# Table S1

Sampling of additional resources that could be leveraged for identifying and validating refugia in the Sierra Nevada ecoregion.

|  |  |  |
| --- | --- | --- |
| Data Resource Type\*[see note]  | **Description** | **References** |
| **Snow** |
| For identifying refugia | Models that describe snowpack dynamics, such as snow residence time, snow water equivalent (SWE)[1-7], some of which are available through Cal-Adapt (<https://cal-adapt.org/tools/snowpack/>) [8,9]. Models for cold-air pooling potential [10], | 1. Rice & Bales 2013, 2. Luce et al. 2014, 3. Thorne et al. 2015, 4. Gergel et al. 2017, 5. Lute & Luce 2017, 6. Roche et al. 2018, 7. Sun et al. 2018, 8. Livneh et al. 2015, 9, Pierce et al. 2018, 10. Curtis et al. 2014 |
| For validating refugia  | Sensor-based data: snow telemetry network (SNOTEL) [1], California Cooperative Snow Surveys [2], Moderate Resolution Imaging Spectroradiometer (MODIS) data for snow cover mapping (with model accuracy assessments in the Sierra Nevada, e.g., [3,4]), remote sensing-based spatial distributions of SWE [5], and hydrological resources to assess/validate downstream function of snow refugia (e.g., California Basin Characterization Model (BCM, [6]), climatic water balance data [7,8], National Park Service river monitoring data [9], historical and projected streamflow metrics [10], Sierra Nevada Sentinel Streams Project [11], and data from downstream water users (municipal, agriculture).  | 1. NRCS 2020, 2. CDWR 2020, 3. Raleigh et al. 2013, 4. Rittger et al. 2013, 5. Rice et al. 2011, 6. Flint et al. 2014, 7. Dobrowski et al. 2013, 8. Abatzoglou et al. 2018, 9. Andrews 2012, 10. Wenger et al. 2010, 11. Thorne et al. 2015 |
| **Fire** |
| For identifying refugia | Fire refugia identification models and modeling approaches [1-6], future fire regime predictions under climate change [7,8], fire return interval departure (FRID) [9]. | 1. Safford & Harrison 2008, 2. Krawchuk et al. 2016, 3. Wilkin et al. 2016, 4. Meddens et al. 2018, 5. Jeronimo et al. 2019, 6. Koontz et al. 2020, 7. Parks et al. 2018, 8. Westerling 2018, 9. Safford & Van de Water 2014 |
| For validating refugia  | Field study [1-3], satellite imagery [4-6], and combination approaches [7]; Federal Wildland Fire Occurrence Data [8]. | 1. Van de Water & North 2011, 2. Berry et al. 2015, 3. Blomdahl et al. 2019a, 4. Kolden et al. 2012, 5. Kane et al. 2015, 6. Meigs & Krawchuk 2018, 7. Meddens et al. 2016, 8. USGS 2019 |
| **Meadows** |
| For identifying refugia | Meadow refugia mapping [1] and meadow prioritization tools [2-4]. | 1. Maher et al. 2017, 2. Vernon 2019, 3. Albano et al. 2019, 4. Gross et al. 2019 |
| For validating refugia  | Maps, assessments, projections, and reports available through the UC Davis Sierra Nevada Meadows Clearinghouse [1] and Sierra Meadows Partnership [2], such as meadow boundary mapping on public lands (e.g., [3,4]). | 1. <https://meadows.ucdavis.edu/>, 2. <https://www.sierrameadows.org/>, 3. Fryjoff-Hung & Viers 2013, 4. Pyrooz et al. 2015 |
| **Old Growth Forest** |
| For identifying refugia | Forest refugia identification [1,2], mapping and syntheses with insights on water stress [3-6], fire [7], and pests [8] | 1. Thorne et al. 2018, 2. Thorne et al. 2020, 3. Flint et al. 2014, 4. Asner et al. 2016, 5. Byer & Jin 2017, 6. Brodrick et al. 2019, 7. Safford & Van de Water 2014, 8. Larvie et al. 2019 |
| For validating refugia | Mapping efforts, range maps, and historic maps on individual tree species (e.g., whitebark pine [1], California black oak [2]).  | 1. Nesmith et al. 2019, 2. Gaman & Casey 2002. |
| **Pacific Fisher** |
| For identifyingrefugia | Pre-drought landscape-scale habitat models [1-5], reproduction, abundance, and population growth [6], compared with post-drought habitat models currently in development [7]. | 1. Davis et al. 2007, 2. Zielinski et al. 2006, 3. Zielinski et al. 2010, 4. Spencer et al. 2011, 5. Spencer and Rustigian-Romsos 2012a,b, 6. Sweitzer et al. 2015. 7. Thompson et al. 2020. |
| For validating refugia | Completed and ongoing studies such as the Sugar Pine Fisher Project, California Department of Fish and Wildlife Fisher Translocation Project, Kings River Fisher Project, Sierra Nevada Adaptive Management Project (SNAMP), U.S. Forest Service Pacific Southwest Region 5 Fisher Regional Monitoring Program, and the Southern Sierra Fisher and Marten Study [1] and more [2]. | 1. Spencer et al. 2015, 2. USFWS 2016 |

