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CONSERVATION ISSUES

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Climate Change Refugia for Biodiversity in the Klamath-Siskiyou Ecoregion

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ABSTRACT: The Klamath-Siskiyou Ecoregion has been a refuge for species during past climate change events, but current anthropogenic stressors are likely compromising its effectiveness as a refugium for this century's projected changes. Reducing non-climate stressors and securing protection for large, complex landscapes are important long-term actions to alleviate climate change impacts on biodiversity. Equally important is the immediate protection of a network of climate change microrefugia, particularly old growth and intact forests on north-facing slopes and in canyon bottoms, lower- and middle-elevations, wetter coastal mountains, and along elevational gradients. Such areas provide local opportunities for vulnerable species to persist within the ecoregion. We identify a provisional set of 22 highest-priority and 40 high-priority microrefugia that occur mostly outside of existing protected areas and along wetter and lower elevations of the ecoregion. Proposed reserve designs, if fully implemented, would capture most of the recommended microrefugia, although we found 11 important gaps. Most of the region's biodiversity, endemic species, and species vulnerable to climate change are invertebrates, non-vascular plants, and fungi that are largely restricted to persistently cool and moist late-successional forests. Opportunities for climate change response for vulnerable taxa will necessarily be local due to a limited capacity of many species to move to new habitat, even over relatively small distances where land use practices create inhospitable conditions. The ecoregion's distinctive and endemic serpentine-substrate flora also is at risk and possible refugia are sites that will retain wet soil conditions, such as seeps and bogs.

Index terms: climate change, ecoregion, Klamath-Siskiyou, microrefugia, refugia

INTRODUCTION

The Klamath-Siskyou Ecoregion (KSE) contains globally important biodiversity–only five other temperate forests regions are as diverse or home to as many endemic species and ancient lineages (e.g., Caucasus, Southwestern China, Southeastern United States, Coastal Plain/Southern Appalachians, Valdivia rainforests of Chile and Argentina; Olson et al. 2001; Tecklin et al. 2011). The special location (latitude and coastal proximity), rugged terrain, climatic stability, and complexity of soils and microclimates have allowed the region to act as a refuge from past climatic changes for species and natural communities requiring cool and moist conditions (Whittaker 1960, 1961; Stebbins and Major 1965; Wagner 1997; Coleman and Kruckeberg 1999; Sawyer 2007).

One might expect that the KSE will continue to function well as a climate change refugium as human-caused climate change progresses. However, cumulative land use impacts combined with projected climate change could have a profound impact on the ecoregion's species and ecosystems. In the KSE, over a century of land use activities (e.g., logging, mining, livestock grazing, damming of rivers, mining, and human-caused alterations of fire) have resulted in loss or degradation of mesic habitats (DellaSala et al. 1999) that may have previously functioned as refugia over millennia. Impacts include loss of contiguous habitat along intact elevational and other environmental gradients that may facilitate climate-related shifts in natural communities and loss and degradation of most of the mature and old-growth forests (e.g., only about 28% of the historic old-growth forests remain; Strittholt et al. 2006), particularly mesic lowland and mid-elevation habitats (Staus et al. 2002). Increasing prevalence of invasive plants and pathogens facilitated by road building and land use practices poses an additional threat to native species and communities (DellaSala et al. 1999).

The existing protected area system (i.e., National and State Parks, Wilderness Areas, National Monuments, Botanical Areas) is inadequate for ensuring the persistence of most of the ecoregion's vulnerable biodiversity (DellaSala et al. 1999; Noss et al. 1999; Carroll et al. 2010). Existing reserves largely protect higher-elevation communities, while the lower-elevation reserves are limited in their geographic extent, thereby missing many distinct lowland species assemblages and areas that may act as potential microrefugia. We define microrefugia as sites with cool and moist conditions conducive to the persistence of species vulnerable to climate change. Thus, our conservation strategy for the KSE builds on prior reserve proposals (Noss et al. 1999; Carroll et al. 2010; KS Wild 2010; Siskiyou Project 2010) by

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adding microrefugia and other elements to create a reserve design more robust to anticipated increases in temperature and changes in precipitation over the century (Koopman et al. 2009).

CORE CONSERVATION ELEMENTS FOR ROBUST RESERVE DESIGN IN A CHANGING CLIMATE

Fundamental to the development of a robust conservation design are three core-planning elements: (1) reduction of non-climate stressors; (2) protection of complex landscapes; and (3) protection of climate change microrefugia. Taken together, they are the foundation for guiding reserve design and conservation implementation in the KSE.

Reduction of Non-Climate Stressors

Reducing non-climate stressors across the landscape, such as curtailing or greatly reducing logging and road building, is the single most important action that land managers can take to help the regional biota and ecosystems persist in the face of a changing climate. The release from stressors should be strategically targeted to critical core habitats, old-growth forest microrefugia, and adaptation corridors along environmental gradients (sensu, Olson et al. 2009). For example, if large complex landscapes were off-limits to logging (only about 13% of the region is strictly protected; DellaSala et al. 1999), and all of the predicted local climate refugia, old-growth forests, and priority corridors in the KSE (e.g., Noss et al. 1999) were effectively protected, this would have a much more positive effect for biodiversity than if most of the area released from logging was in highly degraded, mid-elevation production forests. The release of strategic areas from land use stressors would need to allow maturing forests to once again dominate the landscape.

Protection of Complex Landscapes

Securing a high level of protection and undertaking ecologically based restoration in degraded areas is important, as well as protection of large, complex landscapes with diverse terrains, soils, microclimates and other environmental gradients. In particular, low and mid-elevation habitats in higher precipitation areas (e.g., along the coast) will provide multiple local opportunities for persistence of vulnerable species. In the KSE, conservation groups have identified two areas having these characteristics: a 243,000 ha land bridge known as the proposed Siskiyou Crest National Monument (considered a climate refuge) in southwest Oregon and northern California (KS Wild 2010) and a ~445,000 ha proposed Siskiyou Wild Rivers National Salmon and Botanical Area in southwest Oregon, a hotspot of serpentine flora and wild rivers (Siskiyou Project 2010; Figure 1). Protection of these areas will greatly improve the chances for persistence of a large portion of the ecoregion's terrestrial and freshwater biota even if we are uncertain of the magnitude, timing, and distribution of changes in temperature and precipitation at sub-ecoregional scales (e.g., Murphy et al. 2004; Moilanen et al. 2006).

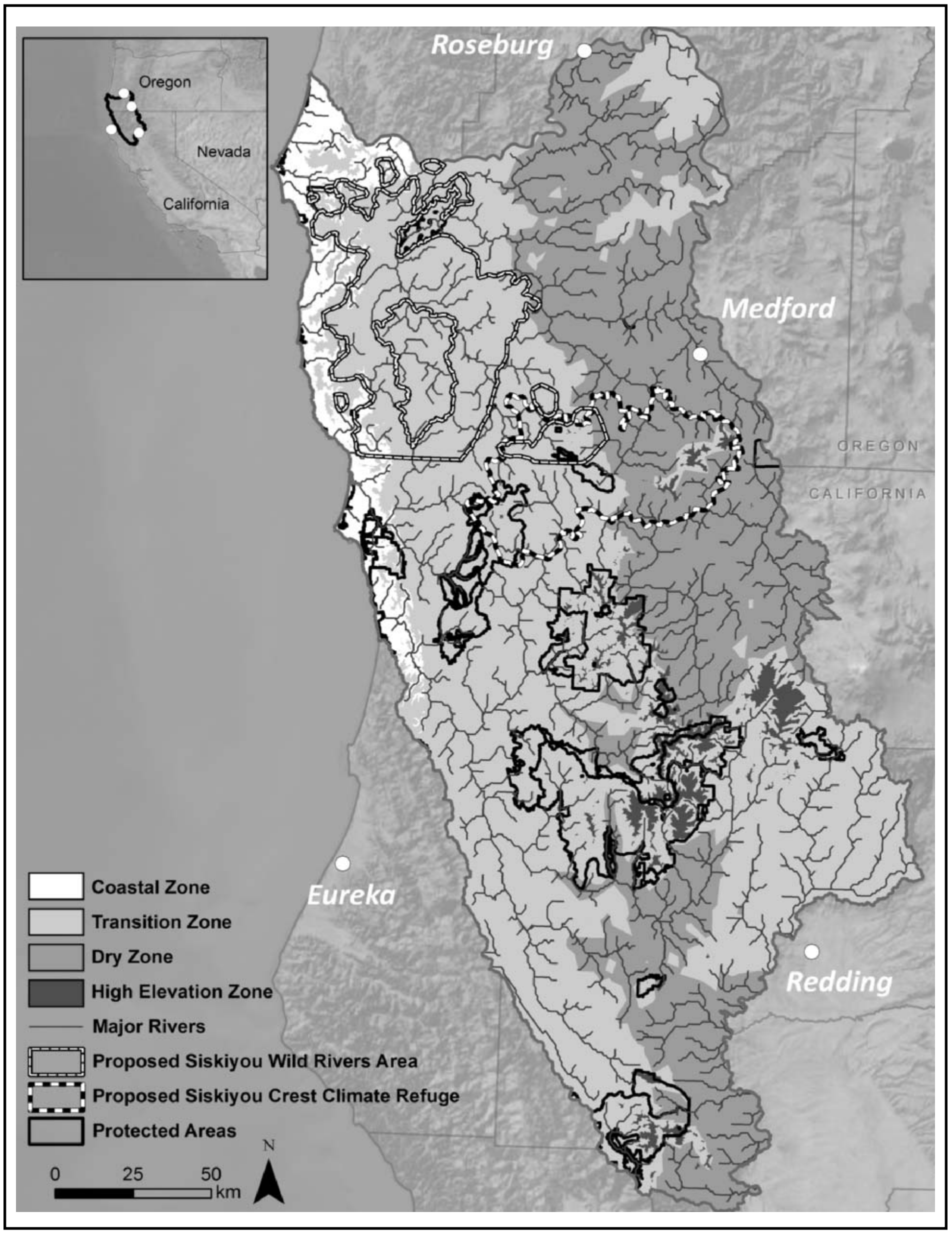

Figure 1. Climate change vulnerability zones (coastal, transition, dry, high elevation) of the Klamath-Siskiyou Ecoregion, southwest Oregon and northern California, used in the analysis to inform priority site selection for conservation action.

Protection of Climate Change Microrefugia

In order to maintain pockets of habitat for climate-vulnerable species, conservation attention should be aimed at securing microrefugia that may uniquely provide opportunities for many species to persist and are particularly threatened due to ongoing habitat degradation and rapid warming. The importance of microrefugia for the long-term persistence of species that are sensitive to climate change is increasingly being recognized (Noss 2001; Loarie et al. 2008, 2009; Rull 2009, 2010; Ashcroft 2010; Dobrowski et al. 2010). In temperate regions, terrain positions and habitat types that maintain persistent cool and moist conditions favorable for effective microrefugia are increasingly well defined (e.g., Dobrowski et al. 2010).

