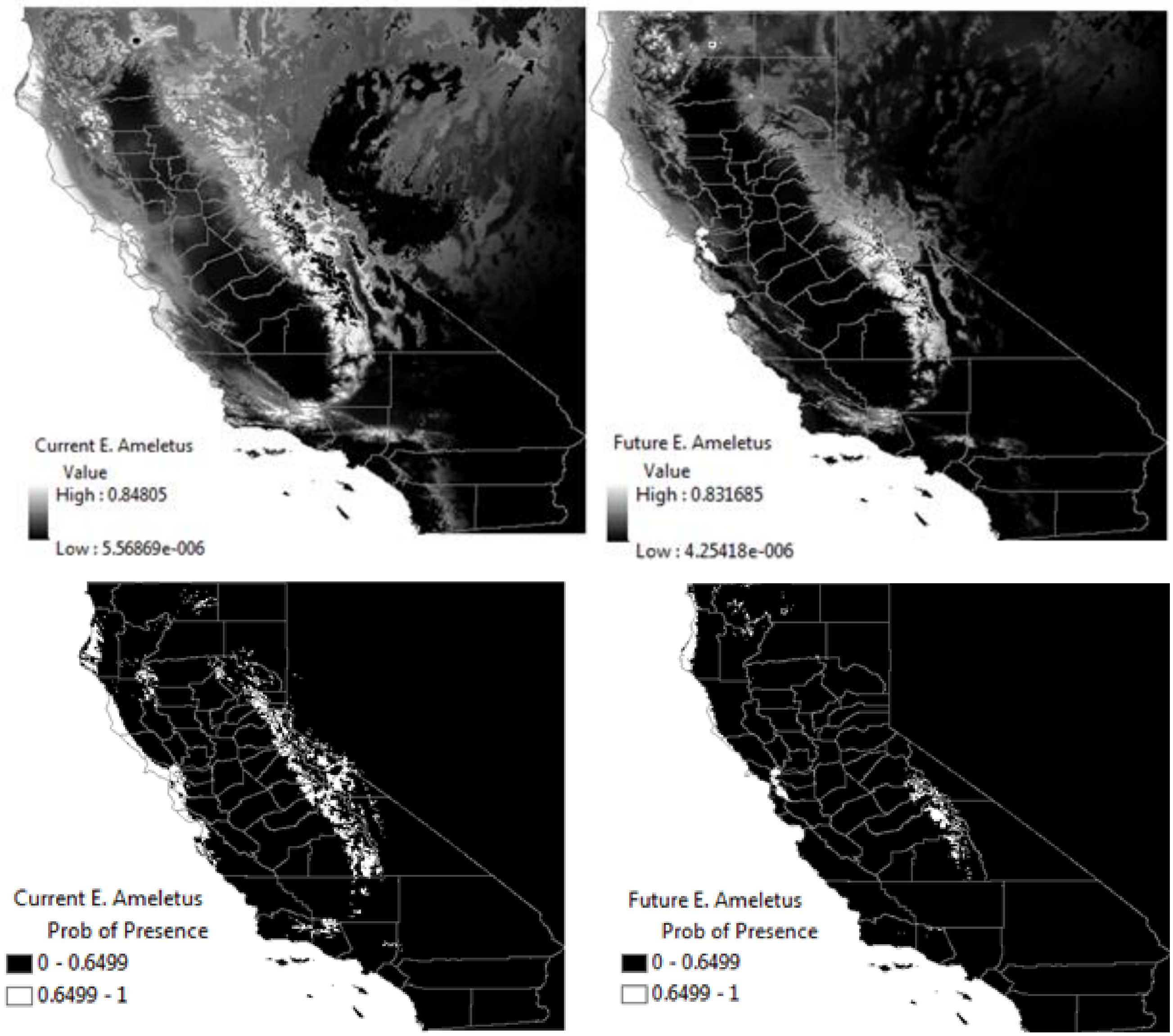


Figure 1. MaxEnt generated probability of presence for *E. Ameletus* of current and future climatic conditions, with presence defined as 0.65 or above. Comparing 2015 to 2050 conditions, *Ameletus* experienced decreases in areas with a high probability of presence. Below is a binary comparison wherein white areas indicate areas with presence.

Richness and Tolerance Value Analysis

To obtain a higher resolution of changes in shifts beyond order levels, I analyzed richness changes and geographical shifts at the genus level. Richness was plotted against rising latitudes for combined EPT, E, P, and T genera in both current and projected climate scenarios. To determine geographical shifts, current and future richness peaks were compared in terms of latitude to visualize distribution changes. In addition to latitude, richness throughout hydrological unit code (HUC) watershed boundaries were also compared. HUC boundaries were developed by the US Geological Survey to determine drainage areas of a major river, closed basins, and combined watersheds (USGS, 2015). This depicts hydrological networks joined together or within close proximity to each other, representing habitat regions for EPT species. Besides richness, another important biomonitoring metric is the Hilsenhoff Biotic Index which estimates the overall tolerance of the community in a sampled area, weighted by the relative abundance of each taxonomic group (SAFIT, 2008). Given tolerance values for each genus, with 0 representing very sensitive taxa and 5 or higher representing more tolerant taxa, the mean tolerance value for each of the 174 sampled sites was calculated for both current and future climatic conditions. Mean tolerance values were also plotted against latitude to observe changes in site sensitivity and species tolerance with different climatic conditions.

RESULTS

Model Performance

Model performance was generally high with an average true statistical skill of 0.562, indicating a model performance closer to +1 than 0 (random performance) (Allouche, 2006). In terms of EPT breakdown, the total percentages of Ephemeroptera, Plecoptera, and Trichoptera species were 43.3%, 18.3%, and 38.4% respectively, of the total observations. Within three orders, I ran each genus under MaxEnt to obtain the percentage of climatic variable importance in determining species distribution in California. This high model performance thus enabled me to include the three benthic macroinvertebrate orders in my analyses and allowed for accurate predictions of changes in biomonitoring metrics.

Individual Taxa

Current Latitudinal Patterns

After inputting WorldClim data for 2015 climatic variables into MaxEnt to represent current climatic conditions, MaxEnt generated percentages of which climatic variable contributed the most during the modeling process. I repeated this procedure for each EPT genus (Figure 2)**.** Overall, precipitation was the most defining climatic feature that heavily correlated with EPT presence, contributing approximately 64±15%. The least defining climatic feature was maximum annual temperature (9±13%) (Figure 2). Within each individual order, each genus had varying percent contributions for the four climatic variables. In all genus cases, precipitation had the highest standard deviation from the average percent contribution. Appendix B contains a complete list of all climatic variable importance for each genus.

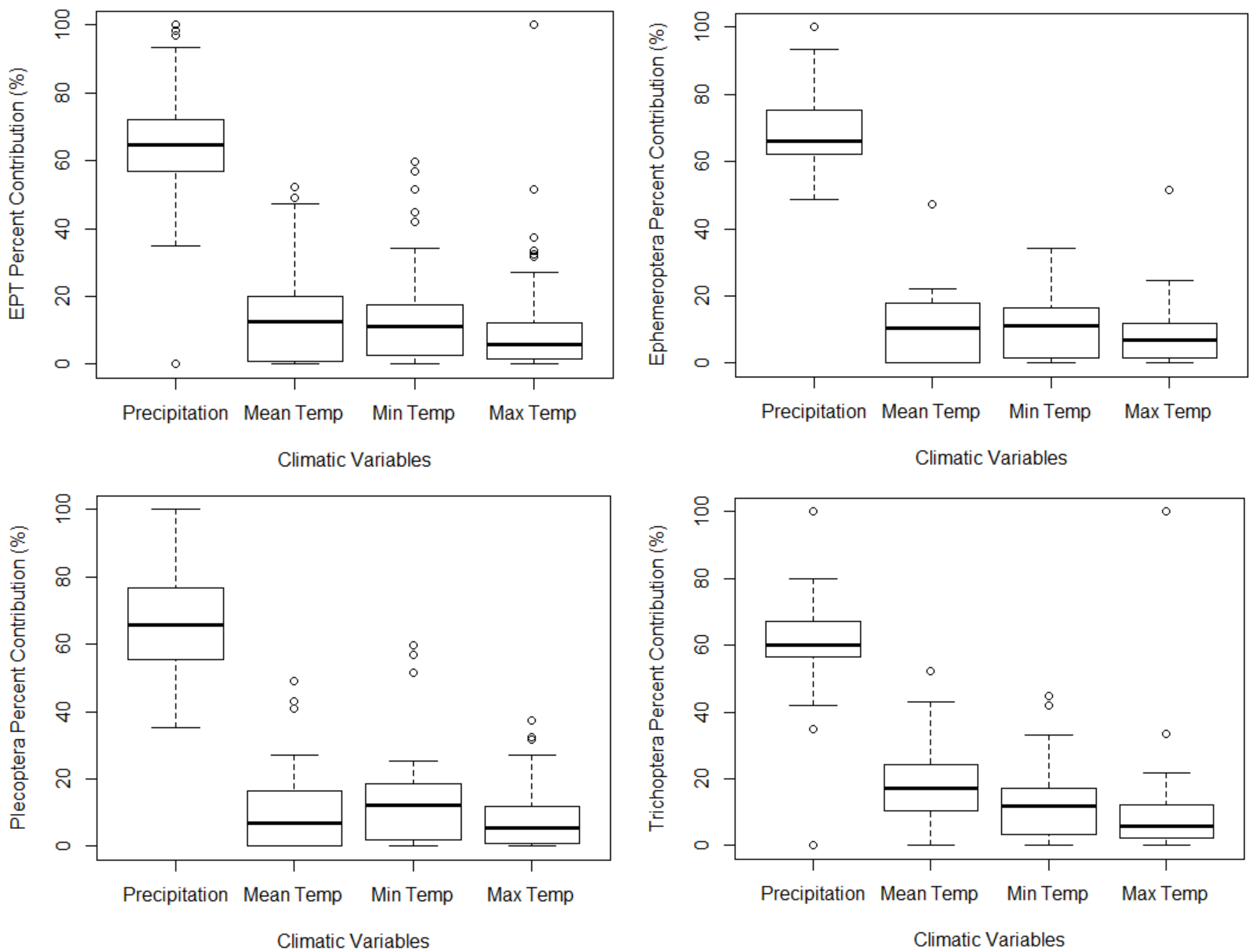
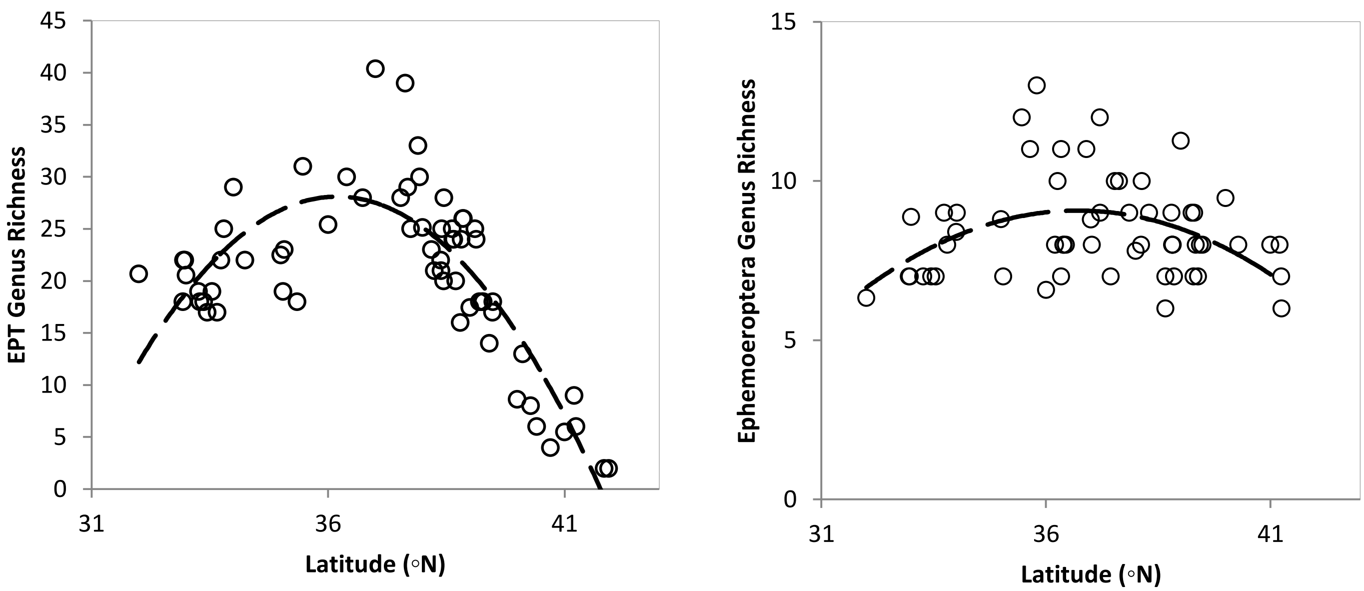


Figure 2. Percentage Contributions of Climatic Variables for Combined and Individual Ephemeroptera, Plecoptera, and Trichoptera Genus. For all EPT taxa, precipitation is the most important climatic variable when determining how species are affected by changing climates. Average percent contribution for precipitation, bioclim variables, minimum, and maximum temperature, are combined EPT (64±15, 13±12, 13±12, 9±13), Ephemeroptera (69±12, 11±10, 11±10, 9±10), Plecoptera (66±18, 11±13, 14±16, 9±11), and Trichoptera (60±14, 17±12, 13±11, 10±15, respectively.

Alongside percent contributions, MaxEnt also generated raster files depicting a logistic estimate between 0 and 1 of the probability of species presence. The probability of presence uses the inputted species sample points along with climatic variables to interpolate across the entire California study site. The logistic output estimates presence probability assuming that sampling design is such that typical presence localities are attributed with 0.5 presence probability. In my model and richness calculations, I defined species presence if the probability was greater than or equal to 0.65 at sample sites.

Combined EPT genera richness showed a quadratic pattern across the latitudinal range of California (Figure 3). Richness peaks for combined EPT taxa peaked at 36.2 ± 8◦N, including: Ephemeroptera (36.7 ± 1.5◦N), Plecoptera (35.7 ± 2◦N), and Trichoptera (36.5 ± 4◦N). Comparing to the quadratic trends of Plecoptera and Trichoptera genera, Ephemeroptera's increase and decrease in genus richness along rising latitude is relatively more linear. There is correspondingly, a smaller standard deviation.



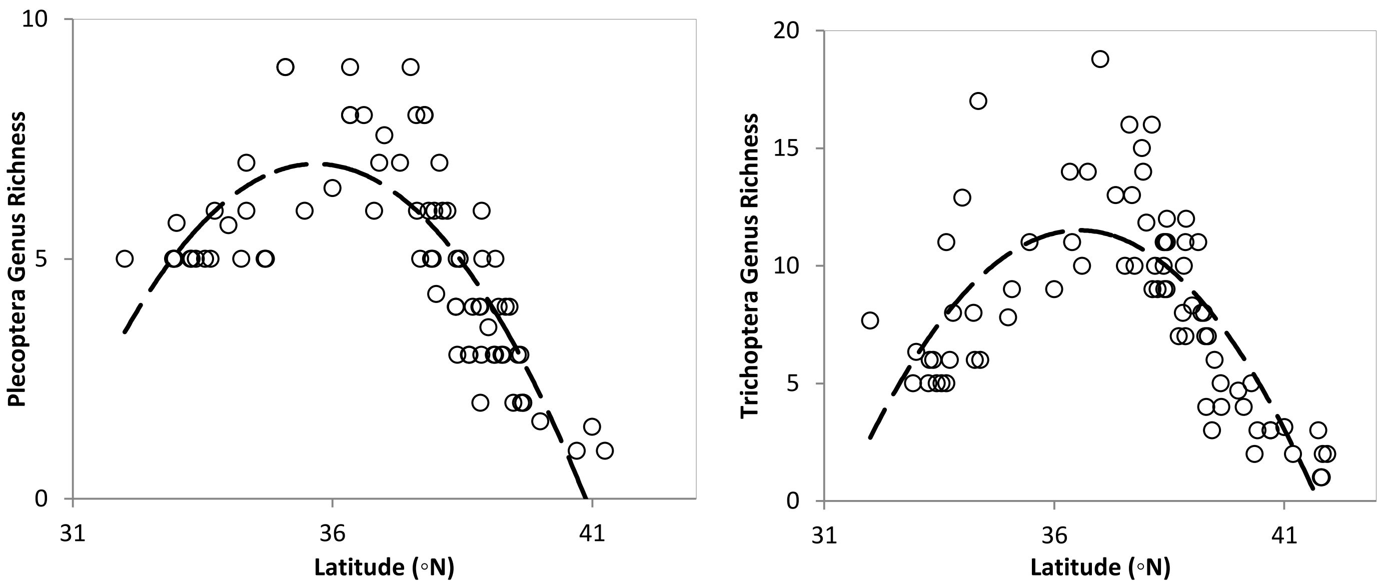


Figure 3. Spatial Patterns of genus richness for combined Ephemeroptera, Plecoptera, and Trichoptera (EPT). The best fit trendline (quadratic) is presented. All graphs depict a peak in richness around 36◦N latitudes. Combined EPT (R^2 = 0.69), Ephemeroptera (R^2 = 0.18), Plecoptera (R^2 = 0.66), Trichoptera (R^2 = 0.59).

Future Predicted Latitudinal Patterns

When comparing richness measures of current and future climatic conditions against latitudes, there is a decreased richness for all of E, P, T, and combined EPT genera. In terms of future conditions, combined EPT genera richness showed a quadratic pattern across the latitudinal range of California (Figure 4). Richness peaks for combined EPT taxa peaked at 37.9 ± 5◦N, including: Ephemeroptera (36.9 ± 2.2◦N), Plecoptera (37.1 ± 1.5◦N), and Trichoptera (37.3 ± 2.6◦N). The overall trend depicts a northward shift on average by 1.025◦N (112km) (Table 1).

	Ephemeroptera Genus	Plecoptera Genus	Trichoptera Genus	Combined EPT Genus
Current Richness Peak	36.7◦N	35.7◦N	36.5◦N	36.2◦N
Future Richness Peak	36.9◦N	37.1◦N	37.3◦N	37.9◦N
Latitudinal Difference	+ 0.2◦N	+ 1.4◦N	+ 0.8◦N	+ 1.7◦N

Table 1. Comparing current and future richness peaks of E, P, and T genera with respect to changing climates. All E, P, and T as well as combined EPT displayed a northward shift.

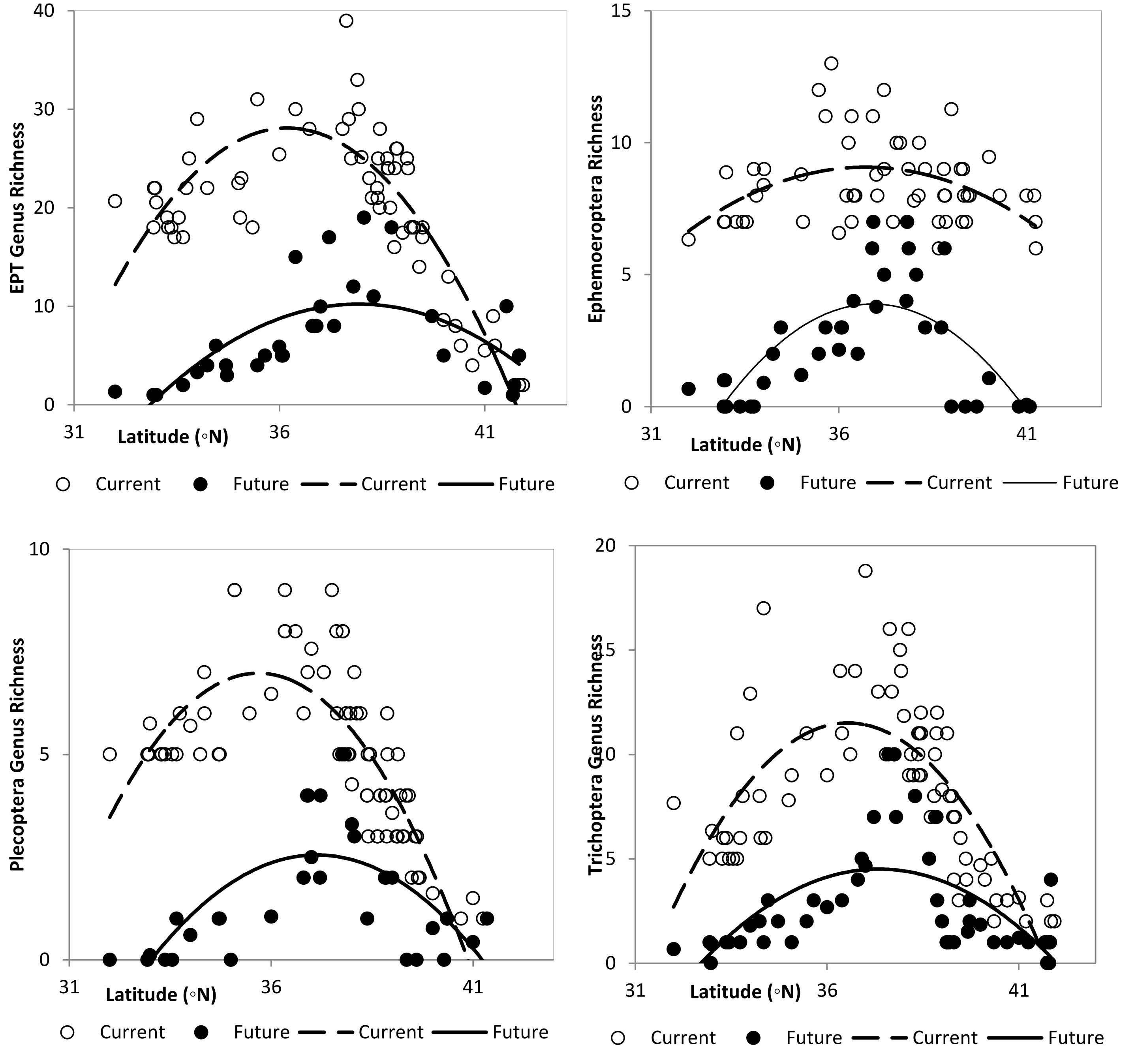


Figure 4. Comparison of Current and Future Spatial Patterns of genus richness for combined Ephemeroptera, Plecoptera, and Trichoptera (EPT) . The best fit trendline (quadratic) is presented. All graphs depict a peak in richness around 37◦N latitudes. Combined EPT (R^2 = 0.49), Ephemeroptera (R^2 = 0.51), Plecoptera (R^2 = 0.47), Trichoptera (R^2 = 0.39).

Besides declines in richness, the abundance of E, P, and T genera also experienced severe declines in counts throughout the 174 sampled sites. E, P, and T genera experienced count percentage declines by 82.9%, 87.0%, and 78.6% respectively comparing 2015 to 2050 conditions (Figure 5). Amongst the Ephemeroptera order, 19.4% of genera disappeared. For Plecoptera, 27.1% genera disappeared, and Trichoptera had 10.9% genera that disappeared. In total, of the 112 different genera, 24 experienced a 100% decline in counts. Besides the genera that disappeared amongst the sampled sites, the five genera with the greatest decrease in richness were: *Caudatella* (-99.0%), *Agraylea* (-97.2%), *Nectopsyche* (-96.8%), *Neothremma* (-96.3%), and *Cinygmula* (-95.1%). The five genera that were least affected were: *Ceratopsyche* (+100%, doubling in numbers), *Zapada* (+33.3%), *Perlinodes* (0%, with no change), *Psychoglypha* (-16.7%), and *Pedomoecus* (-33.3%). Comparing the three orders, Trichoptera genera have the greatest range of percent changes in counts with three genera experiencing the most declines in richness and three genera with the least declines in richness. A further comparison of the top 10 genera with the greatest and lowest richness change is found in Appendix C.

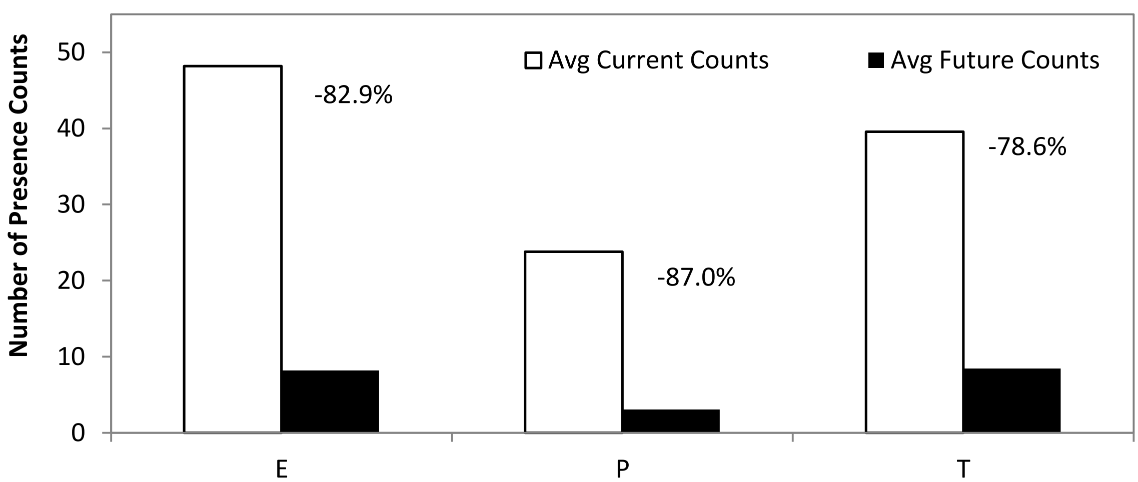


Figure 5. Average E, P, and T genera richness and percent changes in richness for current and future climatic conditions. Overall genera counts all experienced severe declines in counts through the 174 sampled sites throughout California. Plecoptera genera experienced the greatest decline in counts, while Trichoptera genera was least affected.

Biotic Indices and Tolerance Values

Given the environmental sensitivity of E, P, and T taxa, tolerance values have been attributed to each individual genus to be used in biotic indices that will represent freshwater system health. Geographically, overall EPT richness declined within all HUC watershed boundaries for future climatic conditions (Figure 6). Areas throughout the North, East, and South regions of California had richness of 4 or less, based on richness values collected at the 174 sampled sites. By 2050, only two hydrological watershed boundaries had richness between 31-83 – both regions are located in next to the San Francisco Bay. This area is more diverse given the dense freshwater runoff network, or as a result of oversampling.

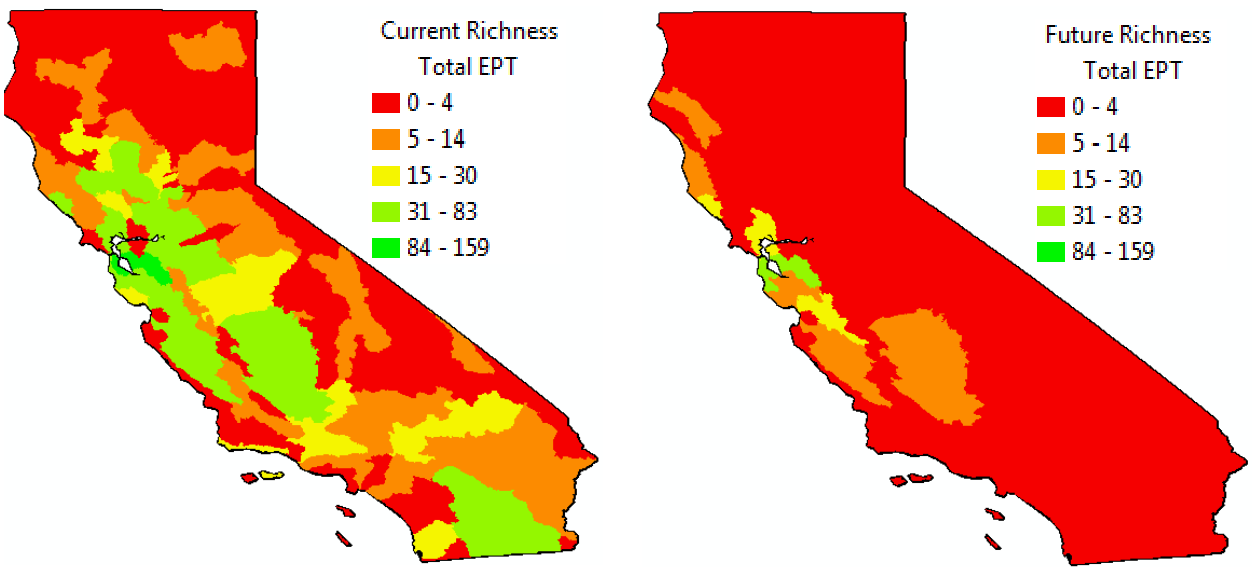


Figure 6. Sum of EPT genera richness in hydrological unit code watershed boundaries (HUC) for current and future climatic conditions. Amongst the 174 sampled sites, the sum of each site were added within each HUC boundary to determine richness with respect to watershed boundaries. Future conditions display high richness decreases with each HUC boundary being negatively impacted by worsening climate change.

Comparing current to projected climatic conditions, average mean tolerance values were 2.44 and 4.26, respectively. The mean tolerance value for 2050 was significantly higher than that of 2015 for all the sites, on average reflecting a 74.4% increase in tolerance, represented by a latitudinal gradient throughout California (Figure 7). Not only were mean tolerance values higher in future conditions, the highest values occurred in mid-latitude regions (35.9◦N to 37.8◦N), which were also regions with the greatest EPT genera richness. There was also a greater standard deviation of mean tolerance values for 2050 conditions (1.63SD) as compared to 2015 conditions (0.47SD), reflecting a greater range of site sensitivity.

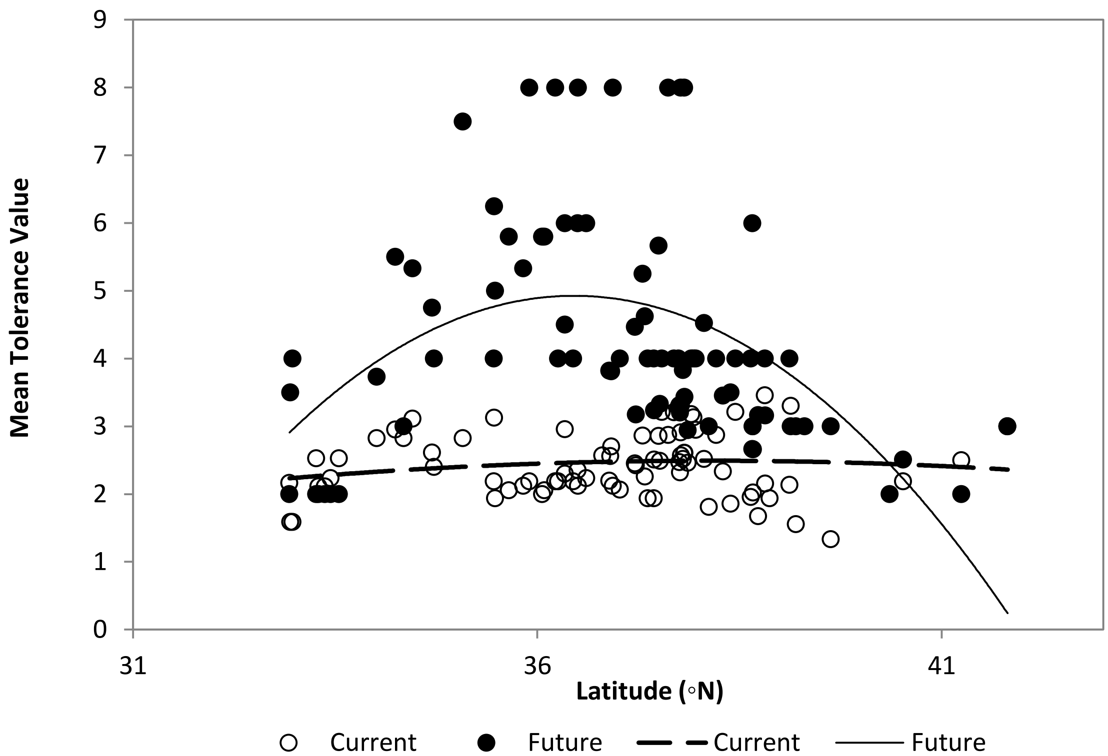


Figure 7. A comparison of current and future mean tolerance values in different sites, by increasing latitudes. Current 2015 show a lower mean tolerance value throughout a latitudinal gradient as compared to 2050 mean tolerance values. In 2050 climatic conditions, mean tolerance values from 36◦N to 37◦N are highest.

DISCUSSION

Developing species distribution models is a critical step to predicting how climate change may shift biomonitoring metrics and our ability to assess freshwater quality in California. Based on the results of the EPT species distribution models and comparisons to the change in biomonitoring metrics, climate change negatively affects EPT genera in California in terms of their distribution and trends in species diversity. Biomonitoring metrics reflect decreases in richness metrics and increases in mean tolerance values over time with warming temperatures. Therefore, this study emphasizes the necessity for environmental managers to adopt conservation strategies that will mitigate the effects of climate change on freshwater biological indicators and overall ecosystem health.

Genera Richness Trends and Patterns

EPT richness decreased for most future modeled sites in California. Current distributions estimate richness peaks in mid-temperature regions where a range of climatically suitable habitats benefit various kinds of freshwater taxa (Heino, 2009). Similar studies by Vinson and Hawkins (2003) found genus-level richness peaks at 40°N, which is higher in latitude than the richness peaks seen in California. This latitude difference may be due to their focus on local richness data and a global-scale analysis. EPT richness measures in California peaked between 36.2°N and 37.8°N, and then decreased with rising latitudes. This peak is explained geographically by the lakes, streams, and rivers present around this region, such as the Tulare-Buena Vista Lakes, San Francisco Bay, Salinas, Panoche-San Luis Reservoir, San Joaquin Delta and many others. Besides HUC boundaries with plentiful stream networks, elevation within these areas is also relatively high, spanning from 1800 to 12000 feet above sea level. This maximum elevation reflects the mountainous terrain and height on the east side of California. Furthermore, snow packs are located in regions with high elevation, and serve as major freshwater resources throughout the summer months.

Although Ephemeroptera species trends were not as strongly observed in current 2015 conditions as compared to that of Plecoptera and Trichoptera species, the latitudinal trends for Trichoptera species were not as consistent in future conditions. Trichoptera species are therefore shown to decline in richness to latitude trends as seen in the other two orders for projected conditions. A similar trend for respective E, P, and T species has been observed by Pearson and Boyero (2009) in their study of gradients in regional diversity of freshwater taxa.

Although past literature show that genera richness peaks are higher in latitude than that of this study's models, past literature by Shah et al. (2015) regarding northward shifts of EPT taxa distributions supports my models. Both Shah et al's (2015) study on species distributional richness in North America and this model for California project E, P, and T species to shift northward on average by 1°N latitude. This shift is towards cooler regions is slow as macroinvertebrate species are constrained by their dependence on hydrological networks. The ability to migrate to higher latitudes and elevation levels will be difficult to overcome given fragmented ecosystems as a result of human activities. Areas with high anthropogenic stressors, such as landuse changes, will lead to poor water quality and restrict EPT species' dispersal capacity (Rife et al. 2004).

Comparing current trends to future predicted trends, there is a strong decline in generic richness for combined EPT, and within individual orders. Warming temperatures and decreasing levels of precipitation impose habitat constraints in terms of temperature, food, and water quality. By 2050, California is predicted to experience higher temperatures and declining snow packs by 1.5% and 25%, respectively (Cal-Adapt, 2016), factors which limit climate suitable areas for EPT genera. Based on the models, only 1.7% of EPT genera benefit from warming temperatures as more potential habitats arise from melting ice to form freshwater streams. Specifically, these genera are *Zapada* and *Ceratopsyche*, with a 33% and 100% increase in counts, respectively, amongst sampled sites. Furthermore, predicted climate change effects are projected to be most severe for Plecoptera species which is supported by other studies (e.g. Hering et al. 2009). This makes sense, given that Plecoptera genera have an overall lower tolerance value of 1.31 ± 0.8, compared to Ephemeroptera (3.21 ± 2.4) and Trichoptera (2.21 ± 2.2). Overall, 97.3% of genera exhibit detrimental losses with climate change.

Biotic Indices and Tolerance Values

Using the assigned tolerance values for each genus to compare mean tolerance values throughout all sampled sites, 2050 projections depict mean tolerance values to be higher than 2015 current conditions. Taxa with higher tolerance values are shown to persist in sites despite warming temperatures and decreasing precipitation rates, due to their ability to withstand climatic changes. Taxa with lower tolerance values disappear in numbers or altogether. Therefore, mean tolerance values for each site appear higher in future conditions, especially around 36 to 37◦N. This shift in mean tolerance values suggests species with higher tolerance are possibly perpetuating at higher rates than species with lower tolerance, especially in mid-latitudes, where richness is higher. Not only are species with higher tolerance persisting, the sampled sites throughout California have also decreased in sensitivity, and are shown to be more negatively impacted by changing climates. In particularly, mid-latitudes with higher richness measures and mean tolerance values are projected to become more sensitive.

Limitations and Challenges

Using MaxEnt, I visually displayed and quantified the magnitude of potential losses and gains of EPT genera under a climate change scenario. Nevertheless, several limitations exist in my data collection, models, and biomonitoring analysis. First, the use of species at the genus level assumes that all species within each genus will have similar niches and responses to climate changes in the future. Species within a genus may have large ranges that have been discounted and overgeneralized (Araujo et al, 2006). However, because I used biomonitoring data, I modeled using the best-available taxonomic resolution for larval aquatic insects at the genus level. Most importantly, species may disappear due to their inability to disperse. Second, when assembling data, I used current climatic conditions and species sampling from 2000-2015 which assumes that past species and climate temperatures have accumulated over time. Third, all data were treated with equal weight, which might have sampling bias, errors, and differences in data collection method. Fourth, model sensitivity should have been tested by running different climatic scenarios. Tests should incorporate varying different combinations of input for optimal conditions for model generation. This can be done by running different climate change projections, or varying environmental parameters ± 10%. Finally, when determining quality and changes of biomonitoring metrics, a large limitation exists in my treatment of models as expected future scenarios. This assumption may not be true given that my models could have errors within. Deviations from metrics may be over or underestimated.

Future Directions

Further analyses of freshwater invertebrate orders and genera outside of E, P, and T can further expand on how climate change affects multiple freshwater taxa. For instance, Diptera genera could be a critical order to analyze as a less-temperature and less-pollution sensitive insect group. These results can then be compared to the results generated from EPT genera to see if temperature and pollution sensitivity is truly affected by climate change. Further studies on other benthic macroinvertebrate taxa will provide more insight to different biomonitoring metrics. Furthermore, when building species distribution models, besides only using MaxEnt and R, I can attempt to generate other models using bioclimatic envelope models, classification and regression trees. These models can then be all tested for performance using TSS to compare which models are best representative of reality. To expand my research, models can be generated, analyzing more orders to obtain a larger amount of data for further comparisons.

Moreover, this research aims to go beyond species distribution modeling of EPT genera in California, by looking at how SDM projects future biomonitoring metric changes. These models allows for better interpretation of how biomonitoring metric changes will lead to water quality changes. This research also only points out how climate change will affect biomonitoring metrics but does not provide methods or solutions that can improve the application of these metrics. Further directions will be to mathematically and statistically create new equations that will factor in climate change. These equations will either replace or build upon pre-existing biomonitoring metric equations to make them resistant to decreasing species richness and abundance with increasing climate change. Another approach will be to recognize percentage change in errors and simply account for a standardized error.

Conclusions and Broader Implications

From generating EPT species distribution models, richness and tolerance displayed both spatial trends and negative impacts as a result of climate change. By analyzing trends on a smaller local scale, I discovered that EPT genera and the biomonitoring metrics associated with them reflected reduced habitat quality with increasing climate change. Although each specific genus exhibited different trends, the patterns of loss remained consistent under future climate scenarios, with a 1.025◦N northward shift by 2050. Although future climatic conditions are a good indicator for EPT genera responses, other variables such as urbanization and habitat fragmentation may increase over time and further threaten freshwater systems. Consequently, freshwater management efforts will be required to mitigate climate change. As biomonitoring metrics are a current standard for interpreting freshwater quality, environmental managers will need to adopt conservation strategies that will protect our threatened freshwater resources. In the larger ecological context, my research addresses the need for better, improved freshwater quality management that will be resistant to climate change as we adjust to the new normal.

ACKNOWLEDGEMENTS

Thanks to the GIF and BIDS team at the University of California, Berkeley, especially Nancy Thomas and Dani Ushizima, who were amazing resources in helping me troubleshoot my species distribution modeling questions. Many thanks to Linda Saunders, Lindsey Agnew, Hannah Hagen, and James Dunn, who all patiently offered great advice, called me out when I fell behind deadlines, pushed me to get my models running. Thanks to Christina Lew, who taught me a ton of tips and tricks for ArcMap and MaxEnt. Thanks to my fellow ESPM 175 peers, who have and will continuously inspire me to give my best in all my life endeavors. Finally, an enormous amount of thanks is due to my mentor Tina Mendez, without whom this project would be nonexistent. Her cheerful enthusiasm and guidance were critical in developing this project. Lastly, I thank my family for all their support to make my achievements possible.

REFERENCES

Allouche, O., A. Tsoar, and R. Kadmon. 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). Journal of Applied Ecology 53: 1223-1232.

Araújo, M., and A. Guisan. 2006. Five (or so) challenges for species distribution modeling. Journal of Biogeography 33:1677-1688.

Ball, J., L. Bêche, P. Mendez, V. Resh. 2013. Biodiversity in Mediterranean-climate streams of California. Hydrobiologia 719: 187-213.

Bonada, N., N. Prat, V. Resh, and B. Statzner. 2006. Developments in aquatic insect biomonitoring: a comparative analysis of recent approaches. Annual review of entomology 51: 495-523.

California Energy Commission. “EXPLORING CALIFORNIA’S CLIMATE CHANGE RESEARCH.” *Cal-Adapt*. 2015. Web. 1 Oct. 2015. <http://cal-adapt.org/>.

Cayan, D., M. Tyree, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, and R. Flick. 2009. Climate change scenarios and sea level rise estimates for the California 2008 climate change scenarios assessment. California Climate Change Center 1: 1-47.

Combes, Stacey. 2003. “Protecting freshwater ecosystems in the face of global climate change.” *Buying Time: A User’s Manual for Building Resistance and Resilience to Climate Change in Natural Systems. WWF Climate Change Program.* Web.

Domisch, S., N. Araújo, N. Bonada, S. Pauls, S. Jähnig, and P. Haase. 2013. Modeling distribution in European streams macroinvertebrates under future climates. Global Change Biology 19: 752-762.

Elith, J., and J. Leathwick. 2009. Species Distribution Models: Ecological Explanation and Prediction Across Space and Time. Annual Review of Ecology, Evolution, and Systematics 40: 677-697.

Elith, J., S. Phillips, T. Hastie, M. Dudik, Y. Chee, and C. Yates. 2011. A statistical explanation of MaxEnt for ecologists. Diversity and Distributions 17: 43-57.

Elliott, J. 1978. Effect of temperature on the hatching time of eggs of Ephemerella ignita (Poda) (Ephemeroptera: Ephemerellidae). Freshwater biology 8: 51-58.

Feeley, K., and M. Silman. 2011. Keep collecting: Accurate species distribution modeling requires more collections than previously thought. Diversity and Distributions 17: 1132-1140.

Heino, J. 2009. Biodiversity of aquatic insects: spatial gradients and environmental correlates of assemblage-level measures at large scales. Freshwater Reviews 2:1-29.

Hering, D., A. Schmidt-Kloiber, J. Murphy, S. Lucke, C. Zamora-Munoz, M. J. Lopez-Rodriguez, T. Huber, and W. Graf. 2009. Potential impact of climate change on aquatic insects: a sensitivity analysis for European caddisflies (Trichoptera) based on distribution patterns and ecological preferences. Aquatic Sciences 71:3-14.

Hijmans, R., J. Elith. 2016. Species distribution modeling with R Introduction. https://cran.r-project.org/web/packages/dismo/vignettes/sdm.pdf. The R foundation for statistical computing

Mandaville, S. 2002. Benthic Macroinvertebrates in Freshwaters – Taxa Tolerance Values, Metrics, and Protocols. Soil & Water Conservation Society of Metro Halifax. Web.

Murphy, J. F., C. E. Davies, and T. A. Corbin. 2008. Developing indicators to climate-induced change in UK river ecosystems. Climate change and aquatic ecosystems in the UK: 1:15-24.

Mulholland, P., G. Best, C. Coutant, G. Hornberger, J. Meyer, P. Robinson, J. Stenberg, R. Turner, F. Vera-Herrera, and R. Wetzel. 1997. Effects of climate change on freshwater ecosystems of the South-eastern United States and the Gulf Coast of Mexico. Hydrological Processes 11: 949-970.

Pearson, R. G., and L. Boyero. 2009. Gradients in regional diversity of freshwater taxa. Journal of the North American Benthological Society 28:504-514.

Rife, G. S., and D. L. Moody. 2004. Aquatic macroinvertebrate communities from the Portage River watershed headwater streams (Wood County, Ohio). Ohio Journal of Science 104: 29–35.

Shah, D., S. Domisch, S. Pauls, and P. Haase. 2014. Current and future latitudinal gradients in stream macroinvertebrate richness across North America. Freshwater Science 33: 1136-1147.

Southwest Association of Freshwater Invertebrate Taxonomists. "Tolerance Values & Functional Feeding Groups." 2008. Web. 29 Apr. 2016.

United States Environmental Protection Agency. Benthic Macroinvertebrate Protocols. *Water: Bioassessment*. Web. 2015.

USGS. "Hydrologic Unit Maps." *Water Resources of the United States*. US Department of the Interior, 2 Sept. 2015. Web. 05 May 2016.

Vinson, M. R., and C. P. Hawkins. 2003. Broad-scale geographical patterns in local stream insect genera richness. Ecography 26:751-767.

APPENDIX A: The 174 Stratified Sampled Sites in California

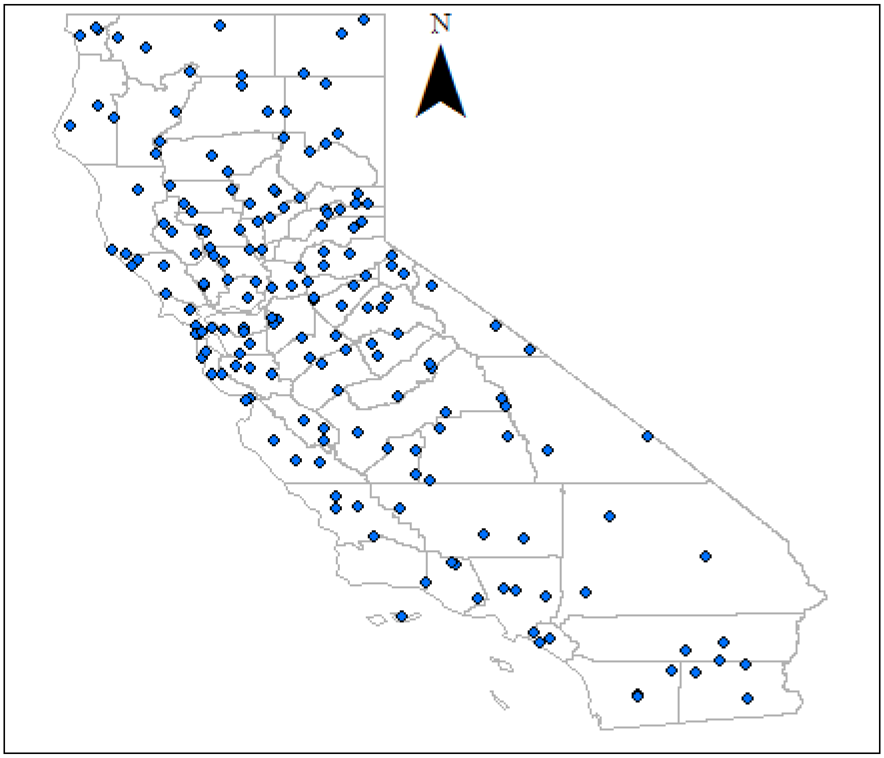


Figure A. 174 sampled sites throughout California, generated through stratified sampling in ArcMap 10.3. Each county has been designated 3 sampled sites, and geographical coordinates are recorded.

APPENDIX B: EPT Genus Climatic Variable Percentage Contributions

Ephemeroptera Genus	Precipitation (%)	Average Temperature (%)	Minimum Temperature (%)	Maximum Temperature (%)
Acentrella	93.5	3.2	2.5	0.8
Ameletus	61.7	14.1	16.8	7.4
Attenella	89.7	7.9	2.4	0
Baetis	72.4	3.9	15.6	8.1
Caenis	69.8	17.6	2.2	10.4
Callibaetis	70.6	22	1.1	6.3
Caudatella	79.1	0	20.9	0
Centroptilum	62.5	19.6	14	3.9
Choroterpes	81.9	0	0.3	17.7
Cinygma	64.8	7.6	8.6	18.9
Cinygmula	59.1	20.5	14.2	6.1
Diphetor	63.9	18	15.1	3
Drunella	67.4	8.2	17.5	6.9
Ecdyonurus	61.6	0	25.7	12.7
Epeorus	69.2	12.7	14.1	4

Ephemerella	60.7	19.6	17.3	2.4
Fallceon	64.8	19.3	10.1	5.8
Heptagenia	83.7	0	0	16.3
Homoleptohyphes	75.7	3	0	21.4
Ironodes	56.5	11.4	19.7	12.3
Leucrocuta	48.6	0	0	51.4
Matriella	65.9	11.9	15.6	6.6
Nixe	65.3	0	34	0.7
Paracloeodes	74.7	0	0.7	24.5
Paraleptophlebia	64.8	10.4	16.2	8.5
Procloeon	100	0	0	0
Rhithrogena	60.5	17.8	10.8	11
Serratella	78.3	12.5	8.4	0.8
Siphlonurus	52.7	47.3	0	0
Timpanoga	66.6	0	33.4	0
Tricorythodes	62.9	17.7	9	10.5
Average Contribution	**69.3**	**10.5**	**11.2**	**9.0**

Figure B1. The percent contributions of climatic variables for different Ephemeroptera genera found in California, generated by MaxEnt using data from California Environment Data Exchange Network. 32 different Ephemeroptera genera were inputted into MaxEnt alongside 2013 climatic conditions to determine percentage contributions for each. Presence data here has been accumulated from 2000 to 2015. Despite differences, the average percentage contribution depicts that precipitation plays the largest role, followed by minimum annual temperature, then mean temperature and finally maximum temperature.

Plecoptera Genus	Precipitation (%)	Average Temperature (%)	Minimum Temperature (%)	Maximum Temperature (%)
Baumannella	61.9	1.6	25.1	11.4
Bisancora	55.7	0	25.2	19.1
Calineuria	54.9	21.2	18	5.9
Capnia	100	0	0	0
Claassenia	77.9	0	22.1	0
Cultus	61.2	24	14.8	0
Despaxia	43.5	12.4	23.6	20.5
Doroneuria	35.3	6.1	51.4	7.1
Eucapnopsis	38.1	0	56.8	5.1
Frisonia	36.5	49	13.7	0.8
Haploperla	53.5	26.7	18.4	1.4
Hesperoperla	97	0	3	0
Isoperla	73.6	13.1	8.2	5.1
Kogotus	67.7	0	0.5	31.8
Malenka	62.8	7.7	18.9	10.7
Megarcys	73	0	0	27

Mesocapnia	62.6	0	0	37.4
Moselia	76.5	1.6	5.1	16.8
Oroperla	36.6	0.3	59.6	3.4
Paraleuctra	67.5	0	0	32.5
Paraperla	47.2	3.4	25.4	24
Perlinodes	77.1	17.4	0.1	5.4
Prostoia	56.8	43.2	0	0
Pteronarcella	84.1	0	15.9	0
Pteronarcys	87.1	3.5	3.6	5.8
Sierraperla	98.4	0	1.6	0
Skwala	42.6	41	16.4	0
Soliperla	92.5	4.3	0	3.1
Soyedina	67.3	15.2	5.9	11.7
Suwallia	57.7	21.7	17.3	3.3
Sweltsa	64.3	9.6	14.1	12
Taenionema	72	11.3	9	7.7
Visoka	69.1	10.1	10.9	9.9
Yoraperla	65.9	26.9	6.7	0.5
Zapada	79.9	14.9	2.5	2.6
Average Contribution	**65.7**	**11.0**	**14.1**	**9.2**

Figure B2. The percent contributions of climatic variables for different Plecoptera genera found in California, generated by MaxEnt using data from California Environment Data Exchange Network. 36 different Plecoptera genera were inputted into MaxEnt. Average percentage contribution depicts that precipitation plays the largest role, followed by minimum, mean, and maximum temperature, respectively.

Trichoptera Genus	Precipitation (%)	Average Temperature (%)	Minimum Temperature (%)	Maximum Temperature (%)
Agapetus	60.7	15.5	15.7	8.2
Agraylea	47.5	37.7	0	14.7
Allocosmoecus	57.1	42.9	0	0
Amniocentrus	58.1	11.5	17.1	13.4
Anagapetus	68.7	27.7	2	1.5
Apatiania	55.9	32.3	9.6	2.2
Arctopsyche	49.3	20.2	16.7	13.8
Brachycentrus	61.9	15.4	22.7	0
Ceratopsyche	44.6	52.1	3.3	0
Cheumatopsyche	61.6	15.4	3.2	19.8
Chyranda	58.1	0	41.9	0
Cryptochia	70.6	29.3	0	0.1
Culoptila	100	0	0	0
Dicosmoecus	56.7	10.2	33.1	0
Dolophilodes	79.8	17.4	0	2.7
Ecclisomyia	58.9	29.8	7.7	3.6

Glossosoma	61.7	17.5	9.1	11.8
Gumaga	48.5	27.6	18.8	5
Helicopsyche	56.8	23.4	16.8	3
Heteroplectron	43.1	16.6	23.7	16.6
Hydropsyche	65.2	16.7	11.7	6.3
Hydroptila	74.2	10.7	9.2	5.9
Ithytrichia	69.8	19.7	8.2	2.4
Lepidostoma	66.3	14.3	14.7	4.7
Marilia	66.2	0	0.2	33.6
Micrasema	68	13.2	14.4	4.4
Mystacides	57.2	28.6	11.1	3.1
Nectopsyche	76.2	0	2	21.8
Neophylax	58.5	2	21.8	17.8
Neothremma	65.4	1.2	14.7	18.7
Neotrichia	56.1	20.9	2.7	20.4
Ochotrichia	67.8	19.6	7.5	5
Oecetis	66.1	18.3	3.6	12
Oligophlebodes	54	0	44.9	1.2
Onocosmoecus	71.7	21.5	5.1	1.8
Oxyethira	65.4	11.6	16.8	6.3
Parapsyche	42.1	23.8	31.7	2.4
Parthina	34.8	30.2	27.6	7.4
Pedomoecus	60	25.5	13	1.4
Polycentropus	52	12.9	25.6	9.4
Protoptila	79.2	0	16.9	4
Psychoglypha	73.7	8.9	5.5	12
Rhyacophila	58.5	10	21.1	10.2
Stactobiella	0	0	0	100
Tinodes	60.2	24.8	4.3	10.8
Wormaldia	60.8	17.6	14.3	7.3
Average Contribution	**60.2**	**17.3**	**12.8**	**9.7**

Figure B3. The percent contributions of climatic variables for different Trichoptera genera found in California, generated by MaxEnt using data from California Environment Data Exchange Network. 46 different Trichoptera genera were inputted into MaxEnt alongside 2013 climatic conditions to determine percentage contributions for each. Unlike Ephemeroptera and Plecoptera, Trichoptera genera on average is most influenced by precipitation, followed by mean, minimum, and maximum temperature respectively.

APPENDIX C: EPT Genera Counts and Corresponding Tolerance Values

Order. Genus	Tolerance Value	Current Count	Future Count	Percentage Change (%)
E. Attenella	2	99	0	-100
E. Heptagenia	4	88	0	-100
E. Leucrocuta	1	81	0	-100
E. Nixe	2	6	0	-100
E. Siphlonurus	7	6	0	-100
E. Timpanoga	7	11	0	-100
E. Caudatella	1	99	1	-99
E. Cinygmula	4	41	2	-95
E. Procloeon	4	80	5	-94
E. Ameletus	0	48	4	-92
E. Ironodes	3	49	5	-90
E. Epeorus	0	52	6	-88
E. Diphetor	5	46	6	-87
E. Matriella	--	42	6	-86
E. Choroterpes	2	32	5	-84
E. Cinygma	2	6	1	-83
E. Rhithrogena	0	6	1	-83
E. Drunella	0	52	9	-83
E. Centroptilum	2	80	15	-81
E. Serratella	2	56	11	-80
E. Ephemerella	1	42	9	-79
E. Homoleptohyphes	4	85	21	-75
E. Paraleptophlebia	4	45	14	-69
E. Baetis	5	49	16	-67
E. Callibaetis	9	70	23	-67
E. Tricorythodes	--	54	19	-65
E. Ecdyonurus	--	41	15	-63
E. Acentrella	4	8	3	-63
E. Caenis	7	51	20	-61
E. Fallceon	4	52	27	-48
E. Paracloeodes	4	16	10	-38
P. Baumannella	2	18	0	-100
P. Claassenia	3	3	0	-100
P. Doroneuria	1	3	0	-100
P. Frisonia	2	3	0	-100
P. Haploperla	1	4	0	-100
P. Megarcys	2	4	0	-100
P. Oroperla	2	3	0	-100
P. Prostoia	2	6	0	-100
P. Pteronarcella	0	14	0	-100

P. Sierraperla	1	102	0	-100
P. Skwala	2	4	0	-100
P. Soliperla	1	99	0	-100
P. Soyedina	2	5	0	-100
P. Despaxia	0	34	2	-94
P. Sweltsa	1	46	3	-93
P. Suwallia	1	30	2	-93
P. Paraperla	0	43	3	-93
P. Calineuria	2	48	5	-90
P. Mesocapnia	1	75	10	-87
P. Bisancora	1	12	2	-83
P. Hesperoperla	2	6	1	-83
P. Kogotus	2	6	1	-83
P. Visoka	0	6	1	-83
P. Capnia	1	69	13	-81
P. Eucapnopsis	1	4	1	-75
P. Paraleuctra	0	7	2	-71
P. Malenka	2	48	14	-71
P. Isoperla	2	48	15	-69
P. Cultus	2	6	2	-67
P. Pteronarcys	0	9	3	-67
P. Yoraperla	1	6	2	-67
P. Taenionema	2	49	17	-65
P. Moselia	0	8	3	-63
P. Perlinodes	2	2	2	0
P. Zapada	2	3	4	33
T. Brachycentrus	1	79	0	-100
T. Dicosmoecus	1	4	0	-100
T. Neotrichia	4	66	0	-100
T. Protoptila	1	13	0	-100
T. Stactobiella	4	6	0	-100
T. Agraylea	8	71	2	-97
T. Nectopsyche	3	156	5	-97
T. Neothremma	0	27	1	-96
T. Culoptila	2	71	7	-90
T. Parapsyche	0	48	5	-90
T. Heteroplectron	1	40	5	-88
T. Onocosmoecus	1	30	4	-87
T. Neophylax	3	44	6	-86
T. Cryptochia	0	7	1	-86
T. Mystacides	4	55	8	-85
T. Chyranda	1	11	2	-82
T. Apatiania	--	5	1	-80

T. Oligophlebodes	0	5	1	-80
T. Parthina	0	15	3	-80
T. Arctopsyche	1	37	8	-78
T. Amniocentrus	--	45	10	-78
T. Ithytrichia	6	54	13	-76
T. Rhyacophila	0	53	13	-75
T. Ochotrichia	--	71	18	-75
T. Micrasema	1	51	13	-75
T. Oecetis	8	72	19	-74
T. Helicopsyche	3	51	14	-73
T. Marilia	0	64	19	-70
T. Dolophilodes	2	10	3	-70
T. Wormaldia	3	50	15	-70
T. Lepidostoma	1	46	14	-70
T. Agapetus	0	53	17	-68
T. Hydroptila	6	62	20	-68
T. Hydropsyche	4	53	18	-66
T. Cheumatopsyche	5	70	24	-66
T. Oxyethira	3	62	22	-65
T. Polycentropus	6	50	18	-64
T. Gumaga	3	41	17	-59
T. Tinodes	2	41	20	-51
T. Allocosmoecus	0	6	3	-50
T. Anagapetus	0	2	1	-50
T. Ecclisomyia	2	4	2	-50
T. Glossosoma	1	6	4	-33
T. Pedomoecus	0	3	2	-33
T. Psychoglypha	2	6	5	-17
T. Ceratopsyche	--	3	6	100

Figure C. Genera Counts and Tolerance Values for each individual E, P, and T genus comparing current to future climatic conditions. Within each order, genera were ordered based on an ascending percentage change in counts.