\* Note that the distinction between resources used to identify refugia and resources used to validate refugia is not always clear. For example, a resource in the “validate” refugia section might alternatively be used to “identify” refugia, but if the resource was used to identify refugia, it may not *also* be used as a validation source. Conversely, a resource in the “identify” refugia section might be used instead to “validate” existing refugia mapping hypotheses, but if it is used as a validation resource, that resource should not have *also* been used in the refugia identification model. Validation resources must be distinct from the approach/data/models used to identify refugia. Thus, the categorizations of identify/validate in this table are often suggestions.

# Table S2

Sampling of additional resources supporting the prioritization and management of refugia in the Sierra Nevada ecoregion.

|  |  |  |
| --- | --- | --- |
| **Data Resource Type** | **Description** | **References** |
| **Fire** |
| For prioritizing refugia | Decision-making tools such as [1] may be helpful. Resources used to identify and validate fire refugia might also be leveraged to prioritize refugia for management (see Table S1).  | 1. Thompson et al. 2016 |
| For managing refugia | Climate-informed post-fire reforestation [1,2], Climate-wise Reforestation Toolkit [3], mechanical treatments to improve resistance to high severity fire [4], fire management decision-making and response planning [5]. | 1. North et al. 2019, 2. Ng et al. 2020, 3. Steel et al. 2020, 4. Becker & Lutz 2016, 5. Thompson et al. 2016 |
| **Meadows** |
| For prioritizing refugia | Sierra Meadows Prioritization Tool [1], and Meadow Decision Support Framework [2,3]. | 1. Vernon 2019, 2. Albano et al. 2019, 3. Gross et al. 2019 |
| For managing refugia | Beaver dam analogs or maintenance of beaver populations to restore incised streams, maintain stage height, and contribute to groundwater recharge [1-3].Restoration projects to restore hydrologic and vegetation function (e.g. [4,5]). American Rivers Meadow Condition Scorecard to assess condition prior to restoration [6]. Mitigation of risk of invasive species/pathogen spread during restoration [7]. Permanent cessation of livestock grazing, fencing off riparian zones, seasonal grazing restrictions [8-10]. Restoration of willow stands for willow flycatcher [11]. Maintaining meadow grass at sufficient heights to support vole habitat for great gray owl [12]. Removal of encroaching conifers via controlled burns [13], or mechanical removal [14]. | 1. Pollock et al. 2014, 2. Fair et al. 2018, 3. Greenwood et al. 2018, , 4. Drew et al. 2016, 5. NPS 2020, 6. American Rivers 2018, 7. Cal-IPC 2019, 8. Kalinowski et al. 2014, 9. Wu et al. 2016, 10. Vernon et al. 2019, 11. Green et al. 2003, 12. Kalinowski et al. 2014, 13. Meddens et al. 2018, 14. Wu et al. 2016 |
| **Old Growth Forest** |
| For prioritizing refugia | See Old Growth Forest Section. |  |
| For managing refugia | Fuels reduction and restoration treatments [1,2]. Consideration of differences in life histories of prioritized species (e.g., oaks and pines might be more likely to occur in old growth forest climate change refugia due to drought and fire tolerance, but are potentially most vulnerable to immediate, non-climate-specific threats like fire suppression and pests) [3]. | 1. Finney 2001, 2. Collins et al. 2011, 3. Safford et al. 2016. |