Because of the rapid speed of climate change (Loarie et al. 2008, 2009), including warmer temperatures (Koopman et al. 2009) and diminishment of fog (Johnstone and Dawson 2010) in the KSE, opportunities for long-term persistence for many species will be local, likely within a scale of a few kilometers, from the location of present populations. Many species will be unable to shift rapidly enough to areas with more favorable conditions. Moreover, most of KSE's species, distinctive (endemic) species, and those vulnerable to climate change are mesophilic, old-growth forest specialists, largely lesser known taxa (by the public) such as invertebrates, fungi, bryophytes, and other non-vascular plants (Olson 1992; Lattin 1993; Olson 2010; Vicente 2010). The majority of these taxa cannot cross even small distances of terrain with unfavorable conditions (e.g., light, hot, and dry; Frest and Johannes 1993; Niwa and Peck 2002). Thus, protection and restoration of microrefugia around extant populations is essential for the long-term perpetuation of the vast majority of the KSE biota. The ecoregion's endemic serpentine flora (Kruckeberg 1984; Harrison et al. 2006; Sawyer 2007) is also highly vulnerable to projected increases in temperature and drying (Damschen et al. 2010) and some taxa may only persist within persistently wet pockets and seeps surrounded by late-seral forests (collectively mature and old growth) that can act as climatic buffers.

Many extant microrefugia and the species and populations they contain may be lost or degraded within a few decades due to ongoing exploitation of forests and landscapes within the ecoregion, particularly at low and mid elevations, slow pace of change that is typical for forest management and protected areas practices, and rapid changes being documented in climate and natural communities (Damschen et al. 2010). Although the long-term efficacy of microrefugia is still uncertain (Carroll et al. 2010; Dobrowski et al. 2010), especially if they remain embedded within largely degraded landscapes, it remains a prudent, bet-hedging strategy in the face of uncertainty to protect a network of microrefugia representative of the ecoregion's distinct species assemblages.

Microrefugia Site Features

Site features for effective microrefugia in the KSE include north-facing slopes, valley bottoms and steep canyons, and sinks and basins because they are shadier and exist where cool air predictably pools in the lower sites (Dobrowski et al. 2010). Such sites are likely to have climate states and trends that are decoupled from regional averages, a requisite for microrefugia to persist through time. Forests with a north-east- and north-facing aspect also have a lower frequency of wildfires that can alter the capacity of habitats to retain cool and moist conditions (Taylor and Skinner 2003; Alexander et al. 2006).

Habitat types that will function well as microrefugia for climate change-sensitive species include late-seral forests, although the greater litter, understory vegetation, and canopy complexity and biomass of old-growth forests (> 150 yrs) makes them superior at retaining moisture (Chen et al. 1999). Late-seral forests that occur in areas with high-precipitation and fog, such as in coastal mountains (Loarie et al. 2008; Ackerly et al. 2010; Carroll et al. 2010) or other areas that experience significant orographic precipitation (e.g., > 1143 mm annual precipitation) will, on average, be better able to retain more moisture and cooler conditions than lower precipitation zones. This is due to more abundant water and greater canopy, understory vegetation, litter biomass, and complexity in these forests. Late-seral forests within watersheds are also superior to degraded, logged, roaded, and burned vegetation for providing cooler stream temperatures and robust aquatic ecosystems (Strittholt and DellaSala 2001; Staus et al. 2010).

Storm tracks, regional rainfall, and fog patterns may shift due to climate change (Dettinger et al. 1998; Salathé et al. 2008; Mote and Salathé 2009; Johnstone and Dawson 2010), but coastal mountains are expected to continue to receive Pacific storms first and much of the region's rainfall into the future (Daly et al. 1994). Certainly, vulnerable species and communities occur at higher elevations and in drier areas towards the eastern portion of the ecoregion, but the vast majority of distinctive biodiversity for the ecoregion (all taxa being considered) occur within the coastal fog and transition zones (Figure 1; Sawyer 2007). The latter zone includes more mesic forests along the Siskiyou Crest (Oregon/California), Eddy Mountains (northwest California), Scott Mountains (northwest California), and Yolla Bolly's (southern limits of the ecoregion) that are relatively far from the coast. In general, the larger and more round a forest block, the greater the core habitat area–internal habitat that does not experience the drying effects of forest edges (Chen et al. 1999).

Natural communities and vulnerable species within refugia also will have improved opportunities for persistence if microrefugia span broad elevational gradients, allowing populations to shift locally over time through contiguous mesic habitat (Noss 2001; Olson et al. 2009). North-South corridors of contiguous natural vegetation are important for many reasons, such as dispersing vertebrates, but a swiftly changing climate will likely limit the ability of most slowly dispersing organisms to move long distances northwards over generations.

REPRESENTATION OF BIODIVERSITY WITHIN MICROREFUGIA:

MESOREFUGIA AS A PROXY

Until patterns of local endemism and beta-diversity for speciose groups, such as invertebrates, are better known, proxies for mapping distinct assemblages can be used to assess how well a network of microrefugia provides refuge to KSE's diverse biota. Useful proxies for assessing representation of biodiversity within and among microrefugia are mesorefugia. We define mesorefugia as large areas that contain nested clusters of microrefugia with similar species assemblages that have functioned as a refugium over millennia (Rull [2009] defines mesorefugia as larger regions to which temperate biotas shifted during glacial maxima). Mesorefugia typically occur at the scale of mountain ranges or watershed complexes along coastlines, and their location along river canyons (e.g., Rogue, Umpqua, Klamath, Eel rivers) may facilitate future expansions and enable vagile species to move more freely across landscapes. Careful selection and protection of microrefugia of varying species assemblages (e.g., plant association groups) within and among mesorefugia would help to achieve representation goals while maximizing the number of extant species that will persist in emerging novel ecosystems.

Mesorefugia analyses complement existing representation analyses that focus on vegetation types and other communities derived from combinations of biophysical features (e.g., Vance-Borland 1999; Staus et al. 2001; Carroll et al. 2010). As such, candidate mesorefugia (Figure 2) for the KSE were initially identified from large-scale biophysical features and locations that predict effective refugia–coastal mountains with complex topography and areas of high precipitation (Loarie et al. 2009; Rull 2009, 2010; Dobrowski 2010). Areas with concentrations of restricted-range (i.e., local endemic) species or relict taxa dependent on cool and moist habitats were also evaluated to refine candidate mesorefugia locations and boundaries (i.e., where multiple species boundaries overlap). These include the distribution of Brewer spruce (Picea breweriana), Engelmann spruce (Picea engelmanni), foxtail pine (Pinus balfouriana) (Sawyer 2007), Plethodon and Dicamptodon salamander species and subgoups (Bury 1973; Mead et al. 2005; Steele and Storfer 2006), and numerous other plants (Sawyer 2007) and invertebrates (Olson 1992), such as harvestman (Briggs 1969, 1971ab), millipedes (Gardner and Shelley 1989; Olson 1992), trapdoor spiders (Cokendolopher et al. 2005), and land snails (Frest and Johannes 1993). We stress the mesorefugia proposed here are provisional and will benefit from more rigorous analyses of biophysical predictors and species distributions.

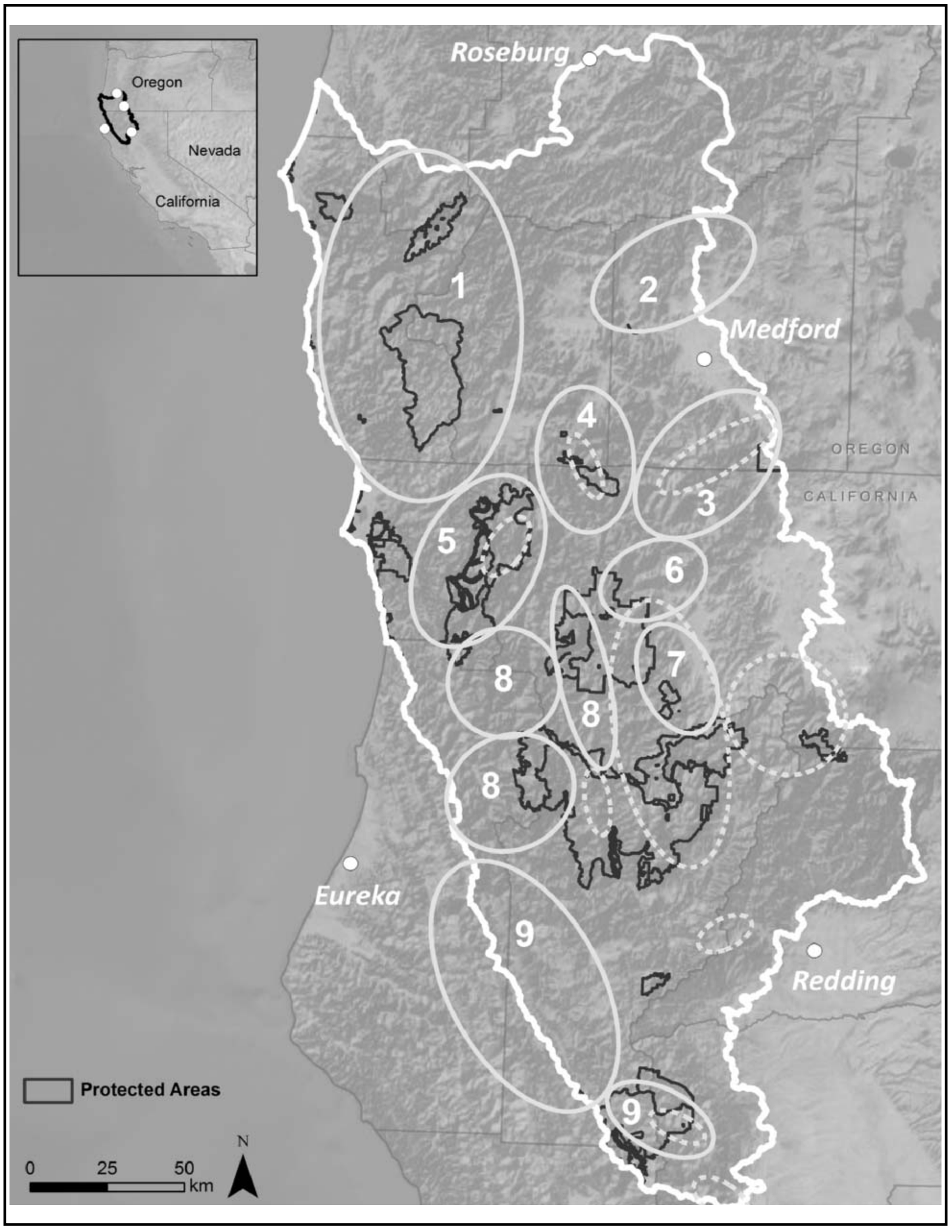

Figure 2. Provisional mesorefugia (ovals) within the Klamath-Siskiyou Ecoregion, southwest Oregon and northern California, approximated from large-scale predictors (e.g., coastal mountains in areas of relatively high precipitation) and an overlay of the distribution of mesophilic, restricted-range species including Plethodontid and Dicamptodon salamanders, Caseyid millipedes, Pentanychid harvestman, endemism zones for vascular plants, and relict conifers. Mesorefugia likely contain concentrations of restricted-range species due to their persistently wet conditions and long-term stability. Dashed ovals represent high-elevation refugia that may, or may not (depending on the severity of warming temperatures at higher elevations), function well under current and future human-caused climate change. Numbering refers to locations discussed in the text.

Based on these criteria and species distribution maps, important mesorefugia for the

KSE include: (1) Kalmiopsis; (2) North Siskiyou Mountains; (3) East Siskiyous; (4) north of the southern bend of the Klamath River; (5) West Siskiyous; (6) Lower Scott Bar River; (7) Russian Wilderness; (8) Lower Trinity River (multiple locations); and (9) Middle Eel/Yolla Bolly (multiple locations, numbers correspond to Figure 2). The Russian Wilderness was selected due to the extraordinary sympatric assemblage of conifer species whose presence could be due to mesorefugia conditions. The mesorefugia located in the coastal zone experiences the highest rainfall in the KSE and is likely to have the highest concentrations of restricted-range and climate change-vulnerable species (contrast Figures 1 and 2). We acknowledge that much KSE biodiversity occurs outside of these mesorefugia, but suggest that ensuring adequate protection of habitats buffered from warming in these zones is an important first step.

The current protected areas system does a poor job of representing the provisional mesorefugia. Only the Kalmiopsis, Siskiyou, Russian, and Middle Eel/Yolla Bolly Wilderness areas and redwood parks encompass portions of likely mesorefugia. In general, Wilderness areas largely protect higher elevations, not the middle and lower slopes where most of the microrefugia are likely to occur. Proposed expanded reserve networks would represent all of the provisional mesorefugia, if implemented, including those at lower and middle elevations (e.g., contrast Figures 2 vs. 3b). We also propose three priority mesorefugia corridors to link: (1) Siskiyou Crest–Kalmiopsis, (2) Kalmiopsis–Siskiyou Mountains, and (3) Trinity/Scott Bar River–Siskiyou Crest (numbers correspond to Figure 3a).

PRIORITIZING MICROREFUGIA

We used our microrefugia site features to identify a set of provisional areas outside extant protected areas that warrant immediate conservation attention. For the portion of the ecoregion outside of formal protected areas, 22 highest-priority microrefugia and 40 high-priority areas containing late-seral forest and other key habitat types (e.g., serpentine barrens) were identified as candidate microrefugia (Figure 3a). Many important old-growth forest microrefugia occur in close proximity to existing protected areas, such as the Kalmiopsis Wilderness. Most of the candidate microrefugia lie towards the western, wetter part of the ecoregion and are generally located at mid and low elevations. Remnants of late-seral forest in the fog zone are particularly important to protect and restore, as they likely contain a sizable proportion of vulnerable species. Some old-growth forest blocks at higher elevation in the eastern part of the ecoregion were also recommended, as they span a broad elevational range and are among the largest remaining old-growth fragments in the ecoregion. Data on late-seral forests were unavailable for some portions of the ecoregion, such as the southwestern coastal hills and the foothills of the Central Valley that may contain additional microrefugia (Figure 3a).

Finer-resolution analyses and field surveys within priority areas (Figure 3a) are required to identify the particular blocks of old-growth forest and bottomland sites that have the highest potential to act as microrefugia. The nature of the landscape and the mosaic of late-seral forests can have a major influence on the efficacy of microrefugia. For example, even a relatively small old-growth forest fragment situated in a steep, north-facing canyon that experiences shade most of the time will likely function well as a long-term refuge for mesophilic species.

In sum, several microrefugia deserve immediate conservation attention, including: southern bend of the Klamath River, California; lower slopes of the Klamath River from around China Point eastwards to Hamburg, California; northern slope of the Scott Bar Mountains and along the lower Scott River in California; old-growth fragments close to the coast in Oregon and in the foothills behind the redwood belt in northwestern California; north-facing slopes of the Middle Smith River, California; larger old-growth pockets to the west of the Kalomiopsis Wilderness, southwest Oregon; southeastern watersheds of the Siskiyou Mountains (e.g., Dillon and Rock Creek area, California); northern Siskiyou Mountains to western Siskiyou Crest region, California; and a network of serpentine-substrate areas representing assemblages of endemic plant species and their surrounding forest buffers mainly in southwest Oregon.

This provisional network of priority climate change microrefugia outside the existing reserve system should be targeted for immediate protection and restoration. A variety of conservation approaches is required because candidate sites are in diverse locations, habitat types, tenures, and land use pressures. Some are located within active federal and state forestry zones, and some are on private lands. The priority areas identified here would not, by themselves, constitute a comprehensive conservation strategy as they are intended primarily to buffer a good portion of the KSE biota from extinction and extirpation due to changing climate, and they would not necessarily address a wide range of other conservation goals and objectives.

MICROREFUGIA AND PROTECTED AREAS

Representation and Existing Protected Areas

We also intersected remaining late-seral forests with north-facing slopes (N, NE, NW, Figure 3ab) and areas of relatively high precipitation with microrefugia characteristics (see Appendix for methods). Using ecoregion-scale data on forest cover and topography, it was challenging to identify the small river valleys and bottomlands that consistently pool cooler air and may function as additional microrefugia. More local-scale data and on-the-ground surveys are required to identify potential bottomland refugia. For similar reasons, we also did not attempt to identify potential microrefugia for the vulnerable serpentine flora.

Based on this analysis, the current protected area network under-represents most of the important microrefugia for the KSE (Figure 3a). For instance, only 16% of remaining old-growth forest occurs within strictly protected areas (Table 1). Some important

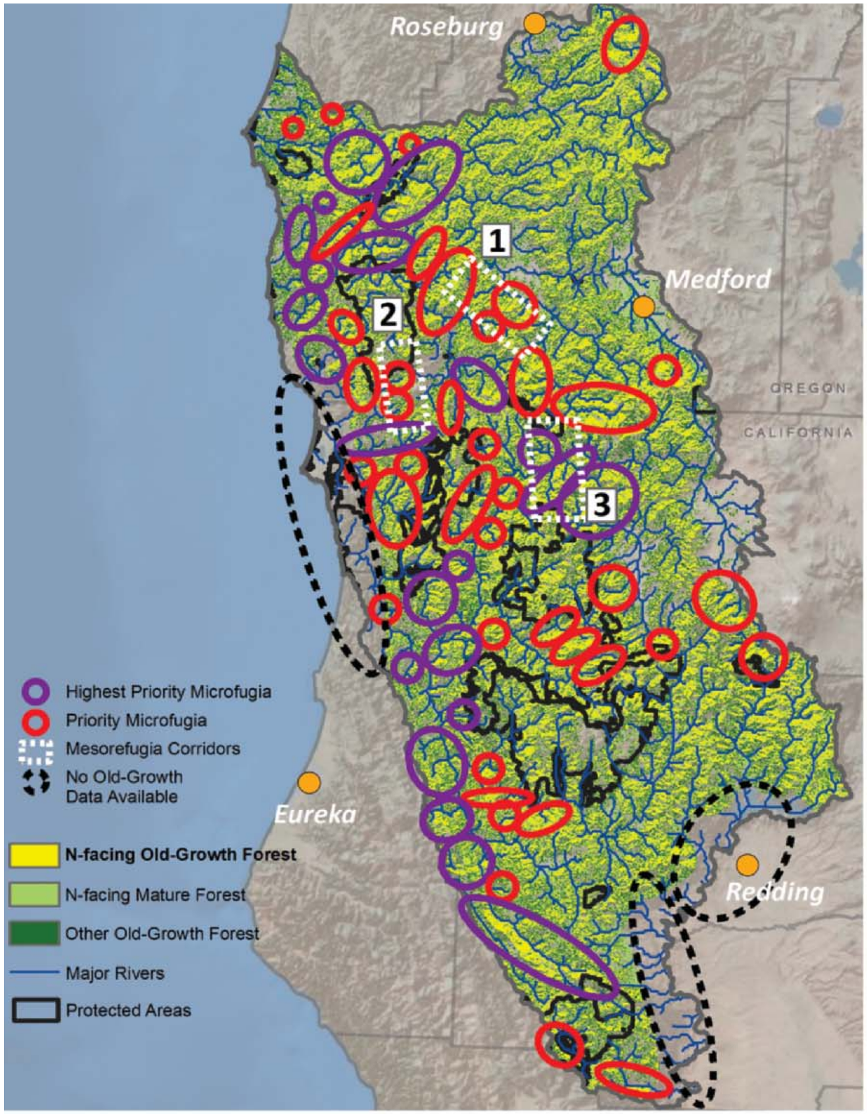

Fig. 3a

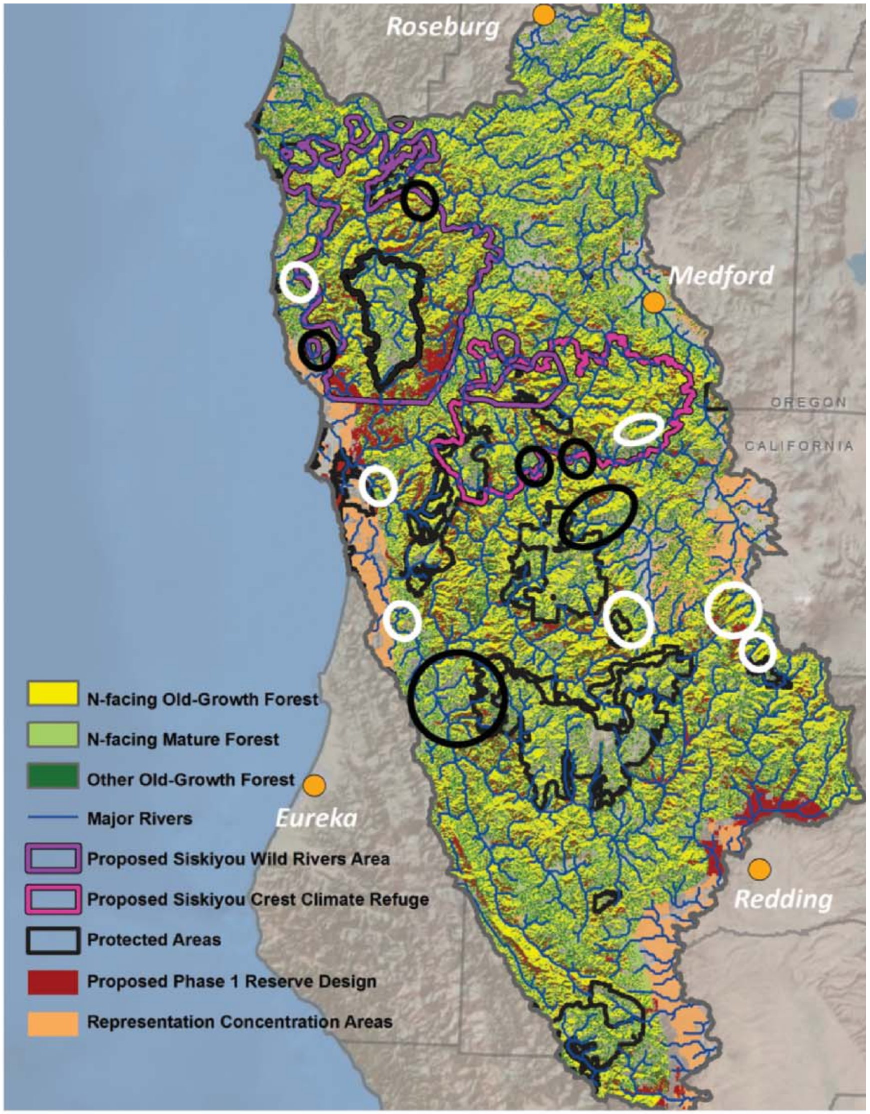

Fig. 3b

Figure 3. (A) Provisional microrefugia (highest priority and priority) and proposed mesorefugia corridors outside (numbers refer to locations described in the text) of formal protected areas in the Klamath-Siskiyou Ecoregion, southwest Oregon and northern California. High-quality microrefugia inside formal protected areas are not identified. The mature forest shown is north-facing only. Circles were drawn based on visual inspection of the mapped old forest polygons. (B) Some priority microrefugia in the Klamath-Siskiyou Ecoregion, southwest Oregon and northern California, which are not encompassed in the proposed expanded reserve network (Noss et al. 1999). Black ovals are highest priority and white ovals are high priority gaps in protected areas coverages. Circles were drawn by visual inspection of old-growth forest concentrations.

Table 1. Area and percentage of north-facing late-seral and old-growth forest (collectively LSOG) in the Klamath-Siskiyou Ecoregion (KSE), southwest Oregon and northern California, by climate change vulnerability zones, extant protected areas, and proposed conservation areas. Data for old-growth forests for some portions of the ecoregion (southwestern coastal, southeastern border) were unavailable; thus, coastal old-growth forest area, inside and outside of protected areas, is underestimated and the drier zone old-growth forest area to a smaller extent.

KSE Area	42,940 sq km (16,579 sq mi)
LSOG within KSE:	
total LSOG	8,380 sq km = ~20% of ecoregion*
total north-aspect LSOG	3,900 sq km = ~9% of ecoregion, ~47% of LSOG*
total high precipitation north-aspect LSOG	1,800 sq km = ~4% of ecoregion, ~22% of LSOG
LSOG within KSE Zones:	
coastal	120 sq km = ~0.3% of ecoregion, ~1.4% of LSOG*
transition	6,120 sq km = ~14% of ecoregion, ~73% of LSOG
dry	2,240 sq km = ~5% of ecoregion, ~27% of LSOG*
high elevation	180 sq km = ~0.4% of ecoregion, ~2% of LSOG
LSOG within Existing Protected Areas:	
0 – 610 m	120 sq km = ~0.3% of ecoregion, ~1.4% of LSOG*
610 – 1890 m	1,140 sq km = ~3% of ecoregion, ~14% of LSOG,
>1890 m	100 sq km = ~0.2% of ecoregion, ~1% of LSOG
combined	1,360 sq km = ~16% of LSOG
LSOG within Proposed Reserve Additions:	
proposed Siskiyou Wild Rivers	500 sq km = ~1% of ecoregion, ~6% of LSOG
proposed Siskiyou Crest	770 sq km = ~2% of ecoregion t, ~9% of LSOG
protected areas	1360 sq km = ~3% of ecoregion, ~16% of LSOG
proposed Phase I*	4130 sq km = ~10% of ecoregion ~49% of LSOG
representation concentration areas*	380 sq km = ~1% of ecoregion, ~5% of LSOG
combined	~14% of ecoregion, ~70% of LSOG
North-Aspect LSOG within:	
proposed Siskiyou Wild Rivers	230 sq km = ~0.5% of ecoregion, ~3% of LSOG
proposed Siskiyou Crest	360 sq km = ~1% of ecoregion, ~4% of LSOG
protected areas	630 sq km = ~1% of ecoregion, ~7% of LSOG
proposed Phase I*	1940 sq km = ~5% of ecoregion, ~23% of LSOG
representation concentration areas*	170 sq km = ~0.4% of ecoregion, ~2% of LSOG
combined	2,780 sq km = ~6% of ecoregion, ~33% of LSOG

* from Noss et al. (1999)

blocks of lower- and middle-elevation old-growth microrefugia occur in existing reserves – such as in the coastal redwood parks, Kalmiopsis, Siskiyou, Wild Rogue, and Russian Wilderness areas, and Oregon Caves National Monument – but many are located outside these areas. While the extant reserve system does help protect an array of ecoregion- and local-endemic plant and animal species and most of the alpine and sub-alpine communities in the KSE (Sawyer 2007), much of the ecoregion's biodiversity and many, if not most, of the vulnerable species occur outside of the existing protected area network.

Representation and Proposed Protected Areas

Prior reserve designs proposed for the KSE include the Phase 1 reserves and Representation Zones proposed by Noss et al. (1999), the Siskiyou Crest National Monument (KS Wild 2010) and Siskiyou Wild Rivers (Sisikyou Project 2010) proposed by conservation groups, and Scenario 3 Plan "interacting current and near-future habitat" of Carroll et al. (2010). These reserves, if implemented, would protect a large proportion of the critical microrefugia within high-precipitation zones and mesorefugia (i.e., 47% the remaining old-growth forest and 22% of north-facing old-growth; Table 1). If all the proposed reserve expansions were implemented, then 70% of remaining old-growth forest and 33% of north-facing old-growth forest would be protected. We identified only five gaps of highest priority and six high priority microrefugia that were not fully contained within the proposed protected area network (Figure 3b). All of the highest priority gaps are critically important sites and should receive immediate conservation attention. Collectively, these gaps contain important coastal and intact old growth areas, local pockets of species endemism, and transitional areas; and they may provide additional mesorefugia corridors.

NEXT STEPS

Additional and more finely resolved priority setting of microrefugia is warranted in the near future. GIS-based spatial analyses supported by field evaluation of candidate microrefugia can assess their species assemblages, landscape context, terrain position, habitat condition, defensibility, and complementarity with other candidate sites. These evaluations can be augmented by additional analyses of past and future refugia based on species distributions and biophysical predictors of climatic and vegetation stability and identification of areas predicted to experience wildfires within historic ranges of frequency and intensity. In addition, targeted surveys of old-growth forest invertebrates and non-vascular plants (e.g., fungi, lichens, bryophytes) are needed to improve our understanding of the distribution of distinct assemblages in order to refine the location of mesorefugia and better design representative networks of microrefugia. Potential refugia for the endemic serpentine flora need to be identified and prioritized. Such areas are likely to be mesic serpentine sites that remain relatively moist even under a changing climate, due to terrain position and other biophysical features (e.g., seeps and bogs). The sites and their surrounding buffer habitats need to be identified and prioritized using a similar approach as for the old-growth forest microrefugia. Identifying and protecting microrefugia complements ongoing modeling of range shifts for vulnerable species and natural communities (e.g., Pearson and Dawson 2003; Loarie et al. 2008; Carroll et al. 2010; Damschen et al. 2010; Harrison et al. 2010), studies of climate sensitivity of species, analyses of how a changing climate will affect wide-ranging species, and assessing the cost and cost-effectiveness of alternative conservation actions.

CONCLUSION

Large natural landscapes and wilderness, the foundation of reserve designs, remains the mainstay of conservation efforts in this and many other localities and is especially important in a changing climate. Without large natural landscapes in relatively good condition, many of the remaining pockets of old-growth forest may not persist or function well as microrefugia. However, for ensuring a robust reserve design that is responsive to climate change, it is prudent to secure priority old-growth forest microrefugia as swiftly as possible while the more time-consuming and uncertain task of conserving larger landscapes continues. Waiting decades for formal "gazettement" of large protected areas without securing microrefugia now may allow continued degradation of these critical refuges. Our recommended approach is somewhat novel for most conservation advocacy, where securing larger priority landscapes proposed in comprehensive strategies is often acted upon first, but the rapidly warming landscape may require a diversification of tactics. As Voltaire cautioned, we should not let the perfect be the enemy of the good.

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Appendix.

Appendix. Methods

The extent, "Proposed Phase 1 Reserve Design" and "Representation Concentration Areas" were downloaded from Conservation Biology Institute's (CBI) data collection on databasin.org. The reserve design and concentration area polygons were featured in "Klamath-Siskiyou Final Report" (1999) by CBI as proposed natural reserves. "Major Rivers" is a subset of the USGS HydroSHEDS dataset (30 s resolution). "Protected Areas," as detailed in the map text, are all federal and state parks, Wilderness Areas, and National Monuments extracted from the PAD US-1.1 protected areas database developed by CBI. "North-facing Slopes" is a reclassification of an aspect raster created from a 30 m NED, which restricts the values to those pointing north (N, NE, NW). "North-facing Old-Growth Forest" was created from a mosaic of CBI's "Late Seral Forest Classification Using ETM+ Remote Sensing Imagery" dataset (Jiang et al. 2004) also on databasin.org and the reclassified aspect raster. The mosaic was reclassified to restrict the values to old-growth forest. These cells were then extracted from the reclassified aspect raster. The same process was done for a reclassification restricting values to both old-growth forest and mature forest, and this becomes "North-facing Mature Forest,"which is all that is displayed when overlayed by "North-facing Old-Growth Forest." "Other Old-Growth Forest" is a reclassified mosaic of only old-growth values overlayed by the previous two rasters. "Annual Precipitation" and "Avg Temp 1971-2000" were taken from the PRISM climate model dataset (precipitation is similarly an average of 1971-2000). "High Rainfall North-facing Old-Growth Forest" was created by extracting only those cells from "North-facing Old-Growth Forest" that intersected with PRISM cells with values over 45 inches (1143 mm) of rainfall.