Introduction

The Lake Tahoe research community has tried to achieve coordinated research over the past nearly 50 years across many important fields of study. The first comprehensive, basin-wide report, was published in 1979 with funding from the National Science Foundation (WFRC IRTF 1979). Numerous reports and synthesis have followed. The most recent review of research in the basin is the Integrated Science Plan for the Lake Tahoe Basin (ISP, Hymanson and Collopy 2010). The ISP developed a comprehensive list of research questions based on the basin-wide reports dating back to 1979. Historically, the primary driver for research has been Lake Tahoe clarity, or on upland and atmospheric processes affecting sediment and nutrient transport to Lake Tahoe. There has yet to be a comprehensive synthesis of the upland ecosystems. The purpose of this review is to explore the questions stated in recent basin-wide reports to determine where research progress has been made in understanding upland ecosystems and identify new questions.

Basin-Wide and Regional Reports

The scope of this review has been focused on five prior basin-wide research reports and assessments for the Sierra Nevada region. The objective is to build on the wealth of existing literature to show progress in order to support a upland ecosystem science plan that supports managers in the Lake Tahoe Basin.

<u>An Integrated Science Plan for the Lake Tahoe Basin: Conceptual Framework and Research Strategies (Hymanson and Collopy 2010)</u>

The Integrated Science Plan (ISP) is a comprehensive review and summary of where research has been in the Tahoe Basin and where it needs to go. The document lays out specific, targeted research questions categorized as meteorology and climate change, air quality, water quality, soil conservation, ecology and biodiversity, or integrating social sciences in research planning. Approximately 100 questions related to the upland ecosystems were highlighted from the ISP and are the primary foundation for the research synthesis presented here.

<u>Tahoe Science Synthesis Report (Knopp et al 2016)</u>

The Tahoe Science Synthesis Report (TSS) is a compilation of nearly 100 basin specific research projects over a decade. The Southern Nevada Public Lands Management Act of 1997 (SNPLMA) ("As Amended" in Public Law 105-263) allotted $300 million from the Nevada Bureau of Land Management over a period of 8 years, which provided funding for research and capital improvements, and led to the development of the Lake Tahoe Restoration Act of 2000 (LTRA) (Public Law 105-506). Approximately $3.4 million in research funds were awarded annually for almost 10 years to the SNPLMA Science Program to develop and understand basin specific systems and research (Knopp et al 2016). The SNPLMA research projects largely targeted and answered many of the ISP questions defined by Hymanson and Collopy and were organized and defined to support management and policy action in the basin. Research projects fell into the categories of air quality, climate change, forest fuels and vegetation management, habitat improvement, lake quality, stormwater management, stream restoration, and science integration.

California's Fourth Climate Change Assessment- Sierra Nevada Region Report (Dettinger 2018)

The Sierra Nevada Region Report (SNRR) is a comprehensive review of climate change impacts and related peer reviewed research across the Sierra Nevada Region of California. The report is organized into ecosystem and biodiversity, water resources, and communities. The scope of review of the Sierra Nevada Region report was referenced primarily to provide answers to the specific upland ecosystem ISP questions compiled, as well as to highlight a more recent review of research gaps and areas of need.

Integrated Vulnerability Assessment of Climate Change in the Lake Tahoe Basin (Catalyst Environmental Solutions 2020)

The Integrated Vulnerability Assessment (IVA) has compiled projections of climate change conditions specific to the Tahoe basin and provided an assessment of how those conditions might translate to systems within the basin. The report has defined lake, upland, and community subsystems and defined key vulnerabilities and implications. The assessment defines a resource's exposure and sensitivity to climate change and provides evaluation of the resource's adaptive capacity. Largely the report defines climatic drivers and provides the foundation for defining systems future response. In addition to the comprehensive report, the California Tahoe Conservancy compiled a series of technical memorandums summarizing each resource and their sensitivities. Those technical memorandums cover Lake Tahoe, aquatic resources, watershed hydrology and streamflow, high-elevation groundwater, low-elevation groundwater, soil moisture and infiltration, forest biological diversity, forest ecosystem dynamics, riparian and aspen ecosystems, meadow ecosystems, wildlife connectivity, public healthy, Washoe Paiute tribe cultural resources, Lake Tahoe surface elevation projects, recreation resources and Lake Tahoe basin infrastructure.

Lake Tahoe West Restoration Partnership

The Lake Tahoe West Restoration Partnership (LTW) is a multi-agency collaborative effort to understand and implement landscape-scale restoration. The project employs an adaptive modeling framework to co-manage Lake Tahoe's west shore forests, watersheds, recreational activities, and communities under future climate projections. The Lake Tahoe West Science Report (Long 2020, in draft) summarizes the achievements and research progress made in understanding the multi-system processes within Tahoe's forested watersheds, and how management implications not only affect desired outcomes, but can be utilized as tools to promote socio-ecological resilience at the landscape scale now and in the future. Multiple supporting articles and reports have been compiled for the project in areas of vegetation, forest carbon and disturbances, fine-scale fire modeling, wildlife habitat, water quality modeling, hydrology and snow modeling, smoke impacts, economics, and decision support tools.

Other Research

Due to similar topographic, climatic, and ecological conditions, research in the central and northern Sierras was included, if directly relevant to the Tahoe Basin, or as a reference to guide more targeted basin specific research. Research referenced outside of the Tahoe basin is peer-reviewed and referenced due to its direct transferability to the basin, or to establish an understanding of where similar research has been accomplished.

Research Questions

The synthesis of questions are largely populated by ISP questions, and have been supplemented by stated needs or research gaps in the subsequent reports. ISP questions have retained their original alphanumeric assignment from the ISP report, and questions from other reports are formatted with the document abbreviation, section of report, and number. A list of abbreviations can be found at the end of this appendix.

The disciplinary organization of research topics varies across all documents and reports. To organize a focused, upland ecosystem synthesis and compilation across all documents, questions and topics in this review have been organized along structure and theme, as opposed to reconciling the topics described in each report. Approximately 150 research questions and stated areas of need have been compiled and organized into three themes. The literature review illustrates three general themes: 1. define baseline conditions and functionality of systems, 2. understand and model responses to pulse disturbances (e.g. fire and droughts), and 3. system response to forward-looking press disturbances, primarily climate change.

Baseline Conditions and Status

For all upland systems there is a need to define historical and/or baseline conditions to inform and evaluate restoration targets. Thus, baseline conditions are relevant historical forest structure and genetic analysis, historical fire regimes, meadow and wetland inventories. Ultimately, this data can be used to develop restoration frameworks and tracking of restoration (primarily meadow and stream) projects, and development of habitat occurrence models, to name a few. There is a need to develop more exhaustive basin wide meteorological datasets, and an acknowledged gap in high elevation hydrologic data including, but not limited to, groundwater levels and water quality, limnology of upland lakes, ephemeral streams, snowpack, and flood characteristics.

The baseline category is intended to develop a foundation of potential target or baseline conditions of a system or resource. Questions either capture a snapshot of the current state, such as species status, populations, and inventories, explore historical conditions, or probe how a current system or resource functions in its current state, without external pressures or disturbances. General data and modeling needs are incorporated in this section as well as the majority or socioeconomic and recreation questions. Table 1 provides specific questions and references that have addressed these questions.

Table 1: Baseline Conditions and Status Research Questions

(OG1) What more can we learn about pro-Euro-American settlement (prior to 1850) characteristics of forests in the Lake Tahoe basin with respect to plant species composition, diameter distribution of trees, snags and logs, and proportional representation of seral stages? How did these characteristics differ according to topographic position (slope, aspect, and elevation), longitude, and soil substrate? What is the relationship between historical stand structure and composition, and existing map products depicting “potential natural vegetation?”	Taylor et al. 2014 Safford and Stevens 2017 Stephens et al 2018 Maloney et al 2011
(FM2) What Are appropriate reference conditions and historical conditions for fens and meadows in the Lake Tahoe Basin?	Sikes et al 2011
(OG3) How did the historical disturbance regime (e.g., fires, landslides, avalanches, insect outbreaks) differ spatially, in intensity and extent, within the Tahoe basin? How did these disturbances shape the structure and composition of the forest? Did upper and lower elevation zones exhibit different spatial patterns of disturbance and resulting structure?	Maloney et al 2001 Maloney et al 2012 Van de Water and North 2010 Vogler et al 2016 Young et al 2017 Shive et al 2018 Hatchet et al 2018
(FM4) How well do predictive models of meadow recovery, with and without restoration, apply to the Lake Tahoe basin circumstances? Which meadows should be used to validate these models, adn what data need to be collected? How should meadows be assigned in a priority scheme for restoration?	2NDNATURE 2010
(FM1) Where are fens and meadows located in the Tahoe basin, and what are their current ecological characteristics and conditions? How important is water chemis-try and ground-water hydrology in establishing and maintaining fen conditions?	Sikes et al 2011 Christensen 2013

Historical Conditions

During the Comstock Era in the late 1800’s the entire west shore of Lake Tahoe was clear cut due to logging, and has been actively managed to suppress fires. The lack of active fire, along with urban development and increased recreational use, has shifted the projection of the forests to a less resilient state. Research progress has been made in defining conditions of those pre-Euro-American settlement forests (Steel et al 2015, Lydersen et al 2013, Taylor et al 2014, Safford and Stevens 2017, Stephens et al 2018, Maloney et al 2011). Additional research has focused on defining historical conditions of aspen communities (Berrill and Dagley 2012, Berrill

2014, Berrill et al 2016), riparian plant and animal communities (Van de Water and North 2010, Van de Water and North 2011), and fens and meadows (Sikes 2011). Where those historical conditions are apt target conditions for restoration is sill up for interpretation. How systems have historically responded to disturbance and vegetation transitions post-disturbance additionally have garnered attention. Baseline conditions have to incorporate a variety of disturbance vectors, such as fire in coniferous riparian forests (Van de Water and North 2010), blister rust infection (Maloney et al 2012), vegetation response to drought and snowpack change (Hatchett and McEcoy 2018, Young et al 2017), and non-conifer vegetation specific response (Maloney et al 2011, Vogler et al 2016, Shive et al 2018).

Restoration Performance Metrics

In addition to the development of target conditions for restoration, there has been a desire to develop comprehensive restoration performance metrics for managers to track progress and determine treatment efficacy. Stocking guidelines for Aspen Restoration have been developed (Berrill and Dagley 2014) and a comprehensive Riparian Ecosystem Restoration Effectiveness framework was developed to review restoration progress (2NDNATURE 2010). There has been review and analysis of specific restoration projects as well as laboratory experiments testing the efficacy of mitigation treatments (2NDNATURE 2013, Fauria 2012, Peek et al 2013). There are gaps in questions targeting system-specific ecological metrics and performance measures for restoration in lake and stream ecosystems, meadow biological diversity, and old-growth forests.

Species and Resource Status

There has been a large focus on compiling datasets and models of the physical and ecological resources within the upland ecosystems. While the biodiversity of the Lake Tahoe ecosystem has been vigorously studied, there is a noticeable gap in research acknowledging upland watershed terrestrial and aquatic fauna. ISP questions have probed specific terrestrial species and while a handful of projects have targeted species (Tempel et al 2016) the bulk of research has focused on forest, aspen, and riparian vegetation (Grulke et al 2020, Liu et al 2019, Maloney 2014, Safford and Stevens 2017). More recent research has evaluated species interactions with post-burn or post-treatment forests, which are discussed in the pulse response section.

