VII. Implications for Species, Populations, & Communities

Rapid climate change in the twenty-first century threatens biodiversity, ecosystem services, and human welfare. While climate change per se is a pervasive feature of earth history, the pace of change currently forecast for the next 100 years is virtually unparalleled in its speed, magnitude, and global extent. If the rate of change exceeds the pace of biological response, especially the capacity of populations to migrate or undergo adaptive evolutionary change, impacts on species distributions, community structure, and ecosystem function may be profound. Species may be negatively affected by physiological stress caused by changes in temperature, water availability, and other environmental shifts, and/or indirectly by habitat degradation and negative interactions with species that benefit from climate change (diseases, parasites, predators, and competitors). Because there is a broad range of possibilities regarding the degree to forthcoming climate change, especially regarding the response of complex biological systems, the severity of predicted responses is unknown, even though the direction of such changes is more certain.

Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, the following general implications of climate change for species, populations, and communities in the NPLCC region have been identified:

1. Shifts in species range and distribution
2. Altered phenology
3. Altered growth and development
4. Shifts in biodiversity, species richness, abundance, competition, survival, and community composition
5. Altered interaction with invasive and non-native species

Chapter VIII provides information specific to mammals, birds, invertebrates, lichens, and mosses. The following structure will be used to present information on the implications of climate change for the NPLCC region’s terrestrial species, populations, and communities:

- **Observed Trends** – observed changes for southcentral and southeast Alaska, western British Columbia, the Pacific Northwest, western Washington, the Klamath Mountains, western Oregon, and northwest California. For context, summary information on observed changes globally or for western North America is also provided.
- **Future Projections** – projected direction and/or magnitude of change for southcentral and southeast Alaska, western British Columbia, the Pacific Northwest, western Washington, western
Oregon, and northwest California. For context, summary information on future projections globally or for western North America is also provided.

- **Information Gaps** – information and research needs identified by literature searches, as well as our summary of the sections missing information in this chapter.
1. Shifts in species range and distribution

Many species are shifting their geographic ranges in response to rapid changes in temperature and precipitation regimes. Often populations track temperature gradients by moving poleward, up in elevation, or to increased depths in the oceans. Changes in distribution are often asymmetrical with species invading faster from lower elevations or latitudes than resident species are receding upslope or poleward. The result is a (presumably transient) increase in species richness of the community in question as a consequence of the variability in rates at which species shift their ranges. However, not all species movements have been poleward or up in elevation.

Range shifts may raise the probability of persistence of species and populations; however the ability to disperse or migrate to new areas does not guarantee survival as there are additional factors such as species interactions and land use change that may influence populations. Species-specific differences in physiological, behavioral, and morphological plasticity may allow individuals and populations to respond in situ and delay or eliminate the need for range shifts; however, in many cases, these responses may be difficult to predict. Recent estimates of the velocity of climate change, described by Loarie et al. (2009) as the speed and residence time of temperature change over space and time, are faster than was previously thought; this has raised concern as to whether species migration rates will be fast enough to track future environmental conditions.

For migratory species, in addition to suitable habitat at either end of their journey, many migratory species require an ecologically coherent habitat network that they can use en route. Changes in any area used by a migratory species are likely to affect all populations of a species, even those that do not use them directly, because of density-dependent habitat selection and mortality.

Observed Trends

Global

Ranges and abundances of terrestrial species shifted dramatically during the last deglaciation. Species varied widely in the timing, magnitude, and direction of these responses, and communities did not

1901 Verbatim from Staudinger et al. (2012, p. 2-17)
1902 Verbatim from Staudinger et al. (2012, p. 2-17)
1904 Verbatim from Walther et al. (2002, p. 391)
1905 Verbatim from Staudinger et al. (2012, p. 2-17)
1911 Verbatim from Williams & Jackson (2007, p. 476)
migrate as intact units. Similar responses occurred during earlier periods of climate change and individualistic behavior is documented for species responding to current climate changes. Initial analyses using pollen records showed post-glacial migration rates of up to 656 feet per year (200 meters per year), but chloroplast DNA evidence of low-density refugial populations of angiosperm (i.e., flowering plant) trees much farther north than previously thought has caused these estimates to be revised. With seeds spreading both from the northern edge of the continuous species range and from previously unidentified, disjunct refugial populations, actual migration rate estimates have been revised to less than 328 feet per year (100 meters per year). Rare long-distance seed dispersal events have likely played a crucial role in increasing effective migration rates relative to the effects of average seed dispersal distances, but such events are hard to quantify or model.

It is now clear that poleward and upward shifts of species ranges have occurred across a wide range of taxonomic groups and geographical locations during the 20th century (Table 29). Whereas the magnitude of elevational shifts of alpine plant species lags behind the isothermal shift of 26-33 feet per decade (8-10 meters per decade), butterflies appear to track decadal warming quickly, matching the upwards and northwards shifts of temperature isotherms.

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Figure 57 shows the biogeoclimatic zones of British Columbia.

Pacific Northwest

Please see Chapters VI (sections 2 through 4) and VIII for additional information on species range shifts.

Northwest California

Information needed.


Verbatim from Williams & Jackson (2007, p. 476). Williams & Jackson cite Wing et al. (2005) for information on similar responses during earlier periods of climate change and Walther et al. (2002) for information on the individualistic behavior of species responding to current climate changes.


Verbatim from Aitken et al. (2008, p. 96)


Verbatim from Walther et al. (2002, p. 391). Walther et al. refer the reader to Table 2 in the cited article for this information. Walther et al. also cite Hughes (2000), McCarty (2001), Walther et al. (2001), and Easterling et al. (2000) for this information.

Verbatim from Walther et al. (2002, p. 391). Walther et al. cite Grabherr et al. (1994) for information on alpine plant species, Parmesan et al. (1999) and Parmesan (1996) for information on butterflies, and Karl et al. (1996) for specific information on matching upwards and northward shifts in temperature. Walther et al. also refer the reader to Table 2 in the cited article to compare this data.
Future Projections

Global

Climate change will lead to loss of range for many species, and thus to loss of genetic diversity crucial for their long-term persistence.\(^{1919}\) Forecasts of terrestrial biomes estimate that the velocity of global temperature shifts will be lowest in topographically complex montane systems (0.05 miles per year; 0.08 km per year) whereas systems with much less topography such as flooded grasslands and deserts, will show higher rates of change (0.783 miles per year; 1.26 km per year).\(^{1920}\)

Alsos et al. (2011) analyzed range-wide genetic diversity in 9581 samples from 1200 populations of 27 northern plant species (i.e., those typically occurring in the bioclimatic zones at the tree line and beyond – the alpine and arctic zones), to assess genetic consequences of range reduction and potential association with species traits.\(^{1921}\) The expected range reduction in these 27 northern species was larger than reported for temperate plants, and all were predicted to lose genetic diversity according to at least one scenario.\(^{1922}\) Loss of genetic diversity varied considerably among species, and this variation could be explained by dispersal adaptation (up to 57%) and by genetic differentiation among populations (up to 61%).\(^{1923}\)

\(^{1919}\) Verbatim from Alsos et al. (2011, p. 1). *Genetic consequences of climate change for northern plants.*


\(^{1921}\) Nearly verbatim from Alsos et al. (2011, p. 1)

\(^{1922}\) Verbatim from Alsos et al. (2011, p. 1)

\(^{1923}\) Nearly verbatim from Alsos et al. (2011, p. 1)
Specific results include:

- **Range reduction**: Range reduction was on average higher under emission scenario A2 (36-43% reduction) than under B2 (26-32% reduction), as expected as the A2 scenario anticipates a more severe climate change than the B2 scenario (Figure 58). The range gain was generally considerably lower than the range reduction, and on average the range change was -24% for A2 CCM3, -30% for A2 HadCM3, -16% for B2 CCM3 and -22% for B2 HadCM3 (2071-2100 vs. 1961-1990).

- **Effect of dispersal adaptation**: Alsos et al.’s (2011) estimates indicated that species without adaptations to long-distance dispersal (and/or herbaceous species) will lose genetic diversity at about twice the rate of species adapted to long-distance dispersal by animals or wind (and/or woody species). However, dispersal adaptation was strongly correlated with growth form in the set of species; thus, the effect of these two traits could not be distinguished. Further, herbs lacking adaptations for long-distance dispersal were estimated to lose genetic diversity at a higher rate than dwarf shrubs adapted to long-distance dispersal.

- **Loss of genetic diversity**: In the worst case scenario, assuming that the model estimating the maximum range reduction will be realized, and that the corresponding loss of genetic diversity will be at the maximum value, all species were expected to lose some genetic diversity, one-third of them greater than 50%. Species expected to lose more of their range were also prone to more severe genetic loss: range reduction alone explained 66–74% of the variation in estimated loss of genetic diversity among species. For more information on shifts in biodiversity, please see Chapter VII.4.

Similarly, amongst insects and seabirds, those species with greater dispersal are better able to respond adaptively to warming temperatures. Birds, insects and many marine species ride winds or currents to aid their migratory journeys, making some of the longest distance migrations possible. Alteration of these currents or winds might make journeys easier, but is more likely to increase energy demands and/or deliver individuals to the wrong locations or at the wrong time.
Southcentral and Southeast Alaska

Populations of species strongly associated with alpine/tundra ecosystems will be reduced in number, fragmented, or eliminated as temperatures increase.\(^\text{1934}\)

Western British Columbia

*Information needed.*

Pacific Northwest

Changes in USDA plant hardiness zones have already been recorded in much of Oregon and will result in concomitant shifts in terrestrial plant communities and open habitats to invasion.\(^\text{1935}\) Plants and animals eventually occupy landscapes vacated by glacial ice, and new alpine lakes often remain after the ice is gone.\(^\text{1936}\) For additional information on future projections for species range and distribution, please see Chapters VI (sections 2 through 4) and Chapter VIII.

Northwest California

*Information needed.*

Information Gaps

A key area of uncertainty is in understanding the mechanisms through which climate change will affect populations, which is an area of active research, particularly in understanding how climate impacts at one point in the life-cycle affect demographic parameters at later points.\(^\text{1937}\) Such cross-seasonal impacts will often be modulated by density-dependent effects, and documenting these will be important in order to assess the fate of migrants under changing climates.\(^\text{1938}\) Traditional approaches, such as climate envelopes and global vegetation models, can be applied to estimate shifts in breeding grounds and non-breeding areas, but as migratory species move between different areas, the uncertainties in predictions are multiplied, particularly when biotic interactions are taken into account.\(^\text{1939}\)

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\(^{1934}\) Nearly verbatim from Kelly et al. (2007, p. 52)

\(^{1935}\) Nearly verbatim from Hixon et al. (2010, p. 325). Hixon et al. refer the reader to the Map on p. 326 of the cited report for information on the change in plant hardiness zones.

\(^{1936}\) Verbatim from Burkett et al. (2005, p. 368)

\(^{1937}\) Verbatim from Robinson et al. (2008, p. 96). Robinson et al. cite Jonzén et al. (2007) as an example of the active research in understanding the mechanisms through which climate change will affect populations.

\(^{1938}\) Verbatim from Robinson et al. (2008, p. 96). Robinson et al. cite Ratikainen et al. (2008) for this information.

\(^{1939}\) Verbatim from Robinson et al. (2008, p. 95-96). Robinson et al. cite Araújo & Luoto (2007) and Martine et al. (2007) for this information.
2. Altered phenology

Climate change is altering the phenology of many species and the timing of their interactions with other species, but the impacts of these phenological shifts on species interactions remain unclear. In general, the effects of phenological shifts on interacting species seem to be largely determined by (1) how the interaction type and/or strength changes over their ontogenies (i.e., the development of an organism) and (2) the relative phenologies of the interacting species. Given that species interactions can strongly determine the structure and dynamics of many natural communities, some of the most profound effects of climate change are likely to be driven by changes in the timing of biotic interactions between species. The effects of these altered interactions can be as strong or stronger than the direct abiotic effects of climate change. For example, decoupled trophic interactions due to climate change may compromise population sustainability and, in some cases, affect species range changes. Changes in the timing of migration could also have profound impacts, particularly with regard to mismatch between trophic levels. Further, the existence of trophic mismatch in prey-predator and host-parasite systems or the collapse of one partner in the interaction will thus have nontrivial demographic effects and cause complex population and range dynamics, generally depending on the relative environmental niches of species from different trophic levels.

The exchanges of energy and CO$_2$ between the biosphere and the atmosphere, via the biophysical and biogeochemical pathways, respectively, are strongly influenced by phenology, that is the timing of the onset and eventual loss (offset), of leaves. Leaf phenology regularly alters land-surface boundary conditions by changing surface albedo, roughness, and surface water and energy fluxes. Leaf onset and offset mark the bounds of the growing season and therefore annual carbon uptake depends strongly on leaf phenology.

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1941 Nearly verbatim from Yang & Rudolf (2010, p. 4)
1942 Verbatim from Yang & Rudolf (2010, p. 1)
1944 Verbatim from Lavergne et al. (2010, p. 332). *Biodiversity and climate change: integrating evolutionary and ecological responses of species and communities.* Lavergne et al. cite Schweiger et al. (2008) for this information.
1945 Verbatim from Robinson et al. (2008, p. 93)
1946 Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. cite Schweiger et al. (2008) for this information.
1947 Verbatim from Arora & Boer (2005, p. 39)
Observed Trends

Global

Numerous ecological studies have now pointed to an important general pattern of species responses to climate change around the world: on average, seasonal life-history events such as leaf unfolding, flowering, insect emergence, or the arrival of migratory birds are occurring earlier than they have in the historical past (Table 29).\textsuperscript{1956} Despite this prevailing trend, however, it has also become evident that species within the same community often show variable phenological responses to climate change.\textsuperscript{1951} For example, an unusually warm spring in northern Japan lead to substantial phenological advances in the flowering of several spring-ephemeral plants relative to their pollinating bees, resulting in dramatically decreased seed production of bee-pollinated species.\textsuperscript{1952}

In general, while many species have shown advances in the seasonal timing of their life-history events to varying degrees, some species have shown no discernible phenological changes, and others have demonstrated delayed seasonal phonologies (Table 29).\textsuperscript{1953} Studies reveal different proportions of bird species which advance, delay or do not change autumn migration, and trends of leaf colouring of trees at neighbouring stations often show contradictory signals.\textsuperscript{1954} In Europe, for example, leaf color changes show a progressive delay of 0.3 – 1.6 days per decade, whereas the length of the growing season has increased in some areas by up to 3.6 days per decade over the past 50 years.\textsuperscript{1955} For additional information on changes in the length of the growing season, please see Chapter IV.2

These differential responses across species indicate that climate change is altering the relative timing of species interactions and influencing which ontogenetic stages interact with each other.\textsuperscript{1956} For example, a recent long-term study in the Netherlands showed different phenological responses to climate change for the relative timing of oak leaf unfolding, the peak biomass of caterpillars, the breeding of insectivorous birds and the breeding of an avian predator, resulting in the disruption of stage-structured interactions across four trophic levels.\textsuperscript{1957}

Western North America

Cayan et al. (2001) analyzed flowering data for honeysuckles and common purple lilacs in the western U.S., including data from Oregon, and reported earlier first bloom dates in the 1980s and 1990s as

compared with data from the 1960s and 1970s.\textsuperscript{1958} They attributed these earlier bloom dates to increased spring temperatures across the region at the end of the 20th century.\textsuperscript{1959}

Another prominent example of phenological shifts revealed through long-term observations of lilac flowering indicates that the onset of spring has advanced one day earlier per decade across the Northern Hemisphere in response to increased winter and spring temperatures and by 1.5 days per decade earlier in the western U.S.\textsuperscript{1960}

<table>
<thead>
<tr>
<th>Location</th>
<th>Observed Changes</th>
<th>Time Period</th>
<th># of species observed</th>
<th>Sources (as provided by Khanduri et al.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hungary</td>
<td>0.2-0.6 days/decade earlier flowering</td>
<td>1851-1944 (144 years)</td>
<td>1</td>
<td>Walkovsky (1998)</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>Earlier flowering by ~0.5-1.2 days/decade</td>
<td>1936-1998 (63 years)</td>
<td>25</td>
<td>Bradley et al. (1999)</td>
</tr>
<tr>
<td>Europe</td>
<td>1.7 days/decade leaf unfolding and 1.4 days/decade delayed leaf coloring and leaf fall</td>
<td>1959-1993 (35 years)</td>
<td>1</td>
<td>Menzel &amp; Fabian (1999)</td>
</tr>
<tr>
<td>USA</td>
<td>1.7 days/decade earlier flowering and leaf unfolding</td>
<td>1959-1993 (35 years)</td>
<td>1</td>
<td>Schwartz &amp; Reiter (2000)</td>
</tr>
<tr>
<td>Canada</td>
<td>2.7 days/decade earlier flowering</td>
<td>1900-1997 (98 years)</td>
<td>1</td>
<td>Beaubien &amp; Freeland (2000)</td>
</tr>
<tr>
<td>Europe</td>
<td>1.7 days/decade earlier flowering and leaf unfolding and 1.2 days/decade delayed leaf coloring and leaf fall</td>
<td>1959-1996 (38 years)</td>
<td>1</td>
<td>Menzel (2000)</td>
</tr>
<tr>
<td>Washington DC</td>
<td>Flowering occurring 0.8-1.5 days/decade earlier</td>
<td>1970-1999 (30 years)</td>
<td>100</td>
<td>Abu-Asab et al. (2001)</td>
</tr>
<tr>
<td>Europe</td>
<td>2.7 days/decade earlier leaf unfolding and 0.8 days/decade delayed leaf fall</td>
<td>1969-1998 (30 years)</td>
<td>4</td>
<td>Chmielewski &amp; Ratzer (2001)</td>
</tr>
<tr>
<td>England</td>
<td>Advance flowering by 4.5 days during the past decade compared to the previous four decades</td>
<td>1954-2000 (47 years)</td>
<td>385</td>
<td>Fitter &amp; Fitter (2002)</td>
</tr>
<tr>
<td>Mediterranean region</td>
<td>Earlier flowering and leaf unfolding occurring by 1.2 &amp; 3.3 days/decade and leaf fall by 2.7 days/decade later</td>
<td>1952-2000 (49 years)</td>
<td>64</td>
<td>Penuelas et al. (2002)</td>
</tr>
<tr>
<td>Japan</td>
<td>0.8 days/decade earlier leaf unfolding and 1.7 days/decade delayed leaf fall</td>
<td>1953-2000 (48 years)</td>
<td>1</td>
<td>Matsumoto et al. (2003)</td>
</tr>
<tr>
<td>China</td>
<td>Phenological growing season extended by 14 days/decade</td>
<td>1982-1993 (12 years)</td>
<td>--</td>
<td>Xiaoqiu (2004)</td>
</tr>
</tbody>
</table>

Source: Reproduced from Khanduri et al. (2008, Table 1, p. 144) by authors of this report.

Southcentral and Southeast Alaska

Information needed.

\textsuperscript{1958} Nearly verbatim from Shafer et al. (2010, p. 177-178)
\textsuperscript{1959} Verbatim from Shafer et al. (2010, p. 178)
\textsuperscript{1960} Nearly verbatim from Staudinger et al. (2012, p. 2-14). Staudinger et al. cite Schwartz & others (2006) for information on the Northern Hemisphere and Ault & others (2011) for information on the western U.S.
Western British Columbia

*Information needed.*

Pacific Northwest

Across the Northwestern and interior Western U.S., time of first bloom for lilac and honeysuckle (*Lonicera tatarica* and *L. korolkowii*) showed a trend toward earlier flowering (average advances of 7.5 days for lilac and 10 for honeysuckle) over an almost 40-year period.\(^{1961}\) Earlier blooming was especially strong from 1970 to 1994 and corresponded with the pulse of spring snowmelt.\(^{1962}\)

Northwest California

*Information needed.*

**Future Projections**

Global

*Please see Chapter VIII for information on global future projections for phenology in birds, invertebrates, and lichens and mosses.*

Southcentral and Southeast Alaska

*Information needed.*

Western British Columbia

*Information needed.*

Pacific Northwest

*Information needed.*

Northwest California

*Information needed.*

**Information Gaps**

In contrast to spring, there is much less information available on autumn phenology.\(^{1963}\)

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\(^{1962}\) Verbatim from Leicht-Young et al. (2013, p. 1)

\(^{1963}\) Verbatim from Khanduri et al. (2008, p. 145)
3. Altered growth & development

Climate change could affect the growth and development of plant and animal species in a multitude of ways, including:

- **Rising CO\textsubscript{2} concentrations will likely increase tree growth rates and carbon sequestration** through a fertilization effect in the short term, but increases may decline subsequently due to soil nutrient limitations.\textsuperscript{1964} Enhanced CO\textsubscript{2} should also increase water-use efficiency (net carbon fixed per unit water) in both the short and long term.\textsuperscript{1965} Increases in the length of the snow-free season and changes in atmospheric evaporative demand are likely to increase plant transpiration, assuming soil water is available.\textsuperscript{1966}

- **Effects on limiting factors:** Climatic variability can alter temperature or precipitation such that limiting factors (e.g., light, temperature, water, nutrients) are exacerbated or mitigated for years or decades at a time.\textsuperscript{1967} Energy-limiting factors are chiefly light (e.g., in productive forests where competition reduces light to most individuals or climates where cloud cover limits light) and temperature (e.g., high-latitude or high-elevation forests).\textsuperscript{1968} Plant growth is reduced when one or more resources are limiting.\textsuperscript{1969} At broad scales, forests of western North America can be partitioned into two climatically mediated classes of limitation: energy-limited versus water-limited domains.\textsuperscript{1970} Limiting factors can of course shift within a species range, or between seasons, as water demands abate and energy needs increase.\textsuperscript{1971} Limiting factors can therefore also be transient, particularly for populations at the transition between energy and water limitation.\textsuperscript{1972}

- **Effects on chilling and heating requirements:** For tree populations, climate change will not alter photoperiodic cues for growth cessation and bud set, but may delay the satisfaction of chilling requirements in winter, or accelerate the satisfaction of heat sum requirements, and may also change the degree of synchrony of reproductive bud development among populations, affecting the potential for long distance gene flow via pollen.\textsuperscript{1973}

- **Effects on successional pathways:** Beyond its direct effects on the dynamics of forest recovery through physiological mechanisms, climate change may also impact successional pathways indirectly by altering the frequency, timing, severity, and spatial extent of disturbances including fires, droughts, storms, floods, and herbivore or pathogen outbreaks.\textsuperscript{1974} Changes in demographic

\textsuperscript{1964} Verbatim from Aitken et al. (2008, p. 103). Aitken et al. cite Millard et al. (2007) for this information.
\textsuperscript{1965} Verbatim from Aitken et al. (2008, p. 103)
\textsuperscript{1966} Verbatim from Pike et al. (2010, p. 713)
\textsuperscript{1967} Verbatim from Littell et al. (2010, p. 131)
\textsuperscript{1968} Verbatim from Littell et al. (2010, p. 131)
\textsuperscript{1969} Nearly verbatim from Littell et al. (2010, p. 131)
\textsuperscript{1972} Verbatim from Littell et al. (2010, p. 131)
\textsuperscript{1973} Nearly verbatim from Aitken et al. (2008, p. 102)
\textsuperscript{1974} Verbatim from Anderson-Teixeira et al. (2013, p. 10). Anderson-Teixeira et al. cite Dale et al. (2001), Westerling et al. (2006), Allen et al. (2010), and Sturrock et al. (2011) for this information.
rates, when compounded over time, can alter forest structure, composition, and function.\textsuperscript{1975} Further, age- and species-dependent responses provide a mechanism by which climate change may push some forests past critical thresholds such that they fail to recover to their previous state following disturbance.\textsuperscript{1976}

- **Effects on migration:** Climatic impacts on migration are likely to be most important for the pre-breeding migration because timing of arrival in the breeding areas is critical.\textsuperscript{1977} Moreover, any additional mortality, or loss of condition, will have a direct effect on breeding population size, unlike mortality on post-breeding migration, which may be compensated for by density-dependent mortality during the non-breeding period.\textsuperscript{1975} For migratory animal species, the quality of habitats (i.e., those used for any part of migration) is particularly important for migrants that use a limited number of widely separated, and often highly productive, stop-over sites.\textsuperscript{1979} Species that need to cross an ecological barrier, such as desert, mountains or ocean, require a large amount of high quality food in a short period of time to ensure they are able to cross the barrier and arrive in good physical condition.\textsuperscript{1980} Failure to arrive in good condition may result in reduced survival or fecundity at later stages in the life-cycle, which may be exacerbated by positive feedback mechanisms, with individuals using the best non-breeding areas able to return to the best breeding sites, because they migrate earlier or faster.\textsuperscript{1981}

**Observed Trends**

**Global**

Tree-ring records have revealed increasing growth rates in numerous forests including high-elevation forests in western Washington, conifers in the white mountains of California, ponderosa pine forests in the U.S. Pacific Northwest, aspen secondary forests in Wisconsin, fir and oak forests in France, and numerous other forests throughout Europe.\textsuperscript{1982} These increased growth rates are generally attributable to increased atmospheric CO\(_2\), temperature, or moisture.\textsuperscript{1983} In contrast, tree growth rates have decreased in response to warming or drought stress in many other forests around the world, including white spruce in

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\textsuperscript{1975} Verbatim from van Mantgem et al. (2009, p. 521). van Mantgem et al. cite Kobe (1996) for this information.
\textsuperscript{1976} Nearly verbatim from Anderson-Teixeira et al. (2013, p. 1)
\textsuperscript{1977} Verbatim from Robinson et al. (2008, p. 91). Robinson et al. cite Kokko (1999) for this information.
\textsuperscript{1978} Verbatim from Robinson et al. (2008, p. 91)
\textsuperscript{1979} Nearly verbatim from Robinson et al. (2008, p. 5)
\textsuperscript{1981} Verbatim from Robinson et al. (2008, p. 91). Robinson et al. cite Gill et al. (2001), Baker et al. (2004), and Norris et al. (2004) for information on the effects of failing to arrive in good condition. Robinson et al. cite Gunnarsson et al. (2005) for information on the effects of positive feedback mechanisms.
\textsuperscript{1983} Verbatim from Anderson-Teixeira et al. (2013, p. 9). Anderson-Teixeira et al. cite Graumlich et al. (1989), Soulé & Knapp (2006), Salzer et al. (2009), and Cole et al. (2010) for this information.
interior Alaska, conifers in the southwest United States, and tropical forests in Panama, Malaysia, and Costa Rica.\footnote{1984}

Rates of forest recovery generally increase with CO$_2$, temperature, and water availability.\footnote{1985} For example, tree growth and carbon cycling in young forests are generally accelerated under combined CO$_2$, warmer, and wetter conditions.\footnote{1986} Drought reduces growth and live biomass in forests of all ages, having a particularly strong effect on seedling recruitment and survival.\footnote{1987} Responses of individual trees and whole-forest ecosystems to CO$_2$ and climate manipulations often vary by age, implying that forests of different ages will respond differently to climate change.\footnote{1988} Although there is strong evidence that CO$_2$ fertilization increases the rate of biomass accrual in young forests, a question remains as to whether elevated CO$_2$ increases the biomass and productivity of mature forests.\footnote{1989}

**Western North America**

In the strongly maritime mountains in western North America, seed-based regeneration depends, as a rule, on the length of the snow-free season, whereas moisture conditions are the controlling factor in the drier regions.\footnote{1990} Koenig & Knops (2000) tested whether annual seed production (masting or mast fruiting) in Northern Hemisphere trees is an evolved strategy or a consequence of resource tracking by comparing masting patterns with those of annual rainfall and mean summer temperatures, two environmental variables likely to correlate with available resources.\footnote{1991} In combination with the switching between growth and reproduction documented by Koenig and Knops (1998), as well as prior work on particular systems, Koenig & Knops’ (2000) results support the hypothesis that annual seed production by forest trees is generally an evolved strategy.\footnote{1992} Although seed production is often likely to be correlated with environmental factors in either case, temporal autocorrelation and patterns of variability do not strongly

\footnote{1984} Verbatim from Anderson-Teixeira et al. (2013, p. 9). Anderson-Teixeira et al. cite Allen et al. (2010) for information on global declines in tree growth rates in response to warming or drought stress, Barber et al. (2000) for information on white spruce in Alaska, Williams et al. (2013) for information on conifers in the southwest U.S., and Feeley et al. (2007b) and Clark et al. (2010) for information on tropical forests.

\footnote{1985} Verbatim from Anderson-Teixeira et al. (2013, p. 1)

\footnote{1986} Nearly Verbatim from Anderson-Teixeira et al. (2013, p. 8). Anderson-Teixeira et al. refer the reader to Tables S1-S3 in the cited article for this information. Anderson-Teixeira et al. also cite Wan et al. (2004), Comstedt et al. (2006), Slaney et al. (2007), Tingey et al. (2007), and Bauweraerts et al. (2013) for this information.

\footnote{1987} Verbatim from Anderson-Teixeira et al. (2013, p. 1)

\footnote{1988} Verbatim from Anderson-Teixeira et al. (2013, p. 1)

\footnote{1989} Nearly verbatim from Anderson-Teixeira et al. (2013, p. 5). Anderson-Teixeira et al. refer the reader to Figure 1 in the cited article for this information. Anderson-Teixeira et al. also cite Körner et al. (2005), Hyvönen et al. (2007), and Norby & Zak (2011) for this information.


\footnote{1991} Nearly verbatim from Koenig & Knops (2000, p. 59). *Patterns of annual seed production by Northern Hemisphere trees: A global perspective.*

\footnote{1992} Nearly verbatim from Koenig & Knops (2000, p. 67). Koenig & Knops cite Norton & Kelly (1988), Sork et al. (1993), Kelly (1994), and Tapper (1996) for information on prior work on similar systems. *Note: The in-text citation for Koenig & Knops (1998) is that cited by Koenigh & Knops (2000). In the cited article, the exact citation is for Koenig & Knops (1998a).*
match those exhibited by either annual rainfall or mean temperature, two environmental factors likely to correlate with available resources in a given year.\textsuperscript{1993}

The large geographic scale on which seed production patterns are often synchronized, both within and between genera, has important implications for wildlife populations dependent on the seeds of forest trees for food.\textsuperscript{1994} In general, resident populations of birds and mammals dependent on mast are likely to be affected synchronously over large geographic areas by both bumper crops providing abundant food and, perhaps even more dramatically, by crop failures.\textsuperscript{1995}

\textbf{Southcentral and Southeast Alaska}

\textit{Information needed.}

\textbf{Western British Columbia}

\textit{Information needed.}

\textbf{Western Washington}

\textit{Information needed.}

\textbf{Western Oregon}

\textit{Information needed.}

\textbf{Northwest California}

Throughout the coast redwood ecosystem (i.e., north to central California coast), nocturnal foliar uptake increased the leaf water content of western sword fern by 7.2\%, and Limm & Dawson (2010) estimated that the western sword fern canopy can absorb $5 \pm 3\%$ (mean $\pm$ standard error) of intercepted fog precipitation.\textsuperscript{1996} Strikingly, western sword fern had the highest foliar uptake capacity in the center of the ecosystem and may absorb 10\% more of the fog its canopy intercepts in this region relative to other regions studied.\textsuperscript{1997} Specifically, the summertime water subsidy potentially obtained through fog drip acquisition appears 10\% higher in the center of the redwood forest range than in the north where total canopy area for fog drip interception is higher or in the south where water is more limiting and demand for fog may be greater.\textsuperscript{1998} Conversely, western sword fern had no foliar uptake capacity in the southern end of the ecosystem.\textsuperscript{1999} These findings suggest that the western sword fern at the southern tip of the redwood ecosystem (i.e., central California coast) may suffer most from low summertime water availability because it had no potential to acquire fog as an aboveground water subsidy.\textsuperscript{2000}

\textsuperscript{1993} Verbatim from Koenig & Knops (2000, p. 67-68)

\textsuperscript{1994} Nearly verbatim from Koenig & Knops (2000, p. 68)

\textsuperscript{1995} Verbatim from Koenig & Knops (2000, p. 68)

\textsuperscript{1996} Nearly verbatim from Limm & Dawson (2010, p. 1121)

\textsuperscript{1997} Verbatim from Limm & Dawson (2010, p. 1121)

\textsuperscript{1998} Nearly verbatim from Limm & Dawson (2010, p. 1125)

\textsuperscript{1999} Verbatim from Limm & Dawson (2010, p. 1121)

\textsuperscript{2000} Nearly verbatim from Limm & Dawson (2010, p. 1121)
Future Projections

Global

For tree populations, widespread species with high fecundity occurring in large populations will likely be able to adapt to climate change in relatively few generations, and will likely survive in the interim as major competitors will be facing the same fate of short-term maladaptation.2003 High rates and distances of seed and pollen dispersal will also contribute positively to their capacity to both adapt and migrate; 2002 Species that occur in small, fragmented populations, or those with low fecundity or late age of sexual maturity, reproductive characteristics more typical of later successional species and high-elevation habitats, will likely suffer greater adaptational lag.2003

Quintero & Wiens (2013) estimated absolute rates of climatic niche evolution for 540 species in 17 clades of terrestrial vertebrates, including groups of mammals, birds, lizards, snakes, turtles, crocodilians, salamanders, and frogs (2090-2100 vs. 2000; six GCMs run under A2).2004 Matching projected changes for 2100 would require rates of niche evolution that are greater than 10,000 times faster than rates typically observed among species, for most variables and clades.2005

Western North America

Populations of temperate and boreal trees show moderate to strong clines (i.e., gradual phenotypic or genetic differences in a species over a geographic area) in phenology and growth along temperature gradients, indicating substantial local adaptation.2006 Many ecologically and economically important genera in temperate and boreal regions contain species pairs capable of interspecific hybridization (i.e., typically, hybrids formed from two species in the same genus), including spruce, pine, poplar, and oak.2007 This possibility is of particular interest in western North America, where several pairs of maritime and more continental taxa have distributions largely separated by major north–south mountain ranges, but have some opportunity for genetic contact through a few major east–west river valleys or over the crest of lower parts of these ranges (e.g., Sitka spruce and white spruce, lodgepole pine and jack pine, and coast Douglas-fir and Rocky Mountain Douglas-fir).2008 Hybridization followed by backcrossing (i.e., crossing a hybrid with one of its parents or a genetically similar individual to achieve genetic composition closer to the parent) or further introgression (i.e., movement of a gene from one species into the gene pool of another through repeated backcrossing) and selection (i.e., for a particular gene or trait) can lead to transgressive segregation (i.e., extreme phenotypes), whereby some individuals can have phenotypes

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2002 Verbatim from Aitken et al. (2008, p. 108)
2003 Verbatim from Aitken et al. (2008, p. 108)
2005 Nearly verbatim from Quintero & Wiens (2013, p. 1095)
2006 Nearly verbatim from Aitken et al. (2008, p. 95)
2007 Nearly verbatim from Aitken et al. (2008, p. 101)
outside of the range of parental species due to complementary allelic effects.\textsuperscript{2009} This may offer a rapid evolutionary path to adaptation to novel environments, as demonstrated for sunflower species.\textsuperscript{2010}

\textbf{Southcentral and Southeast Alaska}

Information needed.

\textbf{Western Washington}

Information needed.

\textbf{Western Oregon}

Information needed.

\textbf{Northwest California}

Given that winter precipitation input to California ecosystems will likely change in the coming decades, understanding the fog drip acquisition potential of fern populations may aid predicting how western sword fern abundance will be affected by climate change.\textsuperscript{2011} If rainfall decreases, western sword fern may rely more on fog water during the summer months to sustain the current frond size, crown density, and total canopy cover.\textsuperscript{2012} If foliar uptake is a plastic trait, fog drip absorption efficiency may increase in response to higher demand for fog if rainfall decreases.\textsuperscript{2013} However, if western sword fern differs genotypically in foliar uptake capacity in the ecosystem today, climatic changes may drive local extinctions of populations unable to efficiently absorb fog water as demand for water increases.\textsuperscript{2014} Because western sword fern depends on fog-water subsidies to maintain optimal summertime water status in many areas, the future canopy cover and distribution of western sword fern in the redwood forest ecosystem may change with further fog loss, affecting the understory ecosystem it helps define.\textsuperscript{2015}

\textbf{Information Gaps}

Systematic comparison of responses of forests of different ages to experimental CO\textsubscript{2} or climate manipulation and to natural climate variability will be crucial to understanding and modeling climate change impacts on forests of all ages.\textsuperscript{2016} It will also be important to understand how altered biogeochemical dynamics and community composition shape successional pathways and the states toward which forests converge as they mature.\textsuperscript{2017}

Although detailed representation of forest recovery dynamics in global models is infeasible, Anderson-Teixeira et al. (2013) believe that two advances will be important to improving the treatment of forest

\textsuperscript{2012} Verbatim from Limm & Dawson (2010, p. 1126)
\textsuperscript{2013} Verbatim from Limm & Dawson (2010, p. 1126)
\textsuperscript{2014} Verbatim from Limm & Dawson (2010, p. 1126)
\textsuperscript{2015} Verbatim from Limm & Dawson (2010, p. 1126)
\textsuperscript{2016} Verbatim from Anderson-Teixeira et al. (2013, p. 16)
\textsuperscript{2017} Nearly verbatim from Anderson-Teixeira et al. (2013, p. 16)
regeneration. First, the most important stand age-dependent physiology and allocation strategies (driven by aging of dominant species and changes in species composition) should be identified and incorporated. Second, although modeling individual species in ecosystem and earth system models is infeasible, it will be necessary to represent the consequences of demonstrated variability in species responses to climate change and inevitable resultant shifts in community composition and ecosystem processes.

2018 Nearly verbatim from Anderson-Teixeira et al. (2013, p. 16)
2019 Verbatim from Anderson-Teixeira et al. (2013, p. 16)
2020 Verbatim from Anderson-Teixeira et al. (2013, p. 16)
4. Shifts in biodiversity, species richness, abundance, competition, survival & community composition

Climate change impacts on biodiversity are projected to increase in magnitude and pervasiveness as CO₂ levels and temperatures continue to rise, and extreme events (for example, heat and storms) increase in frequency and intensity. Climate change will increase the vulnerability of species across the globe to population loss and extinction. Species confronting rapid environmental change will either go extinct or survive in one of three ways: by acclimatizing, evolving, or migrating to suitable habitats elsewhere. Often, more than one of these responses will occur concurrently. The extinction risk increases if suitable habitat conditions either disappear entirely or, as is more likely, if habitats shift more rapidly than resident species can migrate. For many organisms, evolution probably will not occur rapidly enough to keep up with the current and anticipated rapid pace of climate change, especially if habitats have already been degraded by various land uses.

Paleoecological evidence indicates that species respond individualistically to climate change; and thus, the mix of species with which any one species interacts will change as climate changes. Changing species distributions may bring a species into contact with other taxa with which it has never interacted, and entirely new competitive interactions may result. Conversely, climate change may eliminate an important predator, allowing a species to greatly expand its range. Perhaps the most significant interspecies interaction will be with humans due to the impact of our land-use activities on habitat and species distributions and abundances.

Key Terms in this Section

**Abundance:** total number of individuals of a given taxon or taxa in an area, population, or community

**Biodiversity:** the variability among living organisms from all sources, including diversity within species, between species, and between ecosystems

**Ecological community:** an assemblage of species often linked by biotic interactions such as competition or predation and occurring in the same space or time

**Ecological surprises:** unexpected and often disproportionately large consequences of changes in the abiotic or biotic environment

**Hybridization:** the blending or homogenization of genetically distinct lineages, occasionally resulting in the development of a new species

**Keystone species:** species exerting a disproportionately large influence on ecosystems, larger than would be expected from their abundance

Sources: Millenium Ecosystem Assessment (2005), Pojar (2010)

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2022 Verbatim from Klausmeyer et al. (2011, p. 1)
2023 Verbatim from Pojar (2010, p. 30)
2024 Verbatim from Running & Mills (2009, p. 11)
2028 Verbatim from Shafer et al. (2011, p. 212)
2029 Verbatim from Shafer et al. (2011, p. 212-3)
Climate change is having both direct and indirect effects on the way species interact over spatial and temporal scales, with sometimes profound impacts on ecosystem structure and function. Species interactions often influence responses to climate and climate-related traits can evolve rapidly. Adaptation to new climates could moderate the direst predictions of biodiversity loss whereas species interactions could enhance or diminish extinction risks depending on interaction type. As species tend to respond to climate change in very individualistic ways, one of the main impacts of climate change on animal populations will be mediated through the synchrony with their food and habitat resources. Altered synchrony between prey and predators will generally have negative fitness consequences on predator populations. The fertilization effect of increased CO₂ concentrations could significantly alter competitive interactions among species. Higher temperatures can affect food-web interactions by increasing vital rates such as growth and consumption.

For migratory species, as with any environmental change, inevitably there will be winners and losers. The winners are likely to be those species with greater phenotypic flexibility that use widespread habitats and perhaps display weaker migratory connectivity (individuals from one breeding population may migrate to one of many non-breeding areas and vice versa). Thus, common species are likely to become commoner, and scarce species scarcer, resulting in a general decline in biodiversity.

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2032 Verbatim from Norberg et al. (2012, p. 747). Eco-evolutionary responses of biodiversity to climate change. Norberg et al. cite Tylianakis et al. (2008) for information on species interactions influencing responses to climate and Franks et al. (2007) and Balanya et al. (2006) for information on rapid evolution of climate-related traits.
2033 Verbatim from Norberg et al. (2012, p. 747). Norberg et al. cite Skelly et al. (2007) for information on adaptation moderating dire predictions of biodiversity loss and Brooker et al. (2007) and Münkemüller & Bello (2011) for information on the role of species interactions in extinction risk.
2034 Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. refer the reader to the next section in the cited article for information on individualistic species responses to climate change. Lavergne et al. cite Parmesan (2006) for a review of this information.
2035 Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. cite Visser & Both (2005) for this information.
2036 Verbatim from Shafer et al. (2011, p. 213)
2037 Verbatim from Staudinger et al. (2012, p. 2-18)
2038 Verbatim from Robinson et al. (2008, p. 92)
2039 Verbatim from Robinson et al. (2008, p. 92)
Human-induced global change is causing ecological communities to rapidly lose some species and gain others, resulting in interchanges of species, their traits and interactions, and alteration of ecosystem functioning and services. Species gain is derived from colonization and establishment of new species, processes that are increasing in frequency and intensity at global scales via cross-continental introduction, land use change, and climate warming, with demonstrated effects at the ecosystem level.

Populations isolated geographically or environmentally from the main range of their species can evolve genetically distinct races or subspecies. Climate change could increase between-population genetic diversity, insofar as insularity increases (for example, in the alpine zone as treeline moves upward, or on the coast as sea level rises), as disjunctions increase (for example, by long-distance dispersal), or as currently continuous, widespread species distributions become fragmented. Hybridization probably will increase as climate changes, as species and populations migrate and come into contact with related species or populations from which they were previously isolated, and as habitats themselves become mixed up, recombined, and effectively hybridized. Although this mechanism has the potential to help species persist as environmental conditions change, an increase in interspecific hybridization could reduce species richness and diversity, and has important consequences for ecosystem function.

Community composition responds to a complex set of factors including the direct effects of climate, differential species dispersal, and indirect effects associated with changes in disturbance regimes, land use, and interspecific interactions. Despite a general trend for species expanding their ranges northward and/or upward or advancing their phenology, the signature of environmental change on communities seems to be driven by a subset of highly responsive species. This heterogeneity in species responses to climate change will strongly alter the composition of local communities and induce the formation of non-analog communities, where extant species co-occur in historically unknown combinations. However, in many systems, the observed state of the community is not the only possible stable state; a variety of empirical results demonstrate the existence of alternative stable states in

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2041 Verbatim from Wardle et al. (2011, p. 1273)
2042 Verbatim from Wardle et al. (2011, p. 1273). Wardle et al. refer the reader to Figure 2 in the cited article for this information.
2043 Verbatim from Pojar (2010, p. 36)
2045 Nearly verbatim from Pojar (2010, p. 38). Pojar cites Anderson (1948) for this information.
2049 Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. cite Hobbs et al. (2009) and Kullman (2006) for this information.
nature. Systems that are structured by disturbance and are susceptible to abiotic forcing (such as regenerating forests) may be more likely to display alternative stable states.

**Observed Trends**

**Global**

In general, land use change has been the main driver of terrestrial biodiversity loss during the past century. For example, conversion of relatively undisturbed terrestrial ecosystems to agricultural, urban systems or other highly human dominated systems, also referred to as “habitat loss”, is currently the main driver of changes in species abundance globally. Because local-scale losses of native species and ingress of new species occur simultaneously, both net gains and losses of species richness are occurring. Although the Earth is experiencing substantial losses of biodiversity at the global level, both increases and decreases in community diversity are commonly observed at regional and local scales.

The well documented no-analog plant communities (i.e., communities that are compositionally unlike any found today) of late-glacial North America are closely linked to “novel” climates also lacking modern analogs, characterized by high seasonality of temperature. No-analog fossil assemblages are pervasive in Quaternary paleoecological records (i.e., from approximately 2.6 million years ago to the present), documented for plants, mammals, coleopterans (i.e., beetles), mollusks, and foraminifera.

**Southcentral and Southeast Alaska**

The muskrat feeds on sedges, which benefit (due to their use of C$_3$ photosynthetic pathway) as warming continues, while competitors feeding on grasses (C$_4$ photosynthetic pathway) will be at a disadvantage. For additional information on observed trends for mammals and birds in southcentral and southeast Alaska, please see Chapter VIII.1 and VIII.2, respectively.

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2050 Nearly verbatim from Anderson-Teixeira et al. (2013, p. 10). Anderson-Teixeira et al. cite D’Antonio & Vitousek (1992), Savage & Mast (2005), Schröder et al. (2005), Odion et al. (2010), and Scheffer et al. (2012) for this information.

2051 Nearly verbatim from Anderson-Teixeira et al. (2013, p. 10). Anderson-Teixeira et al. cite Didham et al. (2005) for this information.

2052 Verbatim from Leadley et al. (2010, p. 12). *Biodiversity scenarios: Projections of 21st century change in biodiversity and associated ecosystem services.*

2053 Nearly verbatim from Leadley et al. (2010, p. 15)

2054 Verbatim from Wardle et al. (2011, p. 1273). Wardle et al. cite Sax & Gaines (2003) and Bardgett & Wardle (2010) for this information.

2055 Verbatim from Wardle et al. (2011, p. 1273). Wardle et al. cite the Millenium Ecosystem Assessment (2005) for information on global biodiversity loss and Sax & Gaines (2003) for information on changes in community diversity at regional and local scales.

2056 Nearly verbatim from Williams & Jackson (2007, p. 475)


2058 Nearly verbatim from Kelly et al. (2007, p. 63). Kelly et al. cite Inkley et al. (2004) for this information.
Western British Columbia

In British Columbia, the majority of the forest-associated red-listed species occur in the Coastal Western Hemlock, Coastal Douglas-fir, and Interior Douglas-fir biogeoclimatic zones (Figure 57). Specifically, the four lower elevation biogeoclimatic zones (Coastal Douglas-fir, Bunchgrass, Ponderosa Pine, Interior Douglas-fir) of southern B.C. host the most species diversity and concentrations of species at risk. The same four zones plus parts of the Coastal Western Hemlock zone, particularly Vancouver Island and Haida Gwaii (both heavily logged), are most significant with respect to stewardship species (i.e., the ~100 of the 3,841 species assessed for conservation status in B.C. that have all or >50% of their global range, area, or population within B.C. Additional species-specific information for caribou, moose, elk, grizzly bear, cougar, Vancouver Island marmot, Pacific water shrew, spotted owl, pileated woodpecker, and marbled murrelet is available and can be found in Chapter VIII.1 (Mammals) and VIII.2 (Birds).

Pacific Northwest

Information needed.

Klamath Mountains

The coniferous and mixed evergreen forests of the Klamath-Siskiyou region are widely recognized for their globally outstanding levels of biodiversity. Most native species and communities have evolved with fire and many are adapted to, if not dependent on, fire’s periodic occurrence.

Northwest California

Information needed.

Future Projections

Global

To date, only a few species of amphibians, birds, fishes, and gastropods are known to have gone extinct due to the impacts of climate change; however, widespread losses of global biodiversity are projected by numerous studies using a range of modeling approaches and climate scenarios. For example, in the short term, increasing temperatures are likely to lead to increased resource availability in northern polar...
regions and hence increased populations, but, in the longer term, it is thought likely that many species will experience significant resource or habitat loss.

Global biodiversity models project that terrestrial species extinctions (Figure 61), loss of natural habitat, and changes in the distribution and abundance of species, species groups and biomes will continue throughout this century, with land use change being the main threat in the short term, and climate change becoming progressively much more important over the next several decades. Future extinctions could be worse than projected in the most pessimistic scenarