University of Nevada, Reno at Lake Tahoe

State of the Lake Tahoe Basin, 2024

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by

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Acknowledgments

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The impetus for this effort, approach, and creating a living document.

The Lake Tahoe Basin has a long history of engagement from the science and research community to help inform decision-makers regarding environmental challenges facing the basin. The University of California, Davis began regular measurements of lake clarity dating back to 1968. This data set illustrates short- and long-term trends in clarity decline and was instrumental in communicating that a shift in land management and regulatory practices was needed to halt what was identified as an annual average clarity loss of one foot per year. Tahoe forests have undergone dramatic changes from forest clear-cutting practices during the Comstock era to the development boom of the 1960s and the current challenges of climate change. Science and research are at the forefront of providing information on the effectiveness of current practices and modeling for future conditions to help inform prescriptive actions. One of the significant shifts in practices was the launch of the Environmental Improvement Program (EIP) in 1997, establishing an ambitious multi-million-dollar restoration program implemented through a collaboration of federal, state, and local agencies along with the private sector and non-profit groups. The relationship between environmental restoration efforts and science was reinforced with amendments to the Southern Nevada Public Lands Management Act (SNPLMA) that guaranteed $300 million in funding to federal agencies for Lake Tahoe restoration efforts, with $30 million set aside for science and research to guide restoration activities.

The uncertainty of climate change may be the most pressing issue facing the Tahoe basin since it is intrinsic to human, social, and environmental dynamics. It has been documented that as temperatures warm, so does visitation, which impacts already stressed transportation systems and popular recreation sites. Warming conditions can also impact forest health, biodiversity, water quality, and lake clarity, to name just a few subject areas. In addition, studies have estimated the annual costs to infrastructure, such as roads, resulting from changing conditions, potential significant economic losses in the tourism industry, and overall property value declines.

The EIP recognizes the importance of embedding science in decision-making to help ensure project effectiveness and maximize monetary investments. The EIP includes a science component with identified goals of implementing leading-edge science, protecting investments and benefits, maintaining transparency and accountability, and cultivating stewardship. Implementation occurs through the engagement of the Tahoe Interagency Steering Committee and many partnerships across the basin. The Tahoe Science Advisory Council assists in aspects of science implementation, whether through the EIP or with requests from the agencies and steering committee members. The Council was established in 2015 through a Memorandum of Understanding between California and Nevada.

Recognizing this is not an exhaustive review, this report attempts to summarize some of the current knowledge and identify knowledge gaps and opportunities related to the topics presented in the report. The approach utilized by the authors and outlined in a task order from the Tahoe Science Advisory Council included: 1. the convening of an advisory committee comprised of Tahoe Science Advisory Council members, managers, and a nongovernmental organization who would help guide the development of the chapter topics and structure of the report, 2. conducting one-on-one interviews with agency staff to collect information about each subject area (Table 1), 3. summarizing the scientific peer-reviewed and nonpeer- reviewed reports, and 4. presenting the information as short summaries (e.g., bullets or paragraphs) that managers can quickly review. It was recognized at the onset of the task order and through the committee conversations that, given the resources are limited to undertake a comprehensive State of Basin report, we would treat this as an initial effort by the Council and create a living document that could be augmented over time, as more information and resources are available to add topical areas of interest to the report.

Table 1. One-on-one organizational interviews were recommended by the steering committee or selected by the authors to gather information about the subject areas discussed in this report.

Organization	**Staff Interview requests**
California Tahoe Conservancy	Jason Vasques, Jane Freeman
Nevada Department of Conservation and Natural Resources	James Settelmeyer, Dominique Etchegoyhan
Lahontan Regional Water Quality Control Board	Mary Fiore-Wagner, Ben Letton
Nevada Division of Environmental Protection	Jennifer Carr, Jason Kuchnicki, Danilo Dragoni
Nevada Division of State Lands	Charles Donohue, Ellery Stahler
The Tahoe Fund	Amy Berry
Tahoe Prosperity Center	Heidi Hill-Drum, Bill Chan
Tahoe Regional Planning Agency	Julie Regan, Dan Segan
Tahoe Transportation District	Carl Hasty
United States Forest Service, Lake Tahoe Basin Management Unit	Erick Walker

Chapter 1: Forest Health and Wildfire

The Lake Tahoe watershed (the land area that drains to Lake Tahoe) is approximately 505 square miles (323,200 acres). The US Forest Service Lake Tahoe Basin Management Unit (USFS LTBMU) is the primary land manager in the basin. The States of California and Nevada also manage lands through respective state park agencies, the California Tahoe Conservancy (CTC), and the Nevada Division of State Lands (NDSL). Most parcels managed by the CTC and NDSL are commonly referred to as "Urban Lot" parcels, which are typically less than one acre and located within urban and residential areas. The USFS LTBMU also manages "urban lots." The Washoe Tribe and various local governments, including quasi-governmental agencies such as general improvement districts, manage lands on both sides of the Tahoe basin. The result is that over 90 percent of the Tahoe Basin's land area is managed by various public agencies and the Washoe Tribe.

The parcel size, slope, aspect, location in sub-watersheds, and proximity to residential neighborhoods and infrastructure complicate land management. Land managers typically categorize the forested areas into three categories: 1) General Forest, 2) Wildland Urban Interface (WUI), and 3) Urban Lots. WUI parcels are typically undeveloped, forested parcels next to or within proximity to urban or residential areas. The General Forest is the forested land that lies outside the WUI areas and is typically undeveloped and roadless. Most of the General Forest land in the basin is managed by the LTBMU. Forest and fuel management in these three categories pose challenges for land managers.

Historic Practices

During the Comstock Era (1850s to 1900), much of the forest in the Tahoe Basin was clear-cut to provide lumber needed to support the mines of the Comstock as well as the Central Pacific Railroad and the wood markets the railroad served (Lake Tahoe Watershed Assessment, 2000). The logging practices of the Comstock Era were followed by decades of public policy goals to suppress wildfires whenever possible. An altered forest structure historically dominated by pine trees with regrowth by fir trees, coupled with decades of wildfire suppression, has resulted in an overabundance of dead and living biomass. Drought conditions and the additional biomass increase the risk that wildfires will burn hotter and longer than in the previous century. In addition, there is a growing concern that increased human interaction in the forested landscape due to regional population growth and increased recreation demand will increase human-caused wildfires. Many of the fires in the Tahoe Basin since 2000 have been caused by people. The Gondola Fire in 2002 burned about 670 acres between Heavenly Ski Resort and Kingsbury Grade (Figure 1-1). The cause of the fire was determined to be the improper disposal of smoking material. The Angora Fire in 2007 burned about 3,100 acres and destroyed 242 homes. The cause of this fire was believed to be an illegal campfire. The Caldor Fire in 2021 burned over 221,835 acres and was human-caused by target shooting practice. The Caldor Fire did not originate in the Tahoe basin, nor were most acres burned in the Tahoe basin. However, the fire did threaten homes in the City of South Lake Tahoe and Myers area. Of note is that this was only the second documented fire to cross the Sierra Crest. The first documented fire to cross the Sierra Crest was the Dixie Fire earlier that same year.

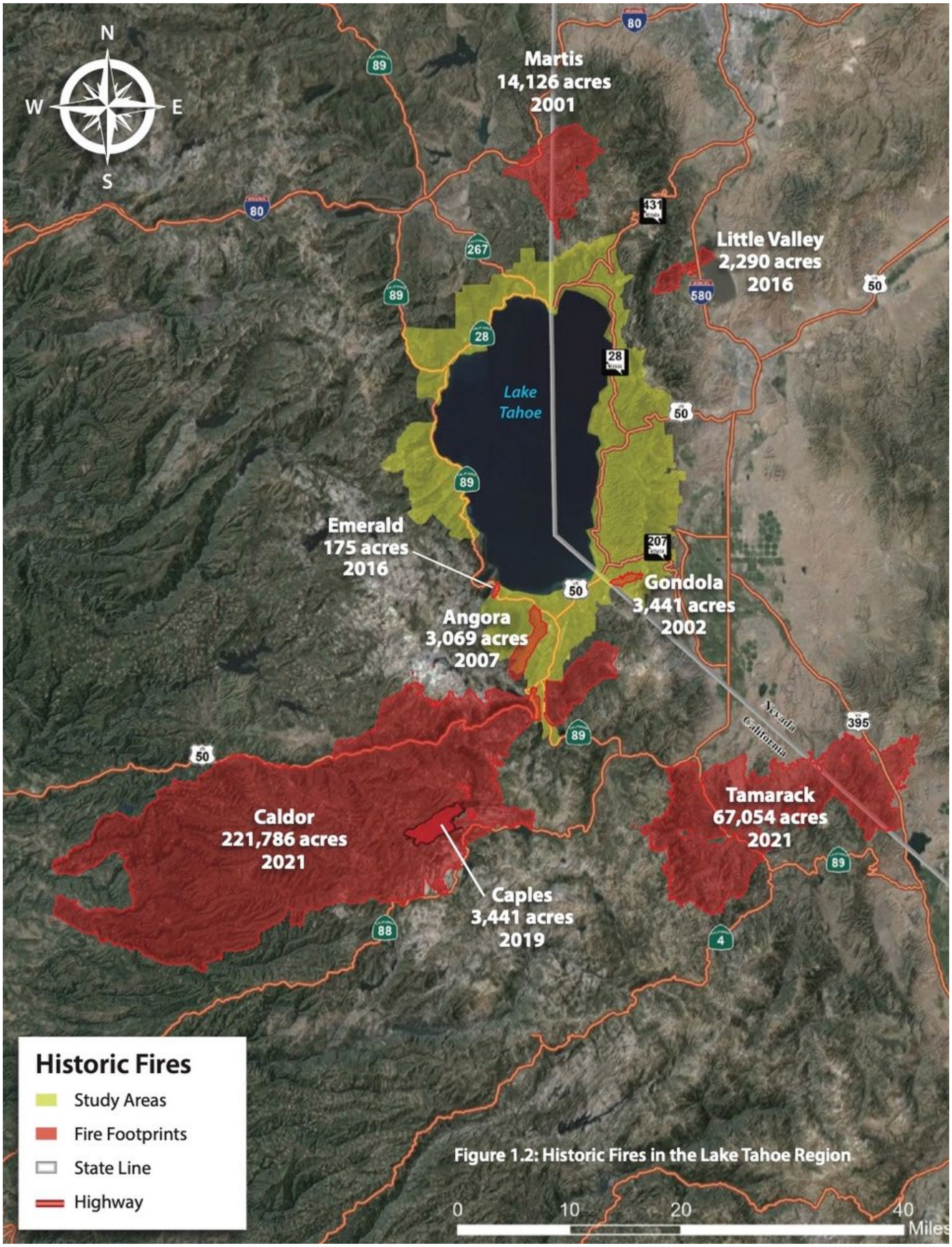

Figure 1-1. Historical large fires within the Lake Tahoe Basin (from Pyroanalysis 2024).

Knowledge Synopsis - Turn of the Century to the Present

The Lake Tahoe Watershed Assessment, published by the Pacific Southwest Research Station (USDA Forest Service), was designed "to collate, synthesize, and interpret available scientific information with a comprehensive view toward management and policy outcomes" (Lake Tahoe Watershed Assessment, 2000). Dozens of contributors from multiple public agencies, research institutions, and scientists collaborated on the assessment, which summarizes key findings regarding forest health and fire.

Forest Composition

- Current (2000) lower montane forests have four times the density, comprised of white fir and incense cedar that is two- to three-fold higher, and Jeffrey pine that is 50 percent less than pre-contact forests. Upper montane forests have experienced a doubling of density, but otherwise, there has been little change in the importance of individual species. Seral stands exhibit a seventy percent higher disease incidence, a five percent greater mortality, and a 184 percent greater tree density than comparable old-growth stands. Most of the increased density is in the youngest cohorts, less than 16 inches (40 cm) in diameter at breast height.
- The basin's old-growth conifer forest today totals 2,138 hectares, which represents five percent of the entire forested area. In pre-contact time, old growth may have occupied 55 percent of the forest area, or 23,424 hectares. Although there is scientific consensus that current proportions are inappropriately low, there is no consensus on an ideal proportion of old growth and other seral stages.

Forest Resilience

- Old-growth forests have lower rates of infestation by dwarf mistletoe (on white fir and Jeffrey pine) and rust (on incense cedar) than second-growth forests, with no difference in bark beetle mortality. Second-growth stands show higher mortality among younger trees than old-growth stands.
- Given current surface and ladder fuel conditions, tree mortality, which represents the severity of the fire's effect on vegetation, would likely be high in most fires. Locations of drought, insect, and pathogen-related tree mortality can decrease the construction of fire lines when fighting wildfires, thus hindering firefighting and increasing tree mortality from fires. These effects are most significant where mortality is widespread and continuous. Drought-stressed trees often succumb to fires more readily than non-drought-stressed trees.
- Increased fire prevention, education, and strategic fuel hazard reduction will reduce the likelihood of damaging fires in the basin. Fire prevention and education can also reduce human-caused ignitions, contributing significantly to fire risk.

Forest Treatment

- Paleo studies suggest that fire played a role in shaping the vegetation within the basin and was likely an important part of the cultural activities of the native Washoe people. Functioning upland ecosystems are only achievable by reintroducing fire into the landscape. While some effects of fire can be at least partially mimicked by mechanical treatment, others cannot. To reintroduce fire in some areas, understory and midstory crowns may require thinning, particularly in pine and mixed-conifer forests. Otherwise,

repeated applications of burning the understory of vegetation would need to duplicate historic fire effects.
- Understory burning is the most effective treatment for reducing surface fuels, which are the most significant contributors to fuel hazards. Other treatments, especially biomass removal, can reduce ladder and surface fuels. These treatments may be most useful near urban areas, where smoke concerns may contribute to reducing burning opportunities.

Science Synthesis Report – Tahoe Science Consortium
The Tahoe Science Consortium (TSC) released a science synthesis report (2016) summarizing key findings from science funded through the Southern Nevada Public Land Management Act. This act was the primary funding source for science and research from 2003 through 2016. The science and research built upon the knowledge provided in the 2000 Lake Tahoe Watershed Assessment. Key findings from the Science Synthesis Report related to forest health and fire include:

Forest Composition
- Increased light attenuation within the atmosphere on the haziest days resulted from large wildfires, of which frequency and intensity are expected to increase due to climate change.
- Climate change impacts on the Lake Tahoe Basin will likely be dictated by more than just temperature and precipitation. Other variables that may or may not be directly attributable to climate change, such as wind speed, dew point, humidity, air pollutant transport, and extreme storm frequency and intensity, are likely to compound impacts on aquatic, terrestrial, and atmospheric environments in the Tahoe Basin.
- Riparian and upland stands appear to be more fire-prone than their historic conditions, with riparian areas significantly more so than adjacent ones.

Forest Treatment
- Biomass burning is a significant emission source of particulate matter, PM2.5.
- Restoration and fuel reduction treatments for riparian forests are a high priority, with objectives like those of adjacent upland forests.
- Burning of wood piles and slash piles did not produce a detrimental change in soil fertility indices such as total soil carbon, nitrogen, phosphorous, pH, inorganic nutrients, or visual observations of fine roots.

Lake Tahoe West Restoration Partnership and Science Findings
Lake Tahoe West focused on restoring the west shore's forests, watersheds, recreational opportunities, and communities impacted by disturbances including wildfire, drought, and climate change. The planning area includes approximately 59,000 acres of federal, state, local, and private lands" (Lake Tahoe West 2020). Lake Tahoe West effort included multiple land ownerships and incorporated an integrated, multi-disciplinary approach to watershed restoration.

The Lake Tahoe West Science Team comprised individuals from the US Forest Service Pacific Southwest Research Station and other research institutions. The scientists collaborated with public agencies, technical experts, and multiple stakeholders representing conservation, fire protection, recreation, homeowners, businesses, and local government. The effort also modeled the planning area over 100 years and evaluated changes to the forest structure, wildlife habitat, water quality and quantity, fire behavior, and snow hydrology, among other factors. The modeling explained how various project scenarios would influence important stakeholder outcomes.

Key findings from the 2020 Lake Tahoe West Science Summary of Findings Report include:

- Alternatives based upon no-treatment would not be as effective in promoting desirable fire effects as increased treatment, both thinning and prescribed burning.
- Increased treatments would bring forest composition and structure closer to historical conditions associated with more natural fire regimes that were deemed favorable.
- Increased thinning and prescribed burning would promote individual species that are priorities for restoration in the Lake Tahoe basin, including yellow pine and aspen.
- Forests in Lake Tahoe West were projected to continue to serve as a carbon sink for many decades. As temperatures in the Lake Tahoe basin continue to warm, forests will likely store more carbon overall due to longer growing seasons, despite the potential for warming-related insect and wildfire disturbances to reduce carbon.
- Treatments are likely to increase fine sediment, and phosphorus loads in the lake, but the increases are expected to be small relative to baseline loads. They may be offset by reduced loading from wildfires over the long term.
- The impacts of wildfires, even when severe, can be mediated by roads and detention basins. Roads had complex and variable effects on runoff and sediment transport. Road fill slopes within the burned areas were predicted to be at high risk of onsite soil loss, as were channels downstream of the road. However, the modeling and field observations indicated that roads and detention basins intercepted sediments eroded following wildfire. Consequently, sound design and maintenance of the road systems, including well-spaced culverts with energy-dissipating outlets, can help limit wildfire impacts.
- Forest understory thinning is expected to increase water yield, which would help counteract expected reductions in water availability in streams, groundwater, wetlands, and Lake Tahoe.
- Removing a substantial portion of conifer overstory could better promote aspen restoration and mitigate fire hazards.
- Thinning-from-below (removing mid- and under- story trees) is effective in meeting short- and longer- term restoration objectives, including lowering surface fuels, restoring forest structure (shifting biomass toward more giant trees), restoring forest composition (shifting biomass toward more shade-tolerant species), promoting drought resistance, and reducing mortality. Additional understory burning could prolong and augment the fuel reduction effects of thinning, mainly where the initial thinning is relatively intensive.
- Smoke modeling suggested that treatment increases would reduce emissions and health impacts from future wildfire events. Modeling of individual events indicated that extreme wildfires would influence downwind communities, possibly in the tens of millions of dollars based upon increases in mortality.
- Fire-focused strategies would also effectively reduce extreme events, but they might still result in smoke impacts, mainly due to their frequency. Managers can time and manage prescribed burns to minimize smoke impacts, but as such burns become larger and more frequent, there is a greater risk that some will result in consequences. A remaining challenge is better quantifying the conditions under which such emissions will occur.

Building upon the significant body of forest health and watershed management research, the Tahoe Science Advisory Council (TSAC) has prepared the *Upland Ecosystem Science to Action Plan: Integrated Research to Inform Greater Resilience in the Lake Tahoe Basins Uplands*. This action plan emphasized creating resilient ecosystems through an integrated approach to upland management and addressing known information gaps. The action plan utilizes the Pillars of Resilience found in the Tahoe Central Sierra Initiative ten-year (2023) with crucial research themes, including defining baseline or restoration targets, quantifying restoration effectiveness, modeling responses to natural and anthropogenic disturbances, the need to translate research into decision support tools accessible to managers, and public outreach (Manley and Wilson, 2020). One item that stands out in this plan is that the upland part of the basin suggests key focal areas that allow for an understanding of forests and other upland ecosystems like meadows, streams, and lakes.

Key questions identified in the action plan include:

- What scientific foundation determines target conditions for resilient forests (e.g., structure, composition, fire dynamics, disturbance dynamics)? What are the limitations of these data, and what additional information is needed?
- What are the most pressing information and functional gaps limiting managers' ability to use fire as a tool and reduce the threat of high-intensity fire in the basin?
- What are the limitations of existing forest growth and fire models? What value would be gained by improving their performance, and what is needed (e.g., data inputs, sub-models, programming) to enhance their performance?
- What landscape information and climate projections —like topography, groundwater, etc.— are necessary to understand future terrestrial vegetation species distributions, vigor, and disturbance?
- How do upslope forest treatments, designed for fuel reduction and fire mitigation, impact meadow and riparian water, carbon, solute, and nutrient fluxes across areas of the Lake Tahoe Basin with different properties?
- How do integrated forest, meadow, stream, lake, and riparian restoration efforts combine to alter water and carbon budgets?
- How transferable are recommendations at the basin scale to targeted watershed-scale restoration approaches that involve meadow and riparian systems?
- How will changing snowpack and rainfall patterns interact with watershed-scale restoration efforts to impact water availability, carbon sequestration, and nutrient fluxes, and how might these factors affect aquatic and terrestrial species, community interactions, and services?
- What is the current distribution (seasonal and annual) of native and nonnative species (vertebrates to invertebrates) within forests, lakes, streams, and meadows within the Lake Tahoe Basin, and how will changing climates affect them?
- What are the potential ecological functions/functional traits (feeding, size, life history characteristics) of native and non-native species within the Lake Tahoe Basin upland ecosystem?
- What water quality and quantity environmental parameters correlate to aquatic species distributions within these systems?

Future Needs and Opportunities

The Tahoe basin has a robust body of forest health science, providing research, tools, and data for forest management in anticipation of changing environmental and social conditions. The body of work shows the benefits of approaching forest health in a holistic, coordinated fashion across multiple disciplines, focusing on improving resilience considering drought and climate change. Tahoe Basin land managers share an understanding of the need to improve the pace and scale of forest health projects. Improved remote sensing data, along with more robust modeling tools, is helping to enlarge planning areas to increase the scale of the project and model the risks and benefits of different project scenarios.

Answering the key questions identified in the Upland Science to Action Plan will provide important information consistent with questions identified as important by land managers, such as impacts from climate change, identification of desired future conditions, information on project effectiveness, smoke impacts from prescribed fire and wildland fire, and providing tools and information for a more extensive, comprehensive approach to fuels and watershed management. The plan is more than just science regarding forest health and wildfires; it addresses the need to understand how climate will change, and which interactions will occur related to biodiversity, hydrology, and downstream ecosystems. Currently, the TSAC is examining opportunities for integrated science-to-action planning to understand better how climate impacts may impact the watershed, providing information to help address priorities for future research. This includes a socioeconomic component to understand better the human population's role in the Tahoe Basin and how strategies may impact the quality of life and the regional economy. In addition, discussions of an integrated science-to-action plan include assessing existing data sets and identifying new needed data sets to better understand the system dynamics, including more holistic forest and meadow ecosystem monitoring.

Chapter 2: Biological Diversity - Basin to Lake

Biological diversity, often called biodiversity, includes all life forms that make up our natural world, such as plants, animals, fungi, and bacteria. Changes in biodiversity can be linked to changes in ecosystem characteristics and can serve as an early warning system for significant disturbances that may follow within an ecosystem. Biodiversity and the interactions across organisms play a fundamental role in governing the traits of an ecosystem valued by people (e.g., water quality, clarity, support for fishing). Some believe there are intangible properties of biological diversity that are part of creation and/ or evolution, and biodiversity has an intrinsic value. Increasingly, there are global, national, federal, and state policies and actions that protect biodiversity. While much of the policies managing Lake Tahoe have focused elsewhere, scientists have demonstrated in other systems that biodiversity and ecosystem traits of interest (e.g. clarity, loading of nutrients and particles) are often interlinked. Here, we divide our understanding of biodiversity into parts, upland and Lake Tahoe, recognizing this is only a first step in acknowledging connections that need to be made in the basin since research related to biodiversity and ecosystem function is missing nearly absent in the basin compared to their encompassing ecosystems (e.g. the rest of the Sierra Nevada, Great Basin).

Biodiversity – Basin-wide

Although there is a long history of research and monitoring in the Tahoe basin, much of the early research has centered on single species instead of overall biodiversity health. In addition, project monitoring focused on threatened and endangered species and compliance with the Endangered Species Act or species identified as threatened by the State of California or Nevada. As land managers move toward forest health projects on a larger landscape, the need for a greater understanding of overall biodiversity in the entire watershed is of even greater importance.

Knowledge Synopsis - Turn of the Century to the Present

Lake Tahoe Watershed Assessment

The Lake Tahoe Watershed Assessment (2000) identified managers wanting to "conserve and enhance existing plant and animal diversity, potentially restoring species that have suffered population declines or extirpation events and eliminating or reducing threats from invasive organisms." Regarding biological diversity, the Watershed Assessment identified nine significant geographic areas constituting Ecologically Significant Areas. These nine areas are old forests; marshes; bogs and fens; deep water plant beds; Lake Tahoe; aspen groves; cushion plant communities; areas with high plant community diversity; and riparian areas with potentially high species richness. Specific findings from the watershed assessment regarding biodiversity include:

- Ecologically Significant Areas constitute geographic areas, species assemblages, or unique or species-rich ecosystem types, thus contributing disproportionately to biological diversity in the basin relative to their spatial extent. The nine Ecologically Significant areas occupy less than five percent of the Tahoe basin.
- Biological diversity in the Tahoe basin has been diminished by losses of native species and the establishment of exotic and invader species. Vertebrate species extirpations have resulted from regional declines, fire suppression, and the basin's geographic (topographic) isolation. Species additions have resulted from direct species introductions, increased human settlement, fire suppression, and geographic isolation.

- Three hundred-seventeen vertebrate species are extant in the basin. One thousand three hundred-eight vascular plant species are confirmed or suspected to occur in the basin. An estimated 379 invertebrate families and 339 genera of fungi also appear in the basin. Studies quantifying the species composition within the Tahoe basin in space, time, and across ecosystems are needed if we are going to understand feedback and protect species under a changing climate.
- Concern about the Tahoe basin's biological diversity is justified based on threats of species extirpation and decline and continued invasion by exotics, leading to further degradation of biological diversity and integrity.
- Many species are also of cultural interest and value. A total of 272 focal species are identified based on ecological and artistic criteria, including 162 vertebrates (60%), 15 invertebrates (5%), 57 vascular plants (21%), 16 nonvascular plants (6%), and 12 fungi (8%). Most species are of concern for ecological reasons, and conservation measures will be required to maintain and conserve biological diversity.
- Several exotic pest species in the basin could cause future ecological damage, primarily through predation and competition with native species. Exotic animals of particular concern include beavers, bullfrogs, introduced trout, bass, opossum shrimp, and crayfish. Noxious weeds of specific concern include tall whitetop, Scotch thistle, and Eurasian watermilfoil.

Science Synthesis Report – Tahoe Science Consortium
The Tahoe Science Consortium released a report including information related to biodiversity. Findings include:

- Abiotic variables (e.g., elevation) within the basin may have a greater influence on species distribution than variability in forest structure.
- Management actions driven by one of a few focal species are not likely to maintain biodiversity if they result in decreased variability in habitat conditions.
- Using multi-species approaches to inform land management can also enhance biodiversity conservation by identifying habitat conditions supporting unique species suites.
- Woodpeckers play an important role in post-fire habitats by rapidly colonizing burned areas and creating cavities used by many other species that rely upon them for nesting, denning, roosting, and resting.
- As drying and warming occur, the suitability of conditions to support cheatgrass will increase.
- Species-specific growth sensitivity to climate and the resulting carbon stock changes varies considerably as a function of the climate projections for a given emission scenario.

Lake Tahoe West Restoration Partnership and Science Findings
The Lake Tahoe West Restoration Project is an ambitious multi-disciplinary approach to forest and watershed restoration of about 59,000 acres consisting of multiple land ownerships. A Lake Tahoe West Science Team was assembled from various agencies, stakeholder groups, and research institutions to provide recommendations under different climate scenarios. Key findings from the 2020 Lake Tahoe West Science Summary of Findings Report regarding upland biodiversity include:

- Increased thinning and prescribed burning would promote individual species that are priorities for restoration in the Lake Tahoe basin, including yellow pine and aspen. Several shade-tolerant species, including incense cedar and white fir, will likely increase without such interventions. Treatments in high-elevation forests would also help mitigate expected declines in red fir.
- Biodiversity, including the diversity of species and functional groups, was largely resilient to model changes in forest management.
- Modeling projections indicated that recruiting old forests across the Lake Tahoe basin increased the availability of suitable habitats for Pacific marten, northern goshawk, and California spotted owl.

We recognize that significant investment is needed to establish regular monitoring programs that track the status of lake and upland biodiversity. A first step is establishing a monitoring plan for biodiversity, implementing models to connect and understand the impacts of the current and future climate conditions on biodiversity, and establishing potential protected areas for sensitive species that have declined over time.

Future Needs and Opportunities (Lake Tahoe Upland Basin)

Upland biodiversity is linked to forest health, and as land managers work to improve the pace and scale of forest health projects to reduce wildfire risk, there is a need to understand better holistic approaches to forest management to enhance biodiversity. This is recognized in the "Ten Pillars of Resilience," which is the foundation of the Tahoe Central Sierra Initiative's ten-year (2023). While the TCSI provides some decision-support tools to plan projects for multiple benefits, such as biodiversity conservation, there is a need for further biodiversity research to inform and update planning tools considering changing conditions.

Upland Ecosystem Science to Action Plan

The Tahoe Science Advisory Council has prepared the *Upland Ecosystem Science to Action Plan: Integrated Research to Inform Greater Resilience in the Lake Tahoe Basin Uplands*. One of the three primary facets of this action plan is the response of biodiversity to restoration projects and climate change. Specific research questions identified in this action plan about biodiversity include:

- What is the current distribution (seasonal and annual) of native and nonnative species (vertebrates to invertebrates) within forests, lakes, streams, and meadows within the basin, and how will changing climates affect them?
- What are the potential ecological functions/functional traits (feeding, size, life history characteristics) of native and nonnative species within upland ecosystems?
- What water quality and quantity environmental parameters correlate to aquatic species distributions within these systems?

The information gained from answering these key questions will continue to provide land managers with the knowledge needed for an integrated approach to upland land management.

Tahoe Environmental Observatory Network

The Tahoe Environmental Observatory Network (TEON) was recently launched to understand better how the Tahoe basin is changing and what can be done to improve resiliency under the changing conditions. This is a collaborative effort led by the US Forest Service Southwest Research and the University of Nevada, Reno, in partnership with the US Geological Survey, Desert Research Institute, and various California and Nevada agencies. The project team has identified a near-term goal to design a monitoring system that combines historical data with current field data collection and remotely sensed data sources. This includes extensive data collection for birds, mammals, bats, aquatic biota, and vegetation. The TEON effort is consistent with the work the Council has started in developing a five-to-ten-year plan integrating science into action. This integrated plan allows one to understand better how upland and aquatic ecosystems are interconnected. Understanding the linkages between upland and aquatic ecosystems can provide land managers with greater capacity to incorporate holistic systems knowledge into restoration planning.

Biodiversity – Lake Tahoe

Lake Tahoe supports native species found within the lake and in neighboring waters, and at least 10 endemic species, which are only found in Lake Tahoe. Since the 1850s, at least 24 species have been introduced to the lake and listed as nonnative or invasive. Species were introduced intentionally during a "cultural imperialism" period when people wanted species in Lake Tahoe like in their place of origin or if species were thought to create a more robust fishery. In the latter part of the 20th century and later, the illegal introduction of nonnative species occurred, all of which seem to have established within the nearshore-edge habitats of the lake, and some causing invasion facilitation, where one species can augment the establishment of other species (e.g., invasive plants establishing habitat for invasive warmwater fishes). Regardless, the impacts of invasive species and other disturbances to the native and endemic species have not been a focus of the lake monitoring program or recent research. Thus, understanding the contemporary status of lake biodiversity is not possible, but using information from the last decades suggests the native and endemic biodiversity have declined, sometimes significantly to the point where their status may not be known without additional studies.

Knowledge Synopsis - Turn of the Century to the Present

The most comprehensive studies of lake's diversity occurred in the 1960s by the bistate (Nevada and California) fish and game agencies. Currently, we have a list of plants, invertebrates, and fish from the main water body of Lake Tahoe, with a more limited understanding of marinas and embayments. Since the 2000s, the agencies supported limited snapshot assessments related to biodiversity in Lake Tahoe. Most studies have focused on assessing invasive species distribution with a focus on focal species prioritized for control, like invasive plants. Here, we focus on native biodiversity within Lake Tahoe and the significant findings from 2000.

Native microscopic algae (phytoplankton)

The phytoplankton in Lake Tahoe is observed in the lake's well-lighted zone and dominated by eukaryotic organisms with some prokaryotic organisms (e.g., cyanobacteria). Phytoplankton in Lake Tahoe are dominated by two phyla (Bacillariophyta and Chlorophyta). Five other phyla are also found within the lake (Crysophyta, Cryptophyta, Cyanophyta, Dyanophyta, and Haptophyta). There are 4 dominant genera based on the biovolume of cells: *Synedra*, *Nitzschia*, *Botryococcus*, and *Cyclotella*. Significant findings from monitoring include.

- The smallest phytoplankton, called picoplankton, can play a significant role in Lake Tahoe and may be increasing in recent decades (Winder et al. 2009). When the lake is physically stratified in temperature, picocyanobacteria, some of which can dominate the nutrient-deficient upper water column, while picoeukaryotes dominate the deeper water. Picoeukaryotes increase when the lake mixes. Thus, changes in mixing patterns and the lake's stability due to changing climates can alter the type and distribution of picoplankton within Lake Tahoe.

- The community of phytoplankton in the lake has shifted over decades (Winder et al. 2009). In recent decades, diatoms have shifted from *Synedra*, *Asterionella*, and *Stephanodiscus* in the 1980s to *Cyclotella* since 2000. Increased stratification and the resulting low nitrogen: phosphorus ratios have been selected for smaller-celled *Cyclotella* diatoms (4–15 micron range) (Winder et al. 2009), which are more efficient at nutrient use.
- It is thought that some zooplankton do not feed as efficiently on smaller cells like *Cyclotella*, suggesting potential changes to the rates of carbon transfer between phytoplankton and zooplankton. The food web effects of the increase in smaller-celled diatoms on lake clarity, zooplankton, and fisheries are an important area of research in Lake Tahoe.
- Despite the removal of sewage from the basin in the 1960s, the pelagic primary production has increased multifold (Chandra et al. 2005). As a result, the invertebrates and fishes that feed at the base of the food web have shifted their energetic uptake from benthic periphyton to pelagic phytoplankton production (Chandra et al. 2005).
- The increase in primary production, however, supports native zooplankton like *Bosmina* that all but disappeared in the lake’s offshore due to predation by invasive mysid shrimp.

Native plants

Native plants occur in nearshore and offshore-bottom habitats in the lake. Nearshore, native plants are largely restricted to marinas and embayments and can be dominated by milfoil (*Myrophillum quintense*), coontail (*Cerotophyllum dimersum*), Canadian waterweed (*Elodea* spp.), leafy pondweed (Potomageton foliosus). These plants likely play an important role in the cycling of nutrients and carbon and provide habitat for native fishes. Rarely do we see these plants in offshore areas in the main lake. In the deeper waters, 3 taxa of plants occur, dominated by stonewort (*Chara* spp). Chara provides habitats for endemic and native invertebrates, including the critically endangered endemic stonefly (*Capnia lacustra*).

What is the status of native plants?

- Shallow water (marina and embayment) supports native aquatic plants among the assemblages of nonnative, invasive plants.
- While there has been only one recent study of the bottom in deep waters of Lake Tahoe (2008-09) to allow comparisons with historical measurements (1962-63), the deepwater ‘plants’ appear to be in decline (Figure 2-1). In the 1960s, deep water macrophytes were found at depths up to 300 meters. The highest density was at depths of 50-60 meters, where nearly all samples had macrophytes (Frantz & Cordone 1967). The 2008-09 sampling indicates no macrophytes at depths greater than 90 meters.
- Historically, plants were found in all areas of the lake, but in 2008-09, perhaps 4-5 acres remained near Stateline, Camp Richardson, and Crystal Bay (Figure 2-2).
- The decline of the plants may occur due to two changes in the lake: a change in transparency and the introduction of species that eat plants (e.g., crayfish).

- *Chara* is partially adapted to life at the bottom of a deep lake by modifying its physiology using different light pigments for photosynthesis. A set of photosynthesis experiments (Chandra et al. 2015) suggests that *Chara* may be able to grow in low-light conditions in the short term. One mystery is why *Chara* is not found at shallower depths; perhaps they are limited by substrate, as it is not found on sand or silt substrate (Chandra et al. 2015) or herbivory by invasive crayfish.

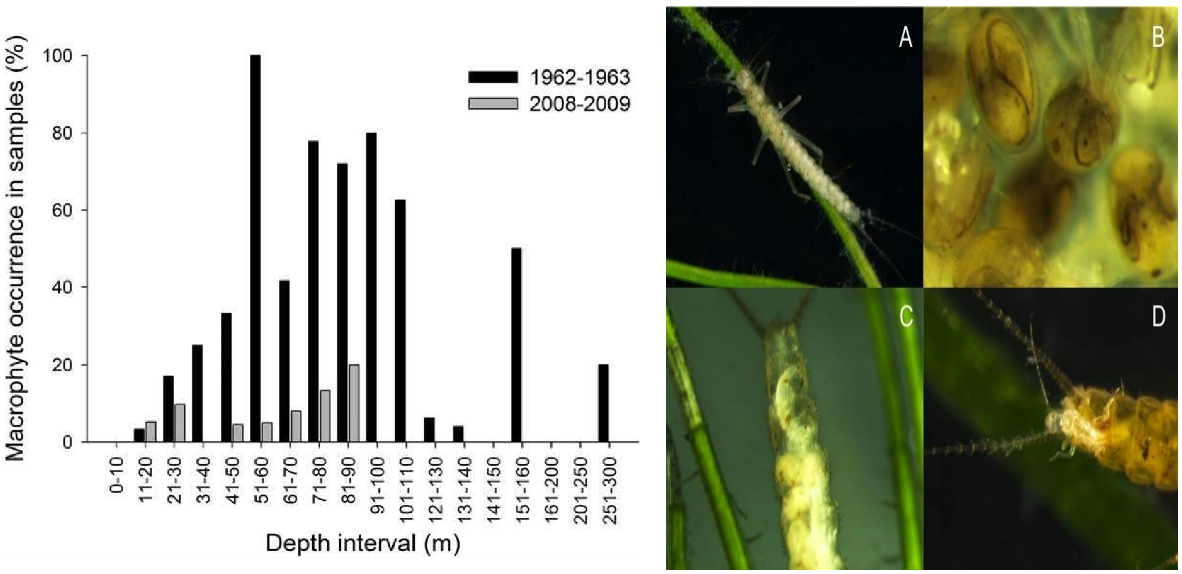

Figure 2-1. Collections of plants in 2008-09 compared to a historical sampling in 1962-63 indicates a dramatic decline of native plants along the bottom of Lake Tahoe (left), and photos of the Tahoe Stonefly including the adult stage (right) - (A), eggs (B), nymph raised in the abdomen of the female (C), and emerging nymph from the mother. The once abundant stonefly has declined dramatically in its range. Should this species be considered for listing due to a decline in its historical range?

What is the status of native invertebrates?

- Table 1 in Caires et al. (2013) contains a complete list of native invertebrates identified during the last survey of the lake bottom in 2008-09.
- Substantial declines have also occurred in the benthic invertebrate community structure. The lake wide- density of total benthic invertebrates decreased by 75%, and the density of endemic taxa decreased by 80 to 100%.
- Pisidium spp. is the only taxon that has increased in lake wide density and biomass. Oligochaete densities declined, but the total invertebrate density of oligochaetes increased by 31% from historical collections, indicating changes in production along the lake bottom and organic matter loading or production in this habitat.
- The biodiversity of chironomids has increased since the 1960s. The chironomid assemblage has shifted from a few genera, which indicated oligotrophic conditions to many genera that are indicators of more eutrophic conditions. This indicates that as the lake increases production and loses clarity, we might find more cosmopolitan species. Simply, clarity loss of 10-15 meters and increased production in the pelagic habitat that settles to the lake bottom are having a profound impact on the communities at the bottom of the lake.

- The endemic taxa of blind amphipods (*Stygobromus* spp.), Turbellaria (*P. tahoensis and D. hymanae*), and stoneflies (*Capnia lacustra*) have undergone the largest density declines in deepwater (50–500 m) areas of Lake Tahoe.
- Tahoe endemic stonefly *(Capnia lacustra*), one of the world's only wingless stoneflies has declined in density and distribution since the 1960s. The lake's deepwater plant beds support the stonefly population and other endemic invertebrates, such as the blind amphipod species. Assigning protected areas and considering restoration projects that recover plant beds could increase stonefly densities and the population of wingless stoneflies.

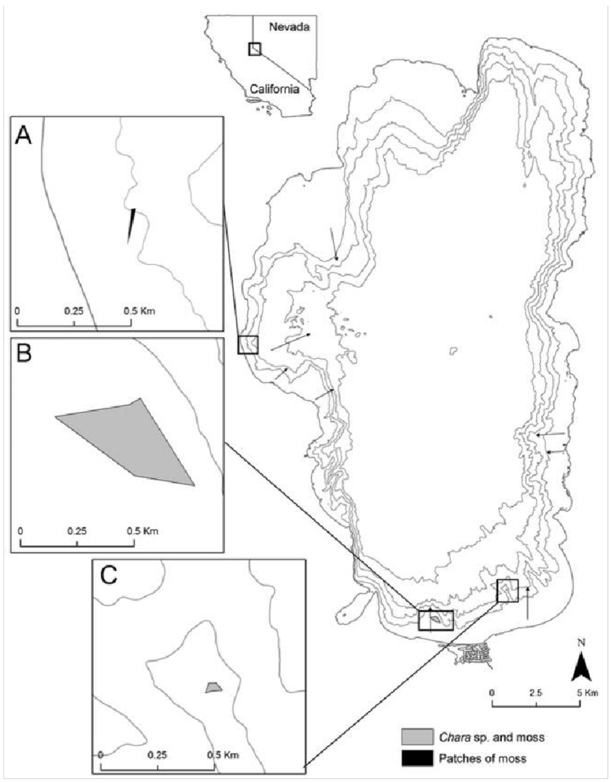

Figure 2-2. 1. Map of 3 areas where the endemic Tahoe Stonefly and other endemic invertebrates have been found in Lake Tahoe. Only 4.5 acres were found of this type of habitat across Lake Tahoe.

What is the status of native zooplankton?

Animals living in the water column called zooplankton can play a central role in connecting energy transfer from phytoplankton to fish. Four major zooplankton groups are native to Lake Tahoe: ciliates, rotifers, copepods, and cladocerans. Historically (1982 and prior), quite a bit of research focused on the role of zooplankton in Lake Tahoe, and little ecological research has been done in the last 40 years. Monitoring of copepods and cladocerans has occurred intermittently by UC Davis – TERC. Sampling of microzooplankton (ciliates and rotifers) has been initiated by the University of Nevada at Lake Tahoe in 2023.

- Rotifers in the pelagic are dominated by 16 species and are widely distributed in the water column from the nearshore to offshore. There are few noticeable differences in composition or density across Lake Tahoe but high variation in densities across seasons, but there are differences in community between Lake Tahoe and Emerald Bay. There is likely much more diversity in the rotifer community in the lake's benthic habitats, which have not been explored.

- The role of rotifers in the lake's clarity and water quality has not been explored. However, laboratory experiments on rotifers collected from other water bodies have indicated that *Keratella* and *Polyarthra* rotifers prefer food particles ranging from 1 to 2 microns in diameter (Ronneberger 1998).
- Cladocerans and copepods are crustaceans; two native species of copepods dominate the waters of Lake Tahoe, *Epischura nevadensis* and *Diaptomus tyrelli,* even with the establishment of invasive mysid shrimp.
- Three native species of cladocerans are found within the lake but at very low densities, with higher densities in Emerald Bay: *Daphnia rosea*, *D. pulicaria*, and *Bosmina longirostris*. The cladocerans continue to be severely impacted by the introduction of mysids (*Mysis diluviana*) in the mid-1960s. They were functionally extirpated from the lake by 1971, with occasional rebounds of the cladocerans over shorter periods when there was enough phytoplankton production to support a population.
- Recently, there was a media/press report suggested that cladocerans may play an important role in controlling the clarity of Lake Tahoe by controlling particles. Peer-reviewed (blind review by scientists) and scientific publications since these claims were made have debunked the role of cladocerans controlling particles or clarity in Lake Tahoe (Bess et al. 2021; Chandra et al. 2024).

What is the status of native fishes?

Historically, the native fish community of Lake Tahoe is like other water bodies in the western Great Basin, reflecting their previous connection through the ancient Lake Lahontan (Nielsen and Sage 2002). The lake supports seven native fish species, including two salmon and trout (Figure 2-3). The native Lahontan cutthroat trout (*Oncorhynchus clarkii henshawi*) was extirpated from Lake Tahoe in the 1930s due to predation and hybridization. Since monitoring of fish is not being done, we rely on a few snapshot studies to assess the current state of fish in the lake.

- Surveys suggest that native fishes have declined since the 1960s, with a continued decrease in abundance between the 1990s and the 2010s. The historic marsh of the Little Truckee River, now the Tahoe Keys, may have been an important breeding ground for natives. This area is now dominated by non-native warm-water fish such as bluegill (*Lepomis macrochirus)* and largemouth bass (*Micropterus nigricans*)(Kamerath et al. 2008), which are competing or preying on native fish in these sensitive habitats.
- Efforts have been underway to recover the native Lahontan cutthroat trout since 1997 when it was considered a priority within the Environmental Improvement Program. However, there has been no scientifically reviewed and published support for a successful recovery in Lake Tahoe or other lakes in the basin except for news media stories or science papers that discuss the approaches for recovery.
- The lake still maintains one native salmonid, the mountain whitefish (*Prosopium williamsoni*). Whitefish are long-lived, with 18-inch fish as old as 15–20 years. Historic observations suggest that whitefish were once abundant (Scott, 1957) but declined rapidly in the 1920s and 1930s.

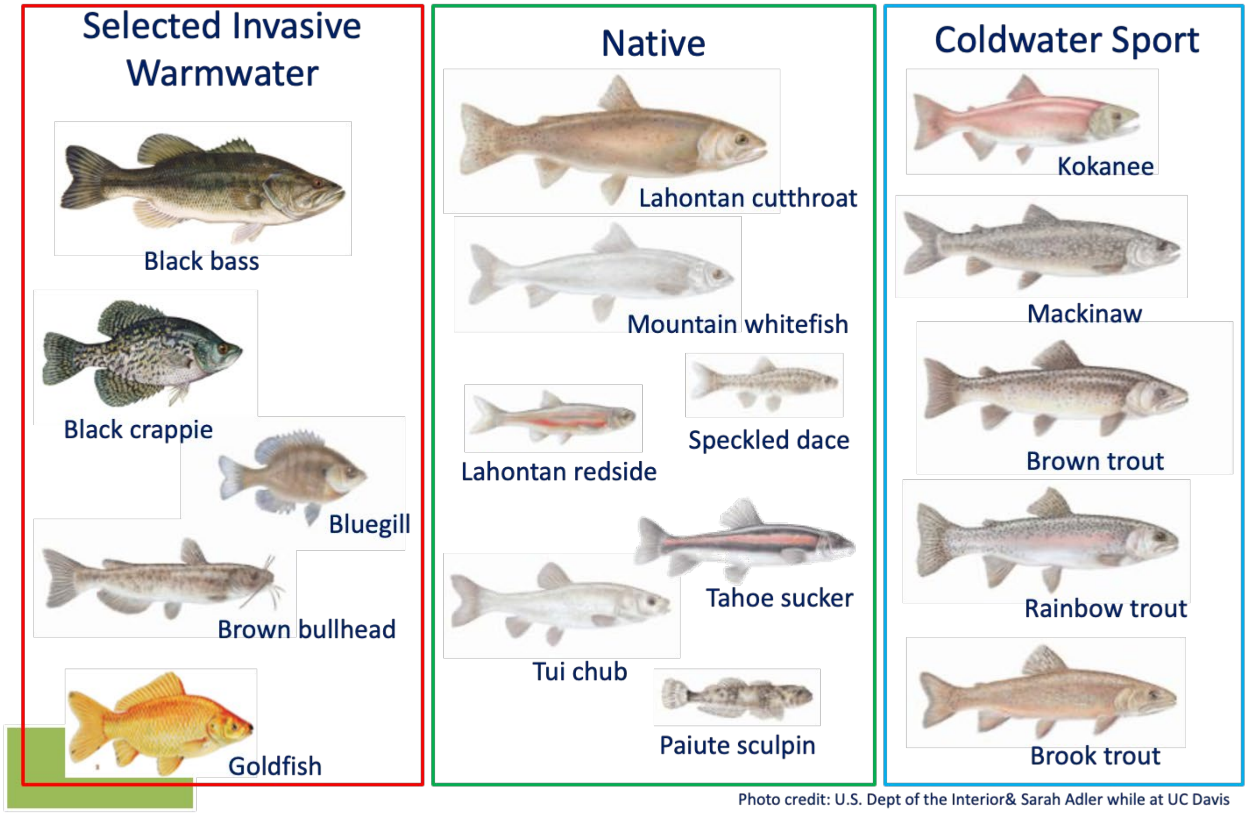

Figure 2-3. Fishes of the Lake Tahoe basin including nonnative species commonly found in the nearshore marinas and embayment's that are warmer in temperature, native species that have declined 10-fold since the 1960s, and "adopted" cold-water, introduced species that are considered fish for recreational capture.

What is the status of native amphibians?

There has been considerable interest in conserving amphibians in small lakes of the Sierra Nevada, but more is needed to know about the amphibians of Lake Tahoe. Amphibians serve as globally relevant, sensitive indicators, yet we have little knowledge of their population and distribution in the Tahoe basin. Given the increase in fungal pathogens (especially the Chytrid fungus) and the historic stocking of fishes in Tahoe and in the smaller lakes and streams in the watershed, it is likely these native taxa declined or become locally extinct. The watershed has six amphibians, all of which warrant conservation attention. (Manley et al. 2000). The long-toed salamander (*Ambystoma macrodactylum*) has declined in California (Jennings 1996), and little is known about its natural history in alpine environments (Tyler et al. 1998). Mountain yellow-legged frogs (*Rana muscosa*) and Yosemite toads (*Bufo canorus*) were likely native to the basin and are California Species of Special Concern, federal candidates for listing (Jennings and Hayes 1994, California Department of Fish and Game 2004, U.S. Fish and Wildlife Service 2004), and USDA Forest Service sensitive species (USDA 1998). Similarly, Pacific treefrogs (*Hyla regilla*) and western toads (*Bufo boreas*) are relatively common throughout the state but have declined in the Sierra Nevada.

Future Needs and Opportunities (Lake Tahoe Biodiversity)

Regarding our understanding of biodiversity in Lake Tahoe, we acknowledge the importance of having baseline studies that provide an understanding of biodiversity within Lake Tahoe. While the studies examining biodiversity have been few and far between (decadal or longer), they do suggest substantial changes in endemic (only found at Tahoe) biodiversity over time. An opportunity remains to develop a monitoring framework for tracking changes in invertebrate and fish biodiversity within the lake, developing scientific studies that connect our understanding of eutrophication, invasive species, and climate impacts on biodiversity so managers can determine what actions need to be designed to protect the lake's biodiversity and implement projects which quantify the feedbacks between water quality and the future physical condition of the lake and native biodiversity. Previous research identified 4.5 acres of benthic habitat for plants, which is critical to supporting the endemic invertebrate diversity within the lake. Potential science-supported actions could include creating protected zones along the lake bottom, which maintain native biodiversity. At the same time, studies are conducted to evaluate the longer-term dynamics and trajectories over time.

Chapter 3: Sustainable Recreation and Transportation

The beauty of the Lake Tahoe Basin has been a visitor draw for decades. As a result, the economy of the Lake Tahoe region continues to be primarily focused on tourism. While there is a recognition that the region's economic health is linked to a healthy and resilient natural environment, many in the Basin are fearful that the Lake Tahoe Basin is suffering from "overtourism," resulting in environmental harm and diminished quality of life. Others have opined that the Tahoe Basin only has issues with overcrowding during certain times of the year and that better recreation and transportation systems, coupled with more robust messaging, are necessary to manage crowds during periods of peak visitation better.

It is common for a certain amount of tension between residents and visitors to exist in popular recreation areas and for locations that receive a large amount of tourism to have to address how to handle visitation. Some news publications have reported that Lake Tahoe is no longer a desirable visitor destination due to overcrowding. In response, the Lake Tahoe Destination Stewardship effort was launched, with a final plan completed in June 2023. This effort was a multi-stakeholder effort that included representatives from the public and private sectors. The plan acknowledges that tourism and visitors are essential to the Lake Tahoe economy, but that increased visitation is causing increased environmental and social problems such as traffic congestion along major highways, peak demand limitations at popular visitor sites, overflow parking in residential neighborhoods, litter and trash removal, rising housing costs, and erosion along roadways caused by illegal parking.

There is a recognition that additional and more robust socio-economic data and studies are needed to identify solutions accurately. While there have been various reports relevant to the Tahoe Basin regarding census information, number of visitors, housing prices, vehicle trips, etc., there has not been a consistent effort to collect and report data holistically for the region. As a result, some of the recommendations from the Lake Tahoe Destination Stewardship effort identify the need for stakeholders to agree upon needed data sets and performance metrics in transportation and sustainable recreation to evaluate whether solutions are achieving desired results. Additional data regarding transportation patterns and human behavior (e.g., litter and illegal parking) have been identified as priorities.

Visitor destination

For decades, Lake Tahoe has been a destination for visitors looking for recreation opportunities and enjoyment of the magnificent beauty of the lake and its surroundings. Population growth in nearby communities and increased interest in outdoor recreation over the last few decades, such as skiing, hiking, biking, and water sports, have steadily increased challenges for land managers, local communities, and residents. During the pandemic, frustration ran high between residents and visitors looking for outdoor spaces.

The Destination Lake Tahoe Stewardship Plan (2023) estimates the Lake Tahoe Basin receives approximately two million unique visitors, spending close to 13 million visitor days. In addition, it is estimated that an additional 4 million visitor days are attributed to day visitors that pass through or use trails without requiring service, bringing the estimated visitor days in the Tahoe basin to approximately 17 million in 2022. This has led to increased stakeholder discussion regarding balancing tourism with the environment. Transportation and mobility are critical factors in moving visitors, decreasing congestion, and protecting environmental quality. While we found little peer-reviewed literature related to visitation and sustainable recreation, there have been reports, plans, and more recent interests to understand tourism and develop policy to engage with visitors. Here we summarize some of the literature but recognize more science investment is needed in this area if we are to solve challenges related to tourism and visitor conflicts.

Knowledge Synopsis - Turn of the Century to the Present

The Lake Tahoe Watershed Assessment (2000) was an extensive and comprehensive overview of the Tahoe Basin ecosystem. However, the assessment acknowledged that "socioeconomic data proved to be dispersed, and for critical issues, data were nonexistent." As a result, many of the key findings regarding social, economic, and recreation were suggestions for critical future research in these areas.

Findings from the Watershed Assessment include:

- The full-time resident population of the basin is under eight percent of the population of the four-county region. Growth rates in the surrounding counties are much higher than the rate of growth in the basin.
- While the basin has eight percent of the four-county region's population, it supplies approximately 24 percent of the jobs.
- To date, relatively little comprehensive economic analysis has been done in the basin. Most economic analyses are focused either by geographic region or by industry. TRPA thresholds do not include specific social or economic indicators, which do facilitate an assessment of changes in the basin.
- Visitor surveys are finding increasing interest in visiting the basin during the "shoulder" seasons of spring and fall, an increasing preference for recreational driving, and a perception of the basin as a full-service resort destination.
- Tourism substantially contributes to traffic congestion in the basin and is an important source of emissions from wood stoves and motor vehicles.

Findings from the Science Synthesis Report completed by The Tahoe Science Consortium's Science include:

- There was no research related to recreation or socioeconomic conditions. However, the report highlighted a future research need for engaging the socioeconomic research community to support the development and implementation of policies, regulations, and programs to protect the unique natural resources and community development of the Lake Tahoe Basin while supporting recreation.

Findings from the nonpeer reviewed, Recreation Resources Vulnerability Assessment technical memo (Winter, USDA, 2019) in the Integrated Vulnerability Assessment (IVA) of Climate Change in the Lake Tahoe Basin include:

- Climate change may substantially impact visitor management and the visitor experience.
- Warming trends are anticipated to result in greater visitor demand throughout the year as residents in neighboring regions seek higher elevations for cooler temperatures.

- Extreme events caused by changing weather conditions, such as flooding or catastrophic wildfires, can temporarily close popular recreation areas, resulting in more significant pressure on nearby open recreation sites.
- Strategic management of recreation and tourism opportunities must be paired with management of natural systems for paired socioecological resilience.
- Natural systems and social systems monitoring and interventions aimed at improvements must both be considered for success.
- Outdoor recreation and tourism represent considerable economic, social, and public health values; thus, where possible, they should be persevered or enhanced. Transdisciplinary approaches will improve outcomes overall.
- Continued monitoring of outdoor recreationists' experiences and outcomes is essential, with particular attention to impacts of increased demand, environmental shifts, or management responses."

Findings from Escaping the Heat: Climate Change and Visitation to the Lake Tahoe Basin (2021) focused on understanding how many days and overnight visitors are in the basin each day and their associated vehicle miles traveled (VMT), and how sweltering days in the nearby Sacramento Valley contribute to increased visitation. It was the first attempt to understand how climate migration as visitors from the region occur from a warming climate. The report findings include:

- Temperature is linked to increased traffic flows, and weekend days (defined as Friday and Saturday) have higher flows than weekdays. This was the most pronounced at Echo Summit.
- Every 10 ºF temperature increase is associated with an increase in traffic volume of 660 vehicles at Echo Summit and an increase of 520 vehicles at the Tahoe City entry point. This translates to an increase of 17,529 miles in-basin VMT from Echo Summit and a 10,010 VMT increase associated with Tahoe City.
- When temperatures are over 100 ºF, traffic counts increase by 770 vehicles at Echo Summit and 660 vehicles at Tahoe City. This results in 20,135 additional VMT for travelers coming over Echo Summit and an additional 12,705 for Tahoe City.
- Traffic counts increase by 880 vehicles at Echo Summit and 398 vehicles at Tahoe City when two days in a row reach over 100 ºF. This scenario resulted in the highest traffic volume increase at Echo Summit compared to other temperature scenarios.
- There was no apparent correlation between overnight elevated temperatures and visitation, so VMT modeling based on overnight temperatures was not computed.
- Model results suggest that hotter temperatures in the Sacramento Valley lead to higher traffic flows in the Tahoe Basin. On days with especially hot temperatures in the Sacramento Valley, particularly days over 100 ºF, an increase of 500 to 1200 vehicles can be expected. This vehicle increase translates to a daily VMT increase of 12,000 to 33,000.

There has been a general understanding that visitation in the Tahoe Basin increases during the warmer summer season, particularly compared with the shoulder seasons; however, this is the first study that directly compares visitation with temperature increases. This provides stakeholders with critical information to predict and plan for climate-driven visitation changes. The report's authors acknowledge that the study was limited by available data sets, and future data collection efforts related to visitors and travel patterns should be prioritized.

Destination Stewardship

The Lake Tahoe Basin economy has been primarily based on tourism for several decades. Balancing a tourism economy with protecting the Tahoe environment and providing an affordable housing inventory remains a challenge. However, these challenges were amplified during the COVID-19 pandemic and associated restrictions. Like many popular outdoor destinations, many people flocked to the Tahoe Basin for day trips to get outside. Anecdotal increases in litter, traffic congestion, illegal parking, and disrespectful behavior were widely reported.

In addition, pandemic restrictions resulted in the temporary closure of workspaces, necessitating an increase in remote work. As a result, popular tourism destinations, such as Lake Tahoe, saw an increase in people relocating from urban areas to resort communities with remote work as an option. This has exacerbated an already challenging housing market that is increasingly pricing out the workforce necessary to support a tourism economy (tourism sector workers) and local communities (teachers, waste management, police protection, fire protection, etc.).

The issues amplified during pandemic restrictions resulted in an unprecedented collaboration to develop a stewardship plan for the Tahoe Basin. This collaboration included a core team of 17 organizations representing community groups, residents (full time and seasonal), business interests, visitor authorities, land managers and visitors. The result of this collaboration was the creation of the Lake Tahoe Destination Stewardship Plan (2023). The nonpeer reviewed plan acknowledges that "Lake Tahoe's communities and economy are rooted in recreation and tourism, touching the lives of all who work, live, and play here. The region has come together to create a shared destination stewardship plan that will balance the needs of the environment, businesses, visitors, and local communities. This new strategy will inspire all to take care of Tahoe."

In developing the plan, the team utilized research and scenario models to inform the final recommendations. The key findings/highlights from the Destination Stewardship Plan include:

- According to the 2020 US Census, there are 54,000 residents in the Tahoe basin and an additional 17,000 in Truckee.
- In 2022, Lake Tahoe experienced about 2 million unique visitors, equaling an estimated 13 million annual visitor days. In addition to the unique visitors, it is estimated that an additional 4 million visitor days can be attributed to what is described in the report as "untethered" visitors bringing the total estimated visitor days to 17 million. "Untethered" visitors are described as those that pass through or use trails or beaches without reserving or purchasing services.
- In 2022, the direct spending of the Lake Tahoe tourism economy, including Truckee, was $4.5 billion, producing a total economic impact that exceeded $10 billion.
- While some believe that the region would be better off with fewer tourists, many stakeholders, residents included, say Tahoe's tourism economy must remain vibrant and strong. Many believe the answer lies in better management of resources for tourism and recreation overall.
- The Tahoe economy has seen an increase in restaurants and retail, but lost a lot of small businesses like plumbers, electricians, hair salons, and independent tire companies.
- Making Tahoe less "auto-centric" ultimately is the key to reducing traffic congestion. More multi-modal transportation options are essential for reducing the basin's motor vehicle traffic.

- Workforce shortages limit public land managers' ability to monitor access, enforce regulations, collect fees, and keep bathrooms clean.

Future Needs and Opportunities

Although tourism and recreation and, relatedly, housing and transportation have been primary issues in the Tahoe Basin for many years, much of the historic work in these topic areas has not been holistic. Recreation providers, public and private, typically collect data for individualized recreation plans for specific locations, but not necessarily considering how individual recreation plans fit into a larger Lake Tahoe system. Similarly, public transportation is currently provided by different agencies in various jurisdictions, which can create challenges in providing a seamless transportation system within the basin and, to and from the basin. The same challenges exist for socio-economic and housing data. There are good data sources, but currently there is no entity at Lake Tahoe tasked with maintaining up to date socioeconomic data regularly.

The Destination Stewardship effort, spurred by resident/visitor frustrations amplified during the pandemic, was a tremendous collaborative effort highlighting the need for constant and continuous collaboration, not only amongst public agencies but must also include full-time residents, part-time residents, commuters, visitors, businesses, non-profit entities, visitor authorities, and researchers. The moment provides an almost historic opportunity for the various stakeholders to coalesce around a shared vision for the Tahoe region and prioritize necessary actions to achieve that vision.

Peak Demand Management: One of the objectives identified in the Destination Stewardship Plan is encouraging visitation during non-peak weekends and visitation to less congested recreation sites. Specifically, the plan states, "Develop and embrace an adaptive, time-sensitive strategy to manage demand and peak volume periods. The strategy will include actions that provide for equitable access to Tahoe's recreational destinations." There is a need for coordinated real-time data across the numerous public and private recreation stakeholders to develop specific actions to achieve this objective, including communication strategies both within and outside the Lake Tahoe Basin.

Transportation: A shift from private auto reliance to other mobility options, such as micro-transit, buses, and non-motorized transportation, is necessary to reduce congestion along Tahoe's roadways. This is supported by priority actions identified in the Destination Stewardship Plan calling for continued investment in expansion of micro transit solutions, shuttle services, and parking limitations or enforcement at highly visited overlooks and trailheads. As with peak demand management, there is a need for continued real-time data for the development of transit and parking operations necessary to achieve desired objectives. In addition to operational decisions, real-time data can be used to inform communication strategies. Transit operations require infrastructure and facilities, which sometimes can be controversial in local neighborhoods. More robust data demonstrating the effectiveness of transit operations can be helpful in communicating desired outcomes to local communities.

Cell phone data is an emerging field in identifying the number of visitors to the basin and origin/destination information. This information is often referred to as "big data" and has been helpful in identifying locations prone to congestion and estimating the number of individuals entering or exiting the Tahoe Basin via private automobile. However, many stakeholders have expressed a desire for more robust or granular cell phone data regarding types of vehicles entering/exiting Tahoe and more granular data on travel patterns within the Lake Tahoe Basin, accounting for residents and visitors. While tourists account for a significant amount of vehicle congestion, particularly during peak visitation times, a sizable number of vehicles are associated with residents commuting to jobs outside of the Tahoe Basin and out-of-basin residents commuting to the basin.

The Destination Stewardship Plan identifies that the Tahoe Basin has lost small businesses outside restaurants and retail. This results in basin residents and businesses relying on basin businesses to travel in the basin to provide basic services such as plumbing, electrical, painting, carpentry, etc., contributing to congestion challenges. Further, a lack of affordable housing options results in many occupations, such as teachers, firefighters, police, and service industry workers, living outside the Tahoe Basin and commuting to Tahoe regularly, adding to congestion and transit challenges. Further research in “big data” is needed to better understand the traffic patterns and types of vehicle users on Tahoe’s roadways.

Parking: An initiative to create a Tahoe Basin Area Parking Enforcement Plan to comprehensively manage and enforce parking requirements is currently underway. This is important, as parking enforcement is seen as a key objective. Research can inform this process by identifying incentives and disincentives most likely to positively change behavior.

Regional Economic Impacts: Multiple studies have been completed to estimate the economic benefits of tourism to the Tahoe basin. Some studies have also included benefits to the Town of Truckee. There are limited studies regarding the financial benefits to nearby communities from Lake Tahoe tourism. All counties in the Tahoe Basin have land and a population base inside and outside Lake Tahoe. This can create an “in basin” and “out of basin” perspective. It has often been stated that Tahoe challenges require regional solutions. A greater understanding of the economic impacts, not just Lake Tahoe and Truckee, to all Tahoe counties can help bring a greater understanding of benefits to both in-basin and out-of-basin residents.

Affordable Housing: Like other tourist destinations, Lake Tahoe needs help providing adequate housing options to support service workers. At the same time, shoulder communities are experiencing the same challenges in providing affordable housing options for needed service workers. There are opportunities for a more extensive regional housing and employment study to identify potential solutions within the basin and shoulder communities.

Demographics/Socioeconomic Data: Currently, no entity regularly collects demographic data specific to the Tahoe Basin, such as population, household income levels, employment rates, and school enrollments. The information can be gleaned from census data and county records. However, this can be difficult and time-consuming, which can often delay decision-making. It also creates challenges in obtaining the necessary data to determine if policy actions are achieving desired outcomes or needing modification. There is a need for the development of consistent metrics, data sets, and protocols.

Discussions with land managers and stakeholders revealed a desire for additional social, economic, and public behavior research and data. Lake Tahoe research has largely been focused on aquatic and terrestrial systems, while social and economic data has been more sporadic. Below are opportunities and questions for science and research to inform policy and management actions that engage and create an informed public:

- Given litter and waste are associated with increased tourism and visitation, what approaches can be undertaken to promote social responsibility related to waste disposal and maximize the level of enforcement that minimizes litter deposition?
- What communications, messaging, and information campaigns are effective with the different users and visitors to the Lake Tahoe Basin?
- What approaches can be adopted to optimize management related to peak visitation and demand? These approaches could span the development of transportation and visitation models or activities (e.g. walking and biking),messaging, and education.
- What are the local and regional economic losses and opportunities associated with investing in peak demand activities and education? How are visitor experience impacts, and can this lead to optimizing strategies related to managing peak demand?
- How many people are visiting the basin during low to high demand, across seasons, and where do they visit and why? There is a lack of data on intra- and interannual data and demographic and cultural information.
- How do visitation and the types of recreational activity affect the introduction of invasive species into the watershed, creeks, and lakes?

Chapter 4: Lake Tahoe Health

The health of lake ecosystems can be determined by several variables, including water quality, metabolic (algal and bacterial) production, food web structure, and biodiversity. As lakes have undergone historical disturbances (e.g., land changes, introduction of species) or influenced by more recent changes in climate (e.g., atmospheric rivers, snow drought), their ability to resist and remain resilient in their structure and function is another way to determine the status of their health. The structure and functional characteristics may depend on the specific lake attributes that are important to managers. However, to understand the factors contributing to the changes in lake attributes over time, research should focus on the connections across habitats (open water or nearshore bottom) and the biological, chemical, and physical feedback that may govern the characteristics of interest to managers.

We discuss two broad aspects of lake health: 1. nearshore water quality, and 2. emerging areas of concern, including plastic pollution and PFAS chemicals. Considerable effort has been undertaken by the Tahoe Science Advisory Council to understand water clarity, a metric of one component of lake health, so we have not included this topic in this chapter. In addition, the loss of native biodiversity, another attribute of lake health, is discussed in Chapter 2 and only used to illustrate areas of convergence or explanatory mechanisms that could be explored to understand lake health. Like the other chapters, we draw from peer-reviewed scientific publications, where possible, but note that much of the publications related to Lake Tahoe are in the gray literature, not peer-reviewed, with more recent reports developed through the Tahoe Science Advisory Council committees and processes (e.g., clarity and lake monitoring). The lack of peer-reviewed publications is of concern, considering that managers and policymakers continue to showcase the importance of scientific information in guiding decision-making. In addition, the availability of publicly available data sets that would aid in multi-institutional scientific discourse remains an opportunity to address in the future.

Nearshore water quality

The nearshore-littoral habitat of lakes plays an important role in the overall ecosystem function of lakes (Vadeboncoeur et al. 2011). Like other clear lakes around the globe, Lake Tahoe's nearshore-littoral has a perceived increase in algal and bacterial biofilms growing along the bottom and metaphyton (algae that is within the water column and along the bottom), suggesting that managing the nearshore habitat based on classic eutrophication paradigm concepts may not be appropriate (Vadeboncoeur et al. 2021). In Lake Tahoe, there have been limited mechanistic investigations of nearshore biofilm development published in the peer-reviewed literature (Naranjo et al. 2019; Atkins et al. 2022, Reuter et al. 1986, Loeb et al. 1986, Loeb et al. 1989, and others); more recently, a number of nonpeer-reviewed reports written as collaborative efforts across institutions (Heyvaert et al. 2015, Chandra et al. 2017) and single institution studies (Chandra et al. 2022, Hackley et al. 2016, Blaszczak et al. 2024) document the ecology of the nearshore. The last multi-institutional, consensus-based understanding of the nearshore condition and potential drivers of nearshore changes occurred in the mid-2010s (Heyvaert et al. 2015, Chandra et al. 2017). We provide a broad overview of the findings from this literature but minimize our discussion related to monitoring the lake's nearshore water quality condition since this is an active area of discussion by the Tahoe Science Advisory Council.

Knowledge Synopsis - Turn of the Century to the Present

Lake Tahoe's nearshore defined and mechanisms contributing to change

Due to the higher transparency in Lake Tahoe, the nearshore extends *"*from the low water elevation of Lake Tahoe (6223.0 feet Lake Tahoe Datum) or the shoreline at existing lake surface elevation, whichever is less, to a depth contour where the thermocline intersects the lake bed in mid-summer; but in any case, with a minimum lateral distance of 350 feet [106 m] lakeward from the existing shoreline. The mean thermocline maximum depth in Lake Tahoe is 21 m (69 feet)."

This definition from Heyvaert et al. (2015) and the summary of factors affecting the nearshore represent a significant amount of effort by a larger working group of managers and scientists (Figure 4-1). One of the authors (Chandra) was a participant in these efforts and wants to emphasize to the reader the level of engagement to find consensus when establishing a "desired condition" for the lake's nearshore environment and the variables that need to be considered to explain changes to this condition. The desired condition agreed to stated, "Lake Tahoe's nearshore environment is restored and/or maintained to reflect conditions consistent with an exceptionally clean and clear (ultra-oligotrophic) lake for the purposes of conserving its biological, physical, and chemical integrity, protecting human health, and providing for current and future human appreciation and use."

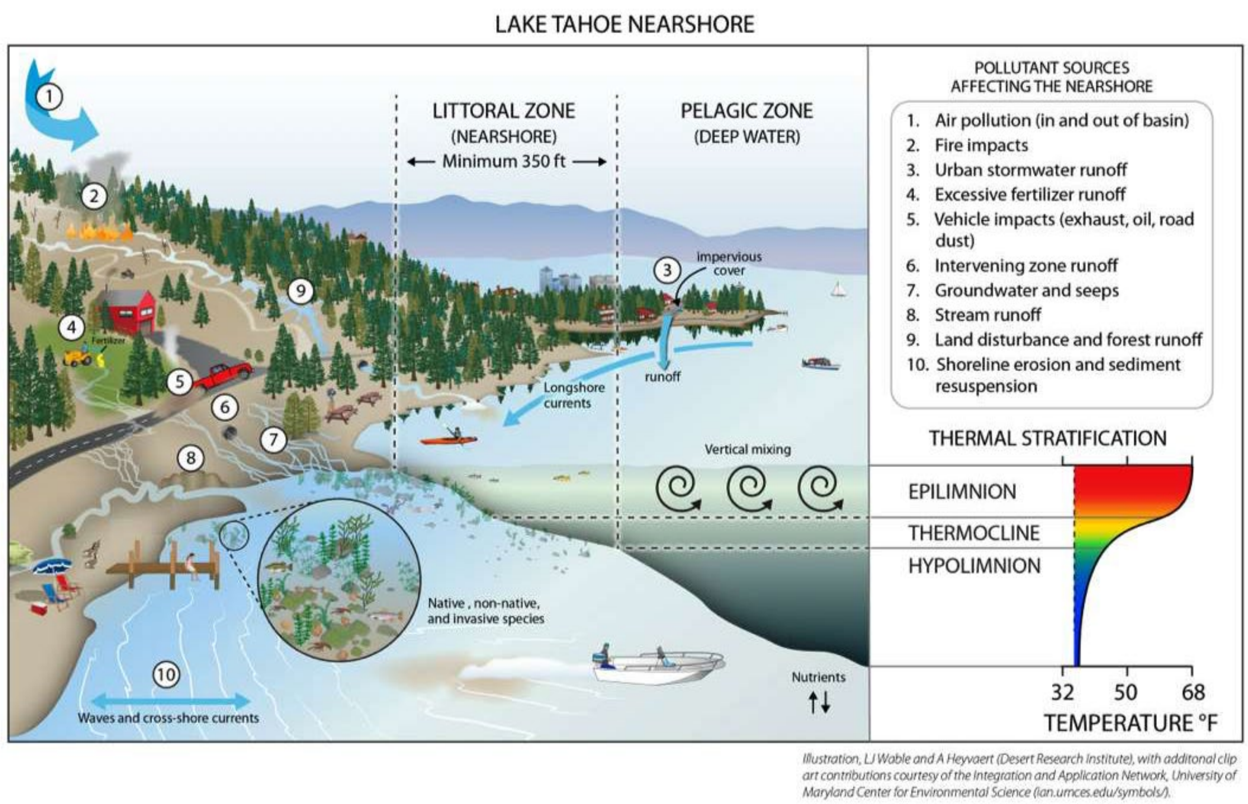

Figure 4-1. Important factors and processes that govern the condition of the nearshore in Lake Tahoe as obtained from Heyvaert et al. (2015).

Building from Heyvaert et al. (2015) and summarizing the work from the publications mentioned above suggests the following factors that affect the water quality and biofilm development that influence the nearshore water quality condition:

- The lake benthic, algal biofilm growth is limited by nitrogen as opposed to colimitation and/or phosphorus in the pelagic habitat of the lake. Thus, controlling algal dynamics may be related to understanding N-chemical species delivery to the nearshore.
- The pathways of nutrient and particle discharge from the sub watersheds and connections through the nearshore and to the offshore may determine water quality conditions.
- The delivery of nitrogen and stream metabolic processes and hydroclimatic conditions can be important for integrating the material moving from a watershed to a lake. This could be important for explaining why there is a decline in long-term nutrient loading to the lake while informing the potential drivers of nearshore water quality changes, including nearshore biofilm production (Blaszczak et al. 2024a, 2024b).
- Nearshore water quality condition (temperature, oxygen, production) is influenced by stream inflow, but there can be important variability in space and time (e.g. distance from the inflow) and with climatic condition (drought versus more wet years). Thus, understanding connections from climate, land to stream, and water play a role in determining water quality conditions (Blaszczak et al. 2024a, 2024b).
- Stormwater inputs, which have higher particles and nutrients along with stream inputs through semi-urbanized watersheds (Rios et al. 2014), play disproportionate roles in managing clarity but also likely influence nearshore water quality.
- Excess runoff from fertilizer or exogenous sources of N or within-biofilm recycled nitrogen may fuel biofilms (Naranjo et al. 2022)
- Localized groundwater sources play a role in driving the development of biofilms (Naranjo et al. 2021).
- While there may be an understanding of the nearshore-littoral zone communities in space, there is a lack of information about communities at depth, successional stages of communities, and fundamental linkages between filamentous and non-filamentous algae along their life history. This is also an issue for other clear-water lakes experiencing enhanced nearshore algal growth.
- Quantifying the influence of the watershed contributions to nearshore water quality at the local, patch scale may be increasing complicated by the feedback from a severely altered biological condition. The lake has many invasive species (plants and animals) that should contribute to water quality and the desired condition of the nearshore. Invasive watermilfoil has been implicated in pumping phosphorus from the sediments into the water column, and there are strong associations between invasive clams and metaphysic algal growth (e.g., Marla Bay and South shore) due to the excretion of ammonium-N and phosphorus (Witman et al. 2011). Invasive crayfish may play a role in contributing to but also controlling algal growth and taxonomic composition through nutrient excretion or grazing on invertebrates which consume algae or direct consumption of biofilms (Chandra et al. 2022). Warmwater fishes also excrete nutrients at the ratios of nitrogen to phosphorus, which contribute to algal growth (Kamerath et al. 2008). In addition to the establishment of invasive species, there has been a reduction in native biodiversity (e.g. fishes have declined 10-fold since the 1960s, significant loss of endemic invertebrates). The altered biology must play a role in local feedback (see below).

- While there is support for the nearshore monitoring of biofilms and metaphyton, we cannot explain the mechanistic drivers solely based on monitoring. Investments in mechanistic studies and modelling are needed.
- The physical (nearshore to offshore, and upwelling dynamics) in the lake at appropriate scales of time should influence the removal of algae through scour and changing temperature and nutrient contributions, which support the growth of biofilms. One strength of the research programs conducted at Lake Tahoe is the development of physical models to understand lake mixing and circulation feedback to the nearshore environment (Heyvaert et al. 2015).
- As climate changes, the physical properties of the delivery of waters from the watershed to the lake and the internal dynamics of the lake (e.g., offshore to nearshore coupling, upwelling, and physical mixing) will change, but how this influences the nearshore condition is not certain.

Future Research and Opportunities – Lake nearshore health

There is a dearth of mechanistic investigations understanding the driver of the nearshore water quality connection in Lake Tahoe in space (e.g., at depth to the lower depths of the photic zone, along the shoreline) and time. Monitoring has focused on the very edge of the lake's nearshore, and monitoring alone will not explain why we see algal growth in one part of a lake but less growth in other parts of the lake. Chandra et al. (2017) efforts developed a conceptual model of processes and factors that may drive water quality. In addition, Vadeboncoeur et al. (2021) offered a series of conceptual models to understand the drivers of filamentous algal growth (benthic and metaphytic). These models were developed through a scientific workshop in Tahoe, involving some of the top freshwater scientists. Using the models from both, consensus-based efforts could be a strong starting point for creating a monitoring program that incorporates information in space and time while also conducting comparative mechanistic studies and water quality modeling of the nearshore. Lake Tahoe can be a leader in understanding nearshore changes as it has many scientists on the Council that are publishing on this topic. However, this will take a coordinated and collaborative effort with a significant contribution of resources to understand the impacts of climate, invasive species, and watershed and stream inflow impacts to the nearshore condition. We need leadership to undertake and create a program like development of the Total Maximum Daily Load program if we are going to support the science needed to quantify changes to nearshore conditions.

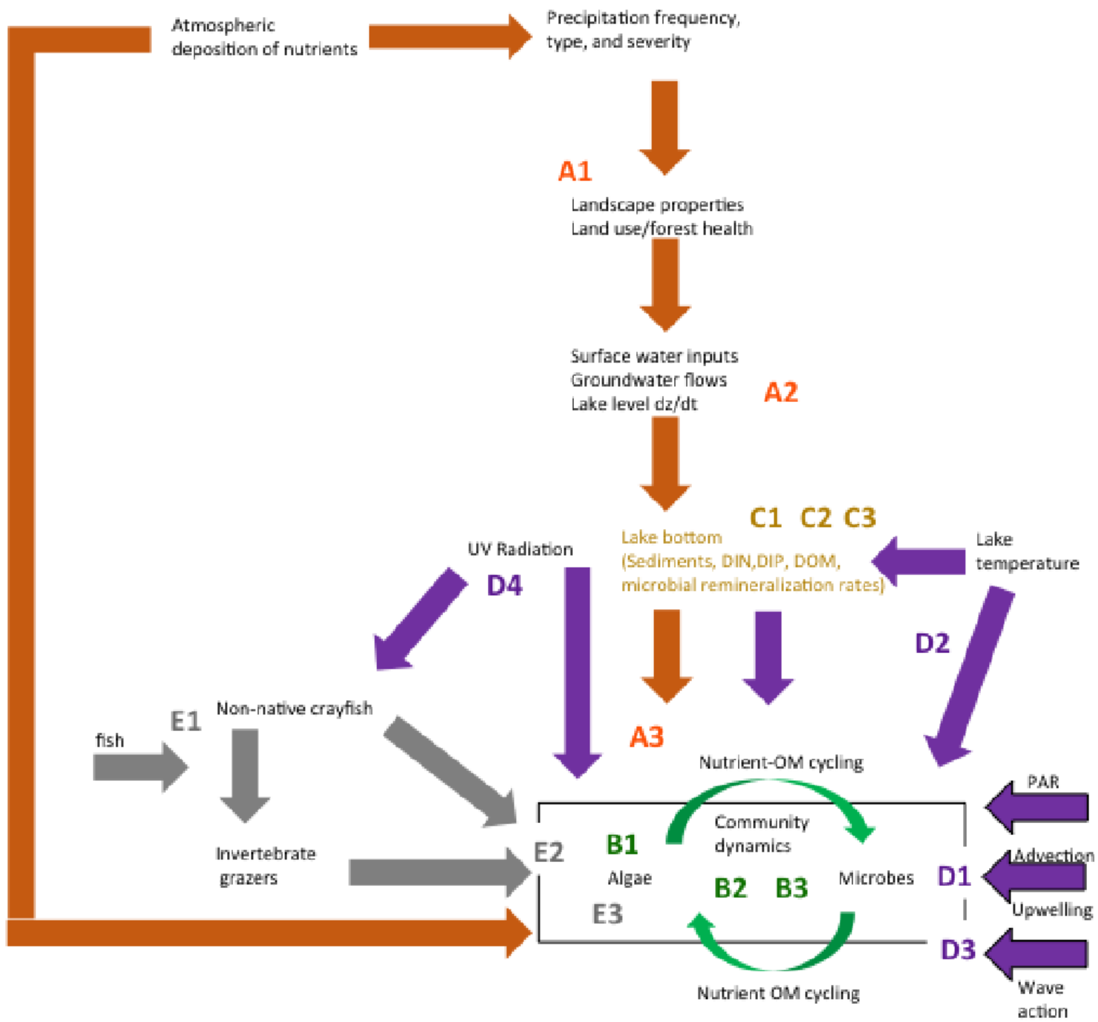

Figure 4-2. Conceptual model describing the factors and processing controlling periphyton growth in Lake Tahoe. Additional models for understanding the mechanisms contributing to filamentous algal growth can be found in Vadeboncoeur et al. (2021).

Emerged Issues – Wildfire, Plastics and PFAS

Wildfire

The direct burning of the watershed and subsequent runoff into the streams and lakes along with the indirect effects of wildfire smoke in the airshed can influence the offshore and nearshore water quality of lakes. In the last decades, Lake Tahoe has experienced several large wildfires in the basin (Figure 1-1). In addition, smoke appeared in the airshed because of within-basin and regional wildfires (e.g., Caldor and Dixie fires, see Chandra et al. 2022). The impact of wildfire smoke in the airshed has been shown to cool a clearwater lake (e.g., Castle Lake- similar trophic state as Emerald Bay or higher elevation lakes in the Tahoe basin), alter the surface and profile of light (ultraviolet and visible) within the water column, and fertilize waters through nutrient and trace metal deposition (Scordo et al. 2021). In addition, changes in light may alter the migration or movement of animals (zooplankton and fishes) but do not seem to affect the overall biomass of zooplankton compared to non-smoke years. The study of wildfire smoke on freshwaters is a novel area of research; there have been several recent research papers (Scordo et al. 2021, Scordo et al. 2022, Smits et al. 2024; Farrugia et al. 2024) that can help guide our understanding of wildfire smoke impacts on Lake Tahoe and other lakes within the basin. Scordo et al. (2022) and Farrugia et al. (2024) provide conceptual frameworks that could be used to build a scientific-based effort to examine the impacts of wildfire to Lake Tahoe and the other lakes within its watershed (Figures 4-3, 4-4).

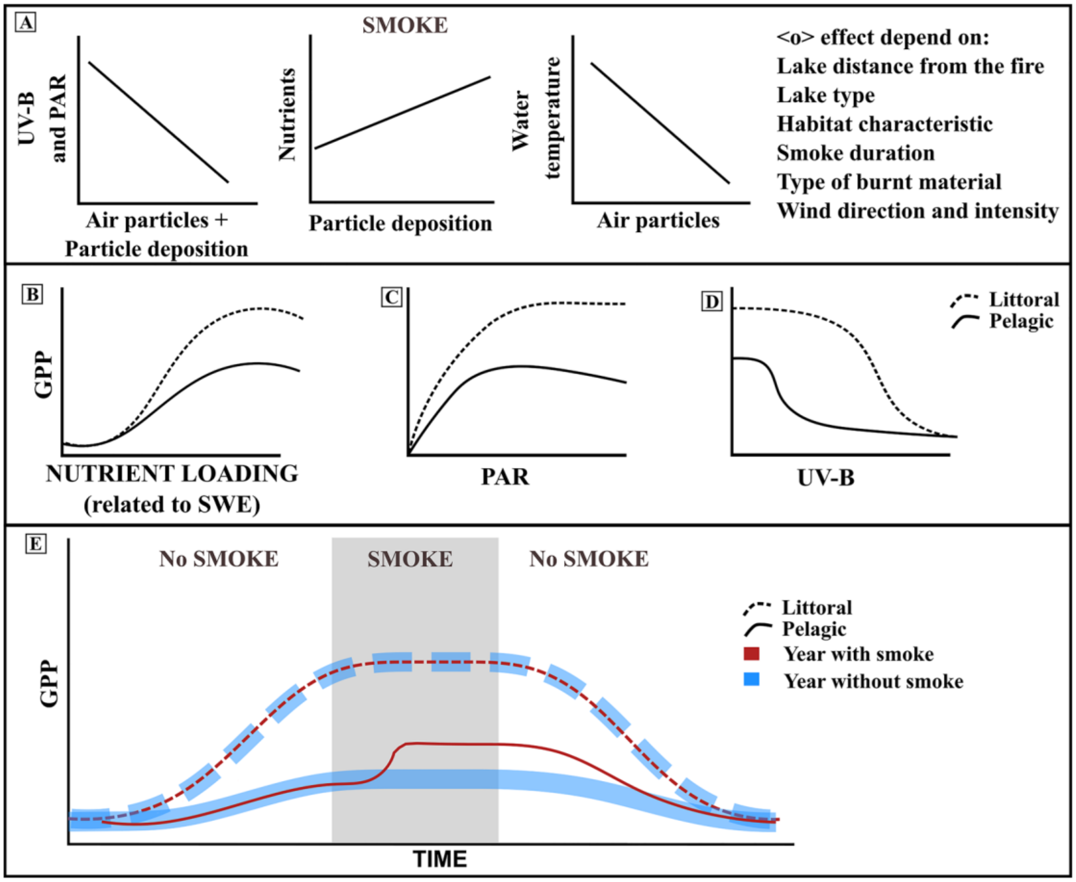

Figure 4-3. From Scordo et al. (2022), a conceptual framework to evaluate the impacts of smoke on pelagic and littoral zone processes.

Figure 4-4. From Farrugia et al. (2024), conceptual models that describe the characteristics of smoke and ash that mediate their effect on lakes within lakes.

Knowledge Synopsis - Turn of the Century to the Present – Wildfire

Related to direct watershed burning impacts to Lake Tahoe and streams within the basin, Olivier et al. (2011) found the 2007 Angora Fire led to earlier and faster melting of the spring snowpack with peak nitrogen (total and ammonium) occurring in the burned area of the watershed. Total nitrogen, nitrate, total and dissolved phosphorus, and turbidity increased following the fire. The burned urban part of the watershed was the largest source of nutrients and sediments, whereas the wet meadow subwatershed downstream of the burned area retained materials. The below average hydroclimate following the fire ,and erosion control efforts both likely helped reduce the amount of material moving downstream. Unfortunately, as is common with research projects within the basin, the monitoring did not continue for this site, so there are no measurements of long-term influences on the lake because of this fire.

There is some research related to the direct influences of wildfire smoke in the basin. Goldman et al. (1990) found that Lake Tahoe's primary productivity increased during regional fires in Southern California, presumably due to the increase of trace metals into the lake. During the Caldor, Dixie and other regional fires of 2021, Chandra et al (2022) found that smoke conditions and deposition can be highly variable, pulsing and waning over time, even though most of the ash by mass was deposited at the southern end of the lake. These would have implications for changing incident and light conditions at depth across this large lake. From a single fixed monitoring station at a buoy in the lake, the atmospheric deposition of particles was a relatively small (0.2%) contributor to overall lake particles. Evaluating the loading based on the collection sites around the lake, indicated the highest ash deposition rates occurred during the first sampling part of the fire and around the southern end of the lake. There was a rapid decrease of particles within the lake during the smoke period, indicating the particles entering the lake were rapidly cleared from the water. Compared to historical information, which shows that Lake Tahoe's algal community is predominantly dominated by diatoms, the 2021 information indicates a change to the larger bodied *Leptolyngbya*, which is a cyanobacteria, immediately after the fires. The quality of the ash deposits around the lake varied in space and time, suggesting that the least amount of mass deposition may have been higher in the quality of metals and nutrients. The higher quality ash stimulated phytoplankton and hence net production in the lake. Smits et al. (2024) found that median gross primary production in the littoral zone increased by up to 40% in 2021. Higher levels of metal deposits were observed in the north/west sites that exhibited lower loads. Thus, analyzing information collected by the US Environmental Protection Agency's IMPROVE program, the loading of toxic metals, and conditions pre- and post-wildfire may be warranted since burning structures associated with wildfire may result in the deposits of metals and other contaminants which influence public health and the ecology of the lake. The complexity of these responses in space and time suggests smoke deposition, characteristics, and responses to lake production can be variable but increase. Thus, regional wildfires that deposit smoke in the basin must be considered if we are going to understand impacts to lake water quality.

Future Needs and Opportunities – Wildfire

It is especially important to set up a spatially explicit airshed and lake monitoring program and invest in scientific efforts that can evaluate the impacts of wildfires (direct burned watersheds and subsequent runoff or wildfire smoke contributions to the airshed) on the lake. Opportunities exist and are outlined in Chandra et al. (2022) but will be presented here briefly.

- Considering the variability of smoke across the basin exhibited by the publicly available air sensors, having calibrated surface light radiometers across the spectral band paired with weather stations around the basin will assist in the impacts of wildfires on nearshore and offshore water quality.
- Measuring the quantity and quality of ash deposition during and after fires will be key to explaining any changes in water quality including the dominance of cyanobacterial and potentially harmful algal blooms.
- Preparing rapid-response, scientific teams that can take advantage ~~of~~ understanding wildfire smoke, runoff quantity and quality will be important if we are going to understand lake health.
- Developing and supporting a more robust lake monitoring program in the nearshore and offshore that includes measurements in space and time presents an important opportunity. Currently, efforts are underway by the Tahoe Science Advisory Council to create the Tahoe Environmental Observatory Network. Supporting a network of sensors with grab samples for water quality (streams, lakes) will help us understand the impacts of wildfire on Lake Tahoe.

Plastics and PFAS
Plastics (macro and micro) additions into Lake Tahoe and subsequent chemicals that source from them, like perfluoroalkyl substances (PFAS), are a major emerging issue around the globe and region. Plastics can influence the ecological condition of freshwaters (Nava et al. 2024), human health, and are unsightly and unwanted, especially in natural areas of significance. PFAS are chemicals that have been used in industrial processes and commercial products. Regulators have identified PFAS as one of the most concerning persistent organic contaminants in the environment and can bioaccumulate in humans, fish, and wildlife. The ecological impacts of PFAS can be large (e.g., decline of salmon), and this is a large subject area that deserves additional attention at Lake Tahoe and the region. Supporting scientific research on plastics and PFAS and their ecological significance is warranted and presents an important area for managers and scientists to engage in as the public is concerned about these issues.

Knowledge Synopsis - Turn of the Century to the Present
Lake Tahoe has the highest concentration of microplastics measured in freshwaters (Nava et al 2022) and there has been quite a bit of media coverage that talks about larger-sized plastic and litter waste on public beaches after holiday weekends. Gjeltema et al. (2023) also observed a higher concentration of microplastics in the spring than in the winter or fall. Both studies identify the types of plastics found in their sampling. In response to growing concern about plastics in the region, the Tahoe Science Advisory Council convened a working group to address microplastics in the lake and suggest opportunities for moving forward (Arienzo et al. 2024). While the emphasis was on microplastics, the nonpeer reviewed white paper does an excellent job of summarizing findings and developing suggestions for monitoring (discussed more below) around microplastics while acknowledging the importance of larger (non-microplastic) littler and the potential role in Lake Tahoe.

There has been little research at Lake Tahoe regarding PFAS except for a few snapshot studies in the lake. Lake Tahoe has the lowest concentration of PFAS in the water but some of the highest in the sediments when a snapshot study occurred (Bao et al. 2020). De Nicola et al. (2023) also evaluated PFAS and characterized the different groups of PFAS within the lake. Comparing Lake Tahoe to other water bodies in the region, the Tahoe Keys Marina had the highest concentration of PFAS of all the mountain lake sites sampled, and the second highest concentration was also found in the offshore of the Upper Truckee River inflow at the south end of the lake. The concentrations were lower than Bao et al. (2020), and the authors acknowledge the variability in time of these measurements and their concentrations, suggesting that studies beyond snapshots should be conducted. Finally, these studies do not attempt to make any linkages to ecological changes in the basin but given the connection between PFAS and salmon-fish declines, one might hypothesize that studying PFAS in relation to the decline of the native biodiversity could be an area of study.

Future Needs and Opportunities – Plastics to PFAS

- Robust monitoring and quantitative approaches to document the plastics from the air to the watershed, to the stream, and to the lake. Capturing the plastics over time and with disturbances (e.g., wildfire smoke deposition, event-based runoff) and tourism are needed at the subwatershed scale. The focus should be on plastics (micro and macro).

Arienzo et al (2024) does an excellent job of summarizing recommendations for microplastics.

- Simply documenting plastic and chemical pollution is a first start when evaluating impacts. However, Nava et al. (2024) found important ecological consequences of plastics within rivers. Similar studies should be undertaken at Lake Tahoe to determine if they influence nearshore water quality cycling and production of biofilms.
- Establish connections (if any) between PFAS concentrations and the ecological health of the lake.
- Convergence around understanding visitor thinking about plastic and litter waste and creating responsible stewardship (see Chapter 3 recommendations). Plastics and chemicals are something the public can rally around understanding, thus connecting social and natural science investigations may allow for an applied area of convergence and exciting research in these topical areas.

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