Basin-wide Datasets

Inventories of fens and meadows, wetlands, stream environment zones, and some groundwater systems have been developed. (Roby et al 2015, Sikes et al 2011, Christensen et al 2013, Pohll 2016). These systems are all considered of high value to the upland ecosystems and have garnered attention and support in restoration practices. Remote sensing has the potential to expand data sets and track physical changes in systems in a more robust way than field observations, which are of interest to be explored and deployed. The development of more in depth and broad spanning basin-wide datasets has the potential to provide large returns due to the potential improvements in modeling. While temperature, precipitation, snowpack and streamflow have all been monitored throughout the basin, climatic variables such as sunshine, humidity, and winds are lacking. Physical characteristics of soil properties, high elevation hydrologic parameters, and flood frequency estimates are outstanding needs as well.

Socioeconomic Value and Recreation

Socioeconomic value and recreation impacts on biological and ecological resources are topics often mentioned but still poorly understood. A small body of research has looked at snowmobile and oversnow vehicle impacts on the environment (McDaniel and Zielinska 2015, Hatchett and Eisen 2019), and the potential impacts of ski resorts on species populations (Slauson and Zielinski 2013). LTW incorporated valuation of cultural resources of the Washoe Indian tribe in their co-benefit/co-management analysis (Long et al, in draft). The LTB upland ecosystems are highly trafficked by locals and tourists alike, many with pets and motorized vehicles. As recreation has the potential to increase, these interactions and relationships need to be probed and understood.

Pulse Disturbance Response

The compiled research questions demonstrate a need to monitor, analyze and better predict system responses to pulse disturbances, such as forest management, development, and mortality events. Progress has been made in quantifying how manipulating forest structure affects the snowpack, fire impacts to soil chemistry, drought induced conifer encroachment, urban development impacts on habitat, and post fire habitat utilization, among others. The Lake Tahoe West Restoration Project answered many fire and forest management related questions, as they relate to efficacy of fuels treatments, air quality impacts of wildfire vs. prescribed burns, carbon budgets, and water quality, water quantity, and habitat impacts of forest management practices. Understanding how the structural changes in the upland systems affects habitat suitability, connectivity and biodiversity and broader watershed hydrology remain outstanding questions.

Pulse disturbances can include natural processes such as drought, wildfires, and insect-mortality or anthropogenic forces such as urban and recreational development and forest management. Questions included in this section describe or explore systems current response to disturbance. Table 2 provides a list of example questions and their corresponding research references.

Table 2: Pulse Disturbance Research Questions

(FR3) How do sensitive and vulnerable animal species associated with montane forests and aquatic inclusions (e.g., ponds and streams) use treated (masticated versus prescription-burned) and untreated areas to meet various needs (e.g., reproduction, foraging, movement, and shelter)?	Manley et al 2015 Tabil et al 2010
(LTW-15.2.1) How would forest thinning affect water yield?	Boisrame et al 2017 Maxwell and St Clair 2019 Roche 2018 Harpoled et al 2020 Krogh et al 2020 Long in draft

(TSS-F2) What is the effect of prescribed burning (pile or broadcast) on soils and how will this affect their ability to infiltrate water and nutrients?	Busse et al 2013 Hubbert et al 2015
(PM3) Develop a better understanding of how various factors or stressors change soil status in Tahoe basin watersheds to assist forest managers in preparing management plans and make predictions about ecosystem response to natural (e.g. fire, insect attack, drought, or erosion) and anthropogenic (air pollution, harvesting, development, or climate change) perturbations. For example, a comprehensive assessment of the effects of both wildfire and prescribed fire, and postfire vegetation, on long-term response in biological and physicochemical soil parameters is needed to better understand fire and its role in restoration ecology.	Adkins et al 2019 Busse et al 2013 Hubbert et al 2015
(TSS-A5) Better approaches are needed to assess and communicate to the public the relative risks and impacts of wildfires vs poor air quality/clarity events.	Taylor 2018 Little Hoover Commission 2018

Forest Management

The Tahoe forests have been actively managed with 85% of the land within the basin owned by the United States Forest Service (USFS) or state agencies. Extensive research has intended to optimize forest management practices for efficacy of treatment and cross-system benefits. There's a significant amount of research analyzing specific fuels treatments (Long et al, in draft, Stanton and Pavlik 2010, Busse et al 2018, Loudermilk 2014, Cansler et al 2019, Knapp et al 2005, Knapp et al 2017), forest regeneration after disturbance (Shive et al 2018, Carlson et al 2012), and post-burn or post-management habitat utilization (Manley et al 2015, Tabil 2010, Campos et al 2020). Physical attributes affected by forest management practices have been researched, such as water yield (Harpold et al, 2020, Krogh et al 2020, Boisrame 2017, Maxwell and St Clair 2019, Roche et al 2018, Asner et al 2016), water quality (Long et al, in draft) and soil chemistry (Busse et al 2013, Hubbert et al 2015, Adkins et al 2019, Long et al, in draft). Air quality impacts of prescribed burns and wildfires have been analyzed (Zhang et al 2013, Chen et al 2011, Chen et al 2010) with a recent focus on developing public knowledge and community understanding that fire is imperative to healthy forests (Taylor 2018, Little Hoover Commission 2018).

The potential levels of exchange that putting fire on a landscape or mechanical thinning can have across systems has provided a foundation to explore the power and potential of in-depth, scientifically driven co-benefit management in the upland ecosystems. A compiled body of literature has laid a solid foundation which has allowed projects like the Lake Tahoe West Restoration Partnership to develop interdisciplinary science teams to employ processed based models across varying disciplines to be incorporated into a landscape scale decision support tool and cross benefit analysis (Long et al in draft, Scheller et al 2019, Abelson and Reynolds 2019). LTW has shown that management can be employed to not only protect communities, but actively restore resilience in Lake Tahoe forests.

Lake Tahoe West

The Lake Tahoe West project has provided a foundation for optimizing landscape scale management. The project incorporated multiple science teams, developed a series of high level process-based models, and included cultural and socio-economic considerations in landscape scale modeling of a series of forest management practices under future climate predictions. The project was a collaborative effort involving management officials, science teams, and stakeholders composed of conservation groups, recreation communities, homeowners and businesses, fire protection agencies, government, and the Washoe Tribe of Nevada and California.

LTW modeled five management scenarios designed to represent different management perspectives and upscaled levels of intervention. Scenario 1 was a passive approach of fire suppression only. Scenario 2 focused management activities, predominantly mechanical thinning, to the wildland-urban interface. Scenario 3 expanded the thinning-based approach further into the forests. Scenario 4 shifted to a fire-focused approach, which relied on prescribed fire and managed wildfire one month out of the year. Scenario 5 was an intensive fire-focused approach where prescribed fires were employed throughout the entire year. These scenarios were modeled in LANDIS-II over a 100-year temporal scale, which simulates future forest growth, succession and disturbances. The future climate conditions modeled incorporated two representative concentration pathways (RCPs) in four global circulation models (GCMs). The primary LANDIS-II model results analyzed were emission of pollutants, key water pollutants, and wildlife habitat. Finer scale modeling was incorporated to analyze landscape fire dynamics (Scheller et al 2019), fine scale fire dynamics (Hoffman et al in draft), forest-snow dynamics (Harpold et al 2020, Krogh et al 2020), water quality and erosion (Elliot et al 2019, Cao et al 2020, Elliot et al 2018), smoke impacts, and wildlife (Slauson et al, in draft).

In collaboration with the design team, science team, and stakeholders, a series of key indicators extracted from LANDIS-II and other modeling outputs were determined to evaluate scenario performance. These indicators were used in the Ecosystem Management Decision Support (EMDS) analysis. EMDS incorporates a logic model (NetWeaver) and a decision model (Criterium Decision Plus). The logic model is used to assess complex environmental data into a single unified variable which can then be utilized in a decision model. The decision model allows for the assignment of weighting using an analytical hierarchy process and parameterized by decision maker perspectives, and provides the ability to assess multiple alternatives through the lens of the decision maker.

A total of 3,300 unique input variables were assessed to determine scenario performance. EMDS provided the framework to analyze large datasets from LANDIS-II while also incorporating process-based modeling that varied spatially and temporally. The resultant is a rich dataset of management performance, multi-system benefits, and a tool available to managers that provides science driven decision support.

Stream and Meadow Restoration

Streams and meadows are the integral pieces that connect and transition between systems in the upland basin and it is understood that maintaining their integrity is imperative. Research historically has progressed through the lens of Lake Tahoe clarity, and therefore sediment and nutrient transport have been the primary analysis in the upland ecosystems. Healthy meadows and wetlands act as a buffer to Lake Tahoe preventing extreme pulse floods and large sediment loads from reaching the lake. Research has focused on utilizing meadow processes to reduce fine sediment load (Schladow 2011, 2NDNATURE) and quantifying the hydrologic effects stream restoration has on montane meadows (Hammersmark et al 2008). The fluvial processes within floodplains are complex and improvements to restoration design are needed to integrate and utilize those system wide processes. Aspen communities tend to reside around streams and meadows, and have a complex relationship with water stress and conifer encroachment. Research has explored the relationship between aspen and conifers as well as fine scale fire in relation to the two (Berrill et al 2017, Berrill et al 2016, Berrill et al 2014, Ziegler et al 2016). Recreation-associated impacts on meadows are not well understood.

Response to Disturbance

Forest canopy interactions are complex in upland ecosystems and different external disturbances can alter those reactions in different ways. Insect mortality and drought can have compounding effects on water budgets. Understanding how systems respond post-disturbance has been highlighted across multiple documents as a high level of need. While some studies in the basin have looked at species specific mortality patterns (Young et al 2017, Maloney et al 2012) there is a lack of research on the subsequent basin impacts.

Press Disturbance Response (Climate Change)

There is a general need to better understand and predict systems response to press disturbances, which is primarily climate change. Outstanding questions remain about how warming conditions will affect ranges and populations of plant and animal species, how prolonged drought and lake levels below dam function will impact downstream communities and management, and how factors and stressors change soil status, slope stability, and hydrologic parameters. Many of the climate focused questions remain outstanding, and subsequent reports have highlighted their importance as well as acknowledging others. There has been a historical research focus on water quality in the basin, while water quantity has been largely neglected. As precipitation shifts to more rain than snow, there is a need to understand the implications that has on receding snowpacks and melt timing, which affects groundwater, streamflow timing, potential mid-winter floods, and summer drought conditions, all of which have cascading effects on the ecology and biodiversity of upland ecosystems.

General climate change predictions for the LTB are that temperatures are expected to increase and variability and intensity of precipitation is expected to increase, although total precipitation volumes may not change significantly. There are gaps in knowledge and areas that need to be explored in order to employ restoration and mitigation that will restore resilience to the upland ecosystems. There is reiteration across documents in understanding how climate change will shift species range and location (Questions IVA-SM1, OG6, CL2, CL3), changing flood frequency and better hydrologic models to predict impacts of rain on snow, spillover precipitation, and declining snowpack (Questions IVA-WH1, IVA-WH2, SNRR-WF3, SNRR-W2, IVA-LGW1, IVA-HGW1, IVA-WH3, TSS-C3) and the residual impacts of extreme meteorological events (Questions SNRR-WF1, TSS-C2, TSS-C1). Table 3 provides examples of press disturbance questions and research references.

Table 3- Press Disturbance Response Research Questions

(CL1) How is climate changing in and around the Lake Tahoe basin?	Catalyst Environmental Solutions 2020 (IVA) Dettinger 2018 (SNRR)
(CL2) How is climate change predicted to change the elevational boundaries between ecosystem types(e.g. montante and subalpine forest, and subalpine and alpine zones) in the Lake Tahoe basin over the next 10 to 100 years?	Lenihan 2008 Dettinger 2018 Catalyst Environmental Solutions 2020 (IVA)
(CL3) How is climate change predicted to change the ranges and populations of plant and animal species of concern over the next 10 to 100 years?	Elsen et al 2020 Maher et al 2017 Moore et al 2017 Morelli et al 2017 Stewart et al 2017 Dettinger 2018
(CL4) What are an effective set of indicators of the physical and biological changes that may occur as a result of climate change?	CES 2020 (IVA)
(OG6) What are the likely spatial changes in range and elevation of sentinel animal and plant species (i.e. species that are sensitive indicators of change) within the Tahoe basin in response to climate change?	Dettinger 2018 (SNRR) Mortiz et al 2008 Steward et al 2017

The primary climate change questions in the ISP set out to define meteorological conditions to be expected in the basin. The IVA and SNRR largely define those expected changes in meteorological forcing and their potential impacts. The IVA highlighted the key vulnerabilities in the upland sub-system as:

- Larger rainfall events over shorter periods will decrease the total infiltration to groundwater, compared with the same amount of annual precipitation spread over smaller events.

- Less groundwater storage will lead to forests encroaching on meadows, and the loss of wetland habitat. In turn, high densities of encroaching conifers will increase the risk of severe wildfire in riparian areas and meadows.
- Vegetation will change due to a combination of drought, increased insect populations and pathogens, windthrow during extreme storms, and greater risk of wildfire.
- Many native plant and animal species are likely to experience shifts in abundance and distribution, and in some cases local extinction.
- Native plant biodiversity may decline because of reduced moisture in forests, especially because the highest species diversity is typically found in more moist forest environments.

Snowpack

Snowpack is expected to recede due to a shift to more precipitation falling as rain than as snow, increasing snow levels, and warmer temperatures. April snow water equivalent will be reduced by 60-100% below 8000 feet (CES 2020). Increasing winter flooding and mid-season melt events are expected due to increased occurrence of rain-on-snow events and potentially higher intensity precipitation events. These storm events are not accurately forecasted and modeled currently and capabilities will need to be improved. The IVA, SNRR, and TSS acknowledge the need for better modeling of the changing inputs and subsequent melt of the Sierra Nevada snowpack.

Streamflow

Streamflow volumes do not show a significant change, but timing is expected to change drastically and maximum daily discharge is expected to increase in all streams, with the Truckee River experiencing a 60% increase for the 20-year storm event. More robust flood frequency data needs to be developed to allow for better management of water resources. Higher intensity storms and more variability in frequency, coupled with receding snowpacks, do not allow for groundwater replenishment and will increase the likelihood and prevalence of drought conditions. How drought conditions affect wildfire risk and how it affects carbon sequestration needs to be understood. As temperatures and streamflow volumes change, it will affect thermal regimes which will cause declines in water quality and may eliminate fish spawning habitat.

Groundwater

Groundwater levels are expected to decline, promoting conifer encroachment in meadows which can increase wildfire risk. Little information is known about high elevation recharge processes and groundwater characteristics, nor is it known how climate will affect other high elevation hydrologic processes. On the other hand, low elevation groundwater systems connected to the lake are expected to remain in sustainable condition over a full range of climate projections and may provide some local climate buffering (Pohll et al 2018). Specific aquifer characteristics need to be established to determine safe levels of groundwater extraction in low level aquifers to protect their use as a sustainable resource.

Soil Moisture

There is very limited data available on current or historic soil moisture conditions. It's been acknowledged across reports the need to define basin-wide soil characteristics. Soil moisture stress is predicted to increase. While groundwater levels may recede, root uptake generally does not as warmer temperatures encourage equal or greater vegetation growth. Drought conditions are expected to drive longer-term changes in forest composition and distribution, as well as increased fire frequency. In some cases, there has been short-term ecosystem accommodation to drought, where vegetation has died back and wildfire has reduced evapotranspiration demands allowing more water to stay within the soils, aquifers and streams.

Biodiversity

Changes in range, location and type are expected nearly across the board for ecotypes in the upland ecosystem due to the hydrologic drivers described above. Conifer encroachment on aspen communities, drying out of meadows, and reduced biodiversity are all expected. Studies have observed species range shifts (Dettinger 2018, Mortiz 2008), and species response to climate change (Lenihan 2008, Elsen et al 2020, Maher et al 2020, Moore et al 2017, Morelli et al 2017, Stewart et al 2017).It is acknowledge in nearly all documents that understanding these range shifts is imperative to conserving biodiversity and managing uplands in a way to better suit species relocations.

Future Forests

Management practices may need to be altered in response to projected environmental effects of climate change (Maxwell et al 2009). Forest management has the potential to not only protect communities from fire, but actively support establishing resilience in forests (Long et al in draft). Forest management has the potential to sequester carbon which may have implications for climate change as a driver itself (Loudermilk et al 2012, Loudermilk et al 2014, Loudermilk et al 2013, Liang et al 2018).

Socio-ecological Resilience Pillars

The Tahoe Central Sierra Initiative landscape developed eight pillars of socio-ecological resilience (Figure 1, Manley et al. in review) which have been incorporated into a multi-benefit analysis of research questions and areas. The pillars categorize management outcomes and provide a framework to integrate disciplinary research with the desired health and well-being of the upland ecosystems and communities. The conceptual model of socio-ecological resilience recognizes that ecological systems and social systems within the Lake Tahoe basin are interdependent and the health and quality of one cannot be achieved without incorporating and considering the other. The eight pillars of socio-ecological resilience are described in Figure 1.

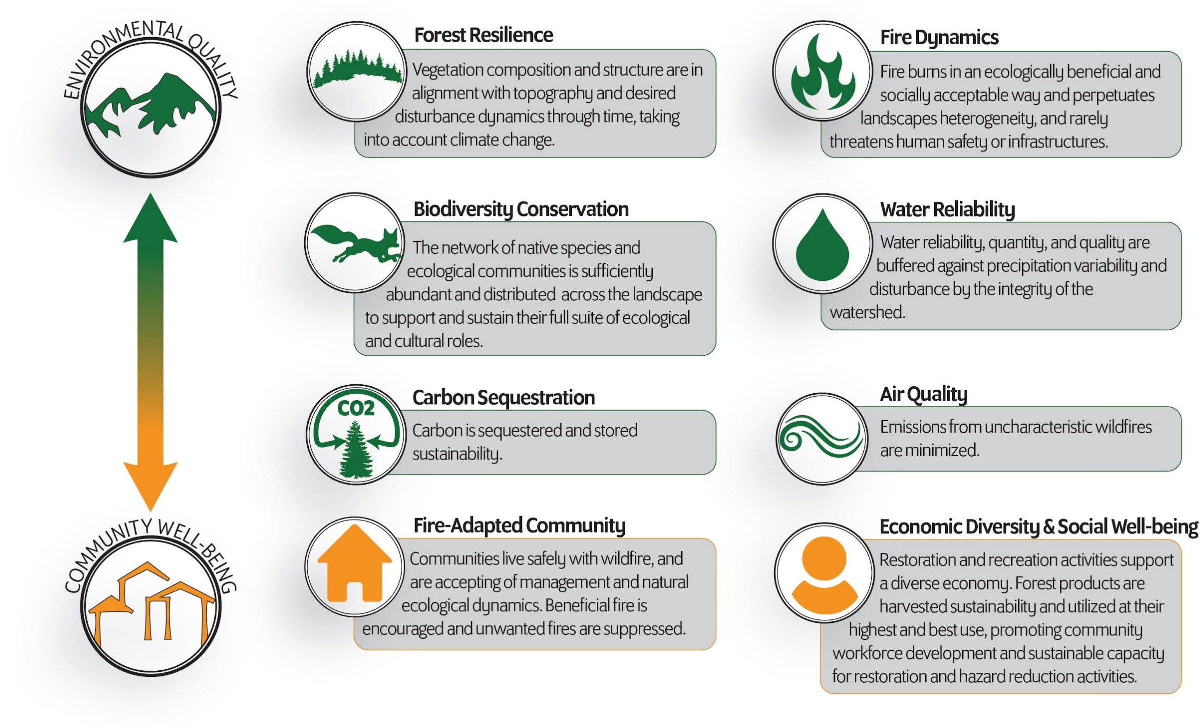

Figure 1- Socio-ecological Resilience Pillars (Manley et al, in review)

The resilience pillars were used to provide research questions with a score of multi-benefit outcomes that research may target. Management officials are often consulted in the development of research projects in the basin, and often cited by managers is the disconnect between academic research and management implementation (Knopp et al 2016). Connecting research questions with the management-outcome focused resilience pillars makes an attempt to bridge this divide and disconnect.

The score assigned to each question is simply a tally of the pillars acknowledged. This process was used to determine priority research areas. The structure of questions was noted to be a primary driver and bias in ranking due to large variance in form and scope. Some questions were broad and wide ranging, which provided more multi-system benefits. For example, ISP-CL1 asks "How is climate changing in and around the Lake Tahoe Basin?" That question has implications for nearly every pillar. In contrast, ISP-RE6 asks "Are existing ski areas predominantly occupied by male martens, and if so, does the extent of this population pose a threat to the persistence of species in the Tahoe basin?" Which is much more targeted and may only have implications for one pillar. Narrowed, specific questions are filtered to the bottom, while the broad overarching questions, that may be too broad for actionable research, are floated to the top. It is noted that the resilience pillars score is not a valuation, and questions without cross-benefits are of no lesser value to Tahoe basin scientific research. This method of ranking by potential management outcomes was not employed as a definitive rule of inclusion or exclusion, but rather a way to highlight the areas and themes that may have higher returns on investment. Table 4 includes all questions that ranked a score of 4 or above.

Table 4- Questions Ranked by Resilience Pillar Score

	Pillar Score	Pillars	Source
(FR2) Are there fuel treatment solutions that are optimal with respect to the multiple forest management objectives that exist in the basin (see question FR1), including considerations of cost? (This question could be addressed within a multiobjective modeling framework; the quality of the answers would depend at least in part on +A2:L145data from the kinds of field studies outlined below and elsewhere in this plan.)	8	FR FD BC WR CS AQ FAC FD & SW	ISP
(LTW-10.3.5) What are the net effects of thinning based scenarios considering avoiding impacts from wildfires?	7	FR FD BC WR CS AQ FAC	LTW
(TSS-F1) How can forest health be restored while minimizing the effects of treatment measures on water quality, air quality, soils, habitats (plants and wildlife), aesthetics, and recreational experience?	7	FR FD BC WR AQ FAC FD & SW	TSS
(LTW-10.3.7) What are uncertainties regarding large landscape burning?	6	FR FD BC AQ FAC	LTW
(LTW-2.2.2) What were the medium-term (11 years post treatment) effect on forest fuels?	6	FR FD BC WR CS AQ	LTW
(CL1) How is climate changing in and around the Lake Tahoe basin?	6	FR FD BC WR CS AQ	ISP
(CL4) What are an effective set of indicators of the physical and biological changes that may occur as a result of climate change?	6	FR FD BC WR CS AQ	ISP

(SNRR-WF4) Improved information regarding developing and future impacts of extreme fires on human communities and landscapes is needed.	6	FR FD BC WR FAC ED & SW	SNRR
(CL5) How might management practice be altered in response to the projected environmental effects of climate change?	6	FR FD BC WR FAC ED & SW	ISP
(SNRR-C2) Temperatures, precipitation, snowpack, and streamflow have been monitored at many weather and snow stations in the region for decades. Other climatic measurements (sunshine, humidity, winds, air quality, and so on) are much less commonly made and maintained, and are needed if we are to detect, track, forecast, and manage for all aspects of the coming climate changes.	5	FD BC WR CS AQ	SNRR
(TSS-A3) Developing the next generation of air quality models to include aerosols, black carbon, and other factors could contribute to better understanding visibility standards, vegetation health, snow albedo and snowpack dynamics, and the impacts of climate change on terrestrial and aquatic ecosystems.	5	FR FD BC WR AQ	TSS
(TSS-F3) How effective are current treatments for improving forest resiliency to fire, insect attack, and mitigating the impacts of a changing climate?	5	FR FD BC WR CS	TSS
(TSS-A5) Better approaches are needed to assess and communicate to the public the relative risks and impacts of wildfires vs poor air quality/clarity events.	5	FR FD AQ FAC ED & SW	TSS
(FR1) How do current fuel treatments and future treatment scenarios simultane-ously affect fire hazard and other values such as scenic and recreational amenity, water yield and quality, soil erosion, old-growth characteristics, and plant and animal diversity (including less-abundant species, narrowly distributed species, and forest and aquatic associates)? What are the effects of spatial distributions of fuel treatments on primary ecological management objectives in the basin, includ-ing (a) connectivity of populations of species expected to be most sensitive to changes in forest structure and understory conditions; and (b) maintaining quality habitat for aquatic species?	5	FR FD BC WR ED & SW	ISP
(SNRR-WF5) The relations between forest-mortality events, like that associated with the recent drought, and wildfire risks and impacts need to be better understood and predicted.	5	FR FD BC WR CS	SNRR
(FM5) How are fens and meadows impacted by current disturbances, including water use, fire suppression, recreation, and beaver activities? Which meadows are most critical to maintaining population of meadow dependent species in the basin?	5	FR FD BC WR ED & SW	ISP

(FR10) What is the relative importance of ozone damage, soil depth, periodic drought, insect attack, and stand density in determining spatial patterns and temporal dynamics of tree mortality and subsequent surface fuel accumulation? What is the optimal range of temporal and spatial dynamics of tree mortality based on current and future climate conditions?	5	FR FD BC WR CS	ISP
(TSS-C1) investigate the role that extreme weather events (e.g., atmospheric river storms, high wind events, prolonged heat waves) may have on aquatic, terrestrial and atmospheric processes in the lake and basin.	5	FR FD BC WR CS	TSS
(IVA-WH1) Winter precipitation in the Tahoe Basin is due to moisture that spills over from the westerly orographic uplift. As the proportion of rain vs. snow increases due to warming, the amount of moisture that spills over to the east of the Sierra Nevada may diminish (Pavelsky et al. 2012). Understanding spillover precipitation and its change in the future has significant consequences for predicting hydrology and water supply to Lake Tahoe and downstream communities.	5	FR FD BC WR ED & SW	IVA
(SNRR-WF3) Improvements are needed in understanding of how snowpack declines, and associated exacerbation of droughts, across the region will impact wildfire risks and the capacity of the region's vegetation, especially large trees and old growths, to accommodate climate change and capture and store carbon.	5	FR FD BC WR CS	SNRR
(OG2) Does the condition of the pre-Euro-American settlement forests in the Tahoe basin represent a satisfactory model for forest restoration (i.e. desired future conditions), and if not, how should it be modified to account for factors such as climate change and irreversible changes in land use? What are the projected changes in range and elevation of dominant tree species within the tahoe basin owing to climate change?	4	FR FD BC WR	ISP
(A2) What was the historical versus the current ecological status of aspen commu-nities and associated plant and animal populations? How have these communities changed in the absence of periodic disturbance from fire? What stand attributes (e.g., stand area, species composition) are critical to maintaining populations of the most closely associated species?	4	FR FD BC WR	ISP
(R2) What was the historical versus the current ecological status of riparian plant and animal communities in the basin? What was the historical role of fire frequency and intensity in shaping riparian-area composition and structure in the basin? What was the historical composition and structure of vegetation in riparian areas, includ-ing the density of standing and downed woody debris?	4	FR FD BC WR	ISP
(SNRR-WF1) Better understanding, models, and predictions of the processes and management of vegetation transitions following extreme fres, extreme drought and pest-caused forest die-offs are needed.	4	FR FD BC WR	SNRR
(SNRR-WF2) Attention and investment in higher resolution monitoring needed to track and predict local and specific large scale die-offs and broad landscape changes are needed.	4	FR FD BC WR	SNRR
(OG5) What were and are the effects of historical logging and fire suppression on forest-associated wildlife species, including composition, abundance, co-occurrence, and diversity?	4	FR FD BC WR	ISP

(SNRR-C1) Climate monitoring, especially in remote and unsullied parts of the region, is needed and should be welcomed.	4	FD WR CS AQ	SNRR
(UR2) Are there threshold levels of development at which sweeping changes in wildlife species abundances and ecological community composition occur?	4	FR BC FAC ED & SW	ISP
(FR6) How do alternative understory fuel treatments (e.g. canopy thinning followed by biomass removal, mastication and mulching, or prescribed burning) affect the trajectory of forest succession, including understory plant and animal species composition, relative abundances, and ecological community states and transitions. Do these treatments differ in resultant opportunities for invasive plant establishment? (It is recommended that the definition of forest succession include tree, shrub, herb, and grass plant forms, and that measurements include rate of fuel reaccumulation so that fire hazard can be calculated.	4	FR FD BC WR	ISP
(FR3) How do sensitive and vulnerable animal species associated with montane forests and aquatic inclusions (e.g., ponds and streams) use treated (masticated versus prescription-burned) and untreated areas to meet various needs (e.g., repro-duction, foraging, movement, and shelter)?	4	FR FD BC WR	ISP
(LTW-15.2.1) How would forest thinning affect water yield?	4	FR FD BC WR	LTW
(LTW-10.3.3) What are the predicted water quality effects of thinning in these scenarios?	4	FR FD BC WR	LTW
(LTW-10.3.4) What would be the water quality effects of pile burning?	4	FR FD BC WR	LTW
(LTW-12.2.1) What would be the effect of closing unpaved roads that are currently trafficked?	4	FR FD WR ED & SW	LTW
(LTW-12.2.2) What would be the effect of actively using unpaved forest roads to support thinning/harvest?	4	FR FD WR ED & SW	LTW
(LTW) What are the impacts of roads on upland erosion and sediment delivery following wildfire?	4	FR FD WR ED & SW	LTW
(LTW-14.2.2) What are the impacts of roads on upland erosion and sediment delivery following wildfire?	4	FR FD WR ED & SW	LTW
(TSS-F2) What is the effect of prescribed burning (pile or broadcast) on soils and how will this affect their ability to infiltrate water and nutrients?	4	FR FD BC WR	TSS

(LTW-9.2.1) What factors influence soil burn severity following fires?	4	FR FD BC WR	LTW
(LTW-9.2.2) What do the results project for soil burn severity from future wildfires?	4	FR FD BC WR	LTW
(LTW-10.3.8) What areas (based on soils) are more susceptible to erosion, under current conditions and following a wildfire and what does that imply for management?	4	FR FD BC WR	LTW
(PM3) Develop a better understanding of how various factors or stressors change soil status in Tahoe basin watersheds to assist forest managers in preparing management plans and make predictions about ecosystem response to natural (e.g. fire, insect attack, drought, or erosion) and anthropogenic (air pollution, harvesting, development, or climate change) perturbations. For example, a comprehensive assessment of the effects of both wildfire and prescribed fire, and postfire vegetation, on long-term response in biological and physicochemical soil parameters is needed to better understand fire and its role in restoration ecology.	4	FR FD BC WR	ISP
(LTW-19.2.1) How would different management regimes compare in terms of smoke impacts over the long term?	4	FR FD AQ FAC	LTW
(LTW-19.2.2) What are the expected smoke impacts of extreme wildfires on downwind human populations, and how do those compare to those from a typical prescribed burn event?	4	FR FD AQ FAC	LTW
(UR11) What is the relative importance of potentially competing uses (e.g., reducing fire risks, or maintaining biological diversity) of urban lots in the urban-wildland interface? What are the tradeoffs among competing uses, both short and long term, including maintaining and restoring biological diversity?	4	FR BC FAC ED & SW	ISP
(TSS-F4) What regulatory and economic factors impact the effectiveness of treatment measures for reducing hazardous fuels, and restoring and sustaining healthy forests?	4	FR FD FAC ED & SW	TSS
(R4) Does stream restoration have desired effects on riparian habitat and associated plant and animal species? How does restoration involving fire or fuel treatments differentially affect species richness or abundance?	4	FR FD BC WR CS	ISP
(FM2) How do current and potential future management and restoration practices in fens and wet meadows, including application of fire or fire surrogates, affect their susceptibility to invasion by unwanted plant species?	4	FR FD BC WR CS	ISP
(SNRR-WF1) Better understanding, models, and predictions of the processes and management of vegetation transitions following extreme fres, extreme drought and pest-caused forest die-offs are needed.	4	FR BC WR CS	SNRR
(IVA-WH2) With a smaller proportion of winter precipitation falling as snow due to increased surface warming, the occurrence of rain-on-snow flooding may increase. Methods to forecast such events and building flood resiliency in the system will need to be improved	4	FR BC WR ED & SW	IVA

(SNRR-W2) Need for accurate estimates of the coming changes in flood characteristics (e.g., food frequencies and magnitudes, food durations, seasonal timing).	4	FR BC WR ED & SW	SNRR
(IVA-LGW1) It will be necessary To evaluate the specifics of aquifer characteristics to establish the extent to which groundwater levels will change with extraction and the corresponding delineation of 0.5 proportional recharge areas (lake versus stream sources).	4	FR BC WR ED & SW	IVA
(IVA-WH3) Warmer temperatures along with longer droughts and increased evaporation may cause Lake Tahoe to go below its natural rim more often, affecting water supply to downstream communities. The Lake's reservoir capacity may need to be managed more actively and dynamically to simultaneously enhance water supply and mitigate downstream flooding.	4	FR BC WR ED & SW	IVA
(TSS-C3) as more winter precipitation comes as rain instead of snow, the impact of changing hydrologic conditions on streamflows, groundwater supplies, and restoration projects needs to be examined.	4	FR BC WR ED & SW	TSS

Questions that scored the highest had to do with the multi-system impacts of forest management and probing ways to optimize forest management practices to incorporate benefits across systems. Additionally, questions regarding how climate is predicted to change in the basin, what impacts those meteorological drivers will have, understanding extreme events (which are expected to be amplified), and how management practices may need to be altered to accommodate those changes. Most questions regarding basin-wide modeling filter to the top, especially defining the need for more accurate hydrologic modeling to better simulate changing snowpack dynamics and the downstream impacts of shifts in incoming precipitation and temperature.

Research Question Abbreviations and Nomenclature

ISP-	
OG	Old-Growth and Landscape Management
FR	Fire and Fuels Management
A	Aspen Management
R	Riparian Area Management
FM	Fen and Meadow Conservation and Management
LT	Lake Tahoe-associated Biota
OE	Other Aquatic Ecosystems
UR	Urbanization
RE	Recreation
CL	Climate Change
SPC	Soil Properties and Conditions
PM	Development and Application of Precive Models for Soil Conervation
CC	Effects of Climate Change as Related to Soil Conservation
PI	Policy Implications (PI) and Adaptive Management Strategies as Related to Soil Conservatior
TSS-	
C	Climate
BWS	Basin-wide Studies
A	Air Quality
F1	Forest Health
SM	Streams and Meadows
S	SocioEconomic Studies
SNRR-	
C	Climate
WF	Wildfire
W	Water
LTW-	
Report Section	