# Refugia S1: Giant Sequoia

*Planning Scope*

Though prioritized within the Old Growth Forest resource, giant sequoias (*Sequoiadendron giganteum*) are also a priority resource by themselves. Giant sequoias can grow past 90m in height, can live for over 3000 years (Sillett et al. 2015), and largely only occur naturally on public land in the Sierra Nevada (Stephenson 1999). Drought-tolerant compared with other tree species in the region (Nydick et al. 2018), giant sequoias depend on fire for reproduction (Harvey et al. 1980, Swetnam 1993). Decades of prescribed burning in Sequoia and Kings Canyon National Park have helped create sunny, open forest conditions that allow giant sequoia seedlings to establish in mineral-rich soils exposed by fire (Meddens et al. 2018), reducing fuel loads and creating conditions necessary to encourage giant sequoia reproduction (Harvey et al. 1980, Stephenson 1999). Given their longevity and that the species has managed to persist through millennia of different climates, giant sequoia groves could themselves serve as an indicator of hydrologic or fire refugia for other species (Su et al. 2017, Nydick et al. 2018).

*Assess Climate Change Vulnerability*

Giant sequoias have low genetic diversity compared with other trees, potentially limiting their adaptive capacity in a changing climate (Dodd & DeSilva 2016). Additionally, they require substantial amounts of water, taking in >2000 kg day−1 (Ambrose et al. 2016). Thus, drought and snowpack decline in the Sierra Nevada create management uncertainty for this species in coming decades. California’s severe drought from 2012-2015 – wherein sequoias fared better than other species – nevertheless revealed new insights about their drought vulnerability (Su et al. 2017, Nydick et al. 2018). Sequoias regulate water loss through leaf-level shedding, but under severe drought they make crown-level adjustments to maintain favorable water status (Ambrose et al. 2018). Though very few giant sequoias died in the 2012-2015 drought, they exhibited varying signs of drought stress: drought-induced foliage dieback was higher at lower elevations, in areas with low densities of adult sequoia, and on steep slopes, suggesting that variation in sequoia drought vulnerability is driven by site water balance metrics (Stephenson et al. 2018). Future severe fire and drought may interact to make giant sequoias more vulnerable to attacks by cedar bark beetle (*Phloeosinus* spp.) (Nydick et al. 2018, Stephenson et al. 2018).

*Identify and Validate Refugia*

Current locations of ~70 sequoia groves are well-established (Rundel 1972, Willard 1994). Climate change refugia mapping for giant sequoia could synthesize existing grove locations, vulnerability maps (Brodrick et al. 2019), satellite imagery-based maps (Su et al. 2017), modeled projections of vegetation exposure under climate change (Thorne et al. 2017), combined field and remote sensing approaches (Martin et al. 2018), and hydrologic refugia mapping or hydrology data (Flint et al. 2014) to identify areas where giant sequoias are likely to persist and be less sensitive to future severe drought. A refugia approach may also help assess whether current sequoia refugia areas will remain refugia under severe drought, and may suggest areas where sequoia could be encouraged to migrate. For example, the existing distribution of giant sequoia groves occurs along a narrow elevation band that tracks the rain-snow transition (Nydick et al. 2018). Future climate projections might identify hydrologically-appropriate areas that will track this rain-snow transition.

*Prioritize Refugial Areas and Implement Management Actions*

Drought vulnerability maps can help guide management action (Nydick et al. 2018). Where climate projections and mapping show sequoia groves that are outside the future climate envelope they are predicted to need, managers are faced with tangible decisions about whether and where to prioritize conservation action. Sequoia may be experimentally planted *ex situ* in areas that have been identified as potential refugia. In experimental planting areas, managers can use prescribed fire to facilitate natural regeneration (Meddens et al. 2018), mechanical treatment to remove competition from smaller neighboring trees (York et al. 2015), and planting at low density or thinning early on in dense stands (York et al. 2013). In areas more vulnerable to drought and beetle attacks, tree species diversity can be increased to enhance resistance to pests.

*Monitoring Effectiveness of Refugia*

The Leaf to Landscape project measured the physiological consequences of drought stress in individual giant sequoia trees (Ambrose et al. 2018), combining field and remote sensing data to measure drought stress (Martin et al. 2018), and using remotely-sensed data to generate maps of forest vulnerability to hot droughts (Brodrick et al. 2019). In addition, the conservation goals of the Save the Redwoods League may align with sequoia refugia planning and assessment to evaluate the status of giant sequoia forest ecosystem health (Burns et al. 2018). To assess refugia effectiveness, these efforts may be combined with other long-term forest monitoring data (e.g., FIA data, Lutz 2015, Das et al. 2016).

# Refguia S2: Old Growth Forests

*Planning Scope*

Old growth forest definitions vary (Wirth et al. 2009), reflecting the diverse values and perspectives of forest scientists and managers. Acknowledging that our definition is likewise informed by our perspectives, we define old growth forests as those that contain many large and old trees (150-200 years), with a complex canopy and understory structure. In the Sierra Nevada, old growth forests are largely composed of mixed conifer-hardwood communities that include ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*), sugar pine *(Pinus lambertiana*), red fir (*Abies magnifica*), white fir (*Abies concolor*), California black oak (*Quercus kelloggi*), Douglas fir *(Pseudotsuga menziesii),* and giant Sequoia (*Sequoiadendron giganteum)* (see next section). They provide important habitat and ecosystem function for many wildlife species, including the state and federally endangered Pacific Fisher (*Pekania pennanti*) (**see Inset S1**), California spotted owl (*Strix occidentalis occidentalis*), northern flying squirrel (*Glaucomys sabrinus*), and pileated woodpecker (*Dryocopus pileatus*).

*Assess Climate Change Vulnerability*

Drought (Williams et al. 2010), wildfire (Westerling 2016), and pests (Bentz et al. 2010) are chief stressors to Sierra Nevada forests that have been exacerbated under current climate change. Unprecedented low precipitation combined with record high temperatures produced the 2012-2015 drought -- the most severe in the last 1200 years (Griffin & Anchukaitis 2014, Mann & Gleick 2015), which caused substantial tree mortality as bark beetle populations expanded across large areas of water‐stressed forest (Fettig et al. 2019). Larger trees in particular were impacted, influencing stand structure by reducing the density and basal area of trees, reducing canopy cover, lowering average tree diameter, and reducing structural class diversity (Fettig et al. 2019, Young et al. 2019).

In climate projections, only 14.6% of California’s natural vegetation lands are predicted to be in vegetative climate refugia by 2100 (Thorne et al. 2020). Mature forests may be more resistant to climate-induced vegetation transitions (Stralberg et al. 2020), but climate change – in combination with decades of fire suppression – has shifted forest composition and structure, increasing the density of small diameter trees, and decreasing the density of large diameter trees (Dolanc et al. 2014, McIntyre et al. 2015). While dense old growth forests probably provide fire refugia in moist forests with mixed-severity fire regimes, this is likely not the case in the drier frequent-fire forests of the Sierra Nevada (Lesmeister et al. 2019, Reilly et al. 2017). Dense canopies may make forests more susceptible to climate change and associated disturbance. For example, where dense canopies are provided by large and very large trees (rather than smaller trees), they are more likely to be resilient to fire, but less likely to be resilient to drought-induced insect mortality (Fettig et al. 2019). These shifts pose uncertainties around future fire regimes and associated management, given interactions with pests, fire suppression, and drought (Mallek et al. 2013, Safford & Van de Water 2014), particularly because some tree species (e.g., oaks, pines) are more drought-tolerant than others (e.g., red fir) (Safford et al. 2016).

*Identify and Validate Refugia*

In refugial mapping pertinent to Sierra Nevada forests, Thorne et al. (2020) used satellite imagery to map vegetative climate refugia under both wetter and drier future scenarios to identify areas with a greater chance of retaining existing vegetation. Additionally, Thorne et al. (2018) evaluated the vulnerability of southwestern US forests and found that forests in the western slope of the Sierra Nevada were climatically at risk under all scenarios tested. Refugial areas that can support old growth forest under changing climate regimes (which in turn promote the refugial microclimates these forests provide) will only occur where landscape position, solar radiation, and moisture deficit align. Mapping landscape facets, as well as projections in actual evapotranspiration (AET) and climate water deficit, and aligning these characteristics with dense forest reference conditions, will be critical for mapping potential old growth forest refugia. See **Table S1** for additional resources.

*Prioritize Refugial Areas and Implement Management Actions*

Refugial old growth forest areas can be prioritized for management action, such as coaxing forest structure towards the natural range of variation to increase resilience (North 2012). To support important characteristics of old growth forest, managers can conduct landscape-scale restoration for priority species (e.g., oak restoration as in Long et al. 2016), targeting plantings and management in areas expected to remain or transition to forest in the future (Stephens et al. 2010), and/or using first entry burns to move conditions towards the natural range of variation (Kane et al. 2019). See **Table S2** for more research supporting the prioritization and management of old growth forest refugia.

*Monitor Effectiveness of Refugia*

Forest Inventory and Analysis (FIA) plot data, collected since 1930, can be leveraged to assess species composition, health, mortality, status, and trend in areas identified as old growth forest refugia (<https://www.fia.fs.fed.us/>). Additional monitoring efforts such as the Yosemite Forest Dynamics Plot and the Sierra Nevada Forest Dynamics Plot Network have been collecting forest data for several decades, providing long-term data relevant to forestry and tree mortality (e.g., Lutz 2015, Das et al. 2016). These data can be combined with species-focused monitoring data, such as Pacific fisher occupancy and population models (e.g., Spencer et al. 2015, Sweitzer et al. 2015) to monitor refugia effectiveness.

# Inset S1

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| **Old Growth Forest Refugia for the Southern Sierra Nevada Fisher**  |
| **Planning Scope:** Extirpated from over half of its previous range due to habitat loss and trapping, the southern Sierra Nevada fisher is one of only two remaining native populations in the state of California (Gibilisco 1994, Zielinski & Lewis 1996) and was listed as federally endangered in 2020. Pacific fishers are associated with the many hallmarks of old growth forests, such as complex structure that includes large diameter trees and varied tree diameters, complex canopy, and quality denning habitat offered by tree cavities of species like California black oak (*Q. kelloggi*) or sugar pine (*P. lambertiana*) (Zielinski et al. 2004, Purcell et al. 2009, Weir et al. 2012, Aubry et al. 2013).**Assess Climate Change Vulnerability:** The southern Sierra Nevada fisher population is estimated at <500. Suitable fisher habitat in this ecoregion is susceptible to fragmentation (Spencer et al. 2015), such as that caused by high severity  | **Image of a small fisher in between two tree trunks.**Photo: Pacific Southwest Research Station, USDA Forest Service |
| wildfires in combination with threats from drought and insect outbreaks (Lawler et al. 2012). Climate change-driven habitat loss and fragmentation amplify the vulnerability of low genetic diversity in this small population (Tucker et al. 2012), which faces additional losses from vehicle strikes and rodenticide poisoning at marijuana grow sites (Gabriel et al. 2015).**Identify and Validate Refugia:** Though no explicit refugia mapping has been conducted, research efforts summarized within the Southern Sierra Nevada Fisher Conservation Strategy (Thompson et al. 2020) might be leveraged to identify and validate refugia.Comparison of pre-drought and post-drought landscape models may provide a fisher refugia identification method. Completed and ongoing studies in California have collectively examined fisher life history, habitat use, responses to vegetation management, landscape-level occupancy modeling, and more (e.g., Spencer et al. 2015, USFWS 2016). However, scientific understanding is changing given massive tree mortality from the 2012-2015 drought, paired with emerging consequences of the 2020 Creek Fire. See **Table S1**.**Prioritize Refugial Areas and Implement Management Actions:** Prioritized fisher refugia should be managed to stabilize key habitat, restore landscape permeability, and promote landscape heterogeneity (Thompson et al. 2020). Management can include restoration of ecological processes, prescribed fire and mechanical treatment, and improvement of habitat connectivity (Spencer et al. 2015), marijuana grow site enforcement and remediation to reduce the threat of rodenticide poisoning (Gabriel et al. 2015), and fisher reintroductions to sites within and near refugia, ideally conducted within an adaptive management framework (Spencer et al. 2016). **Monitor Effectiveness of Refugia:** To evaluate the impact of refugia on fisher persistence, long-term forest dynamics data (e.g., FIA data: <https://www.fia.fs.fed.us/>, Lutz 2015, Das et al. 2016) and post-fire severity mapping tools (see Fire Refugia section) could be combined with survey data that informs Pacific fisher occupancy and population models (e.g., Spencer et al. 2011, Spencer et al. 2015, Sweitzer et al. 2015, Blomdahl et al. 2019b).  |

# Inset S2

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| **Alpine Refugia for Whitebark Pine in the Sierra Nevada Ecoregion** |
|  Photo: National Park Service | **Planning Scope:** Whitebark pine (*Pinus albicaulis*) is a foundational species in high elevation areas of the Sierra Nevada, defining community structure upon which other species and ecosystem processes depend (Tomback & Achuff 2010). Found at the highest elevations, often on poor soils and steep slopes, they reduce soil erosion, help regulate downstream flow of snowmelt and run-off, provide food and shelter for understory species, and persist within seed banks to serve as post-fire pioneers (Tomback et al. 2001). They also provide habitat for proposed endangered Sierra Nevada red fox. Loss of whitebark pine from the subalpine ecosystem could cause major shifts to the alpine community.**Assess Climate Change Vulnerability:** Whitebark pine have suffered declines due to historic fire suppression (Keane et al. 2012, 2017a), and face threats from white pine blister rust (*Cronartium ribicola*) and mountain pine beetle (*Dendroctonus ponderosae)*. Though the interactions between future pest, drought, and fire dynamics under climate change are unknown, evidence indicates that mountain pine beetle outbreaks in the Sierra Nevada may be driven by drought (Millar et al. 2012, Meyer et al. 2016). |
| **Identify and Validate Refugia:** Future projections of habitat size, location, and elevation distribution in the Sierra Nevada predict that Whitebark pine may move geographically but not suffer large declines (Moore et al. 2017). The species may persist in some alpine zones at lower basal areas, and impacts of climate change will vary locally (Keane et al. 2017b). Researchers have also identified genetic refugia for whitebark pine resistant to white pine blister rust, based on drought tolerance, cold hardiness, and genetic diversity (Barrows et al. 2020).**Prioritize Refugial Areas and Implement Management Actions:** 91% of California’s whitebark pine range falls in the Sierra Nevada, but 94% of these stands have management limitations, and accessible management areas only cover a very small portion of the range (Meyer et al. in review). Thus, beyond the fact that much of the range already falls on protected land, further management of prioritized refugia may be limited under current land tenure circumstances. In accessible management circumstances, refugia might be supported through restoration and prescribed burning (Keane et al. 2017b) and genetic diversity approaches (Barrows et al. 2020). Climate change scenario planning for whitebark pine could inform future adaptive management (Kellermann et al. 2019). **Monitor Effectiveness of Refugia:** Long-term monitoring of high-elevation whitebark pine communities by the Forest Service (Slaton et al. 2019, Meyer et al. in review) and National Park Service (McKinney et al. 2011, Nesmith 2018, Nesmith et al. 2019) might be used to assess whether refugia are functioning as desired over time.  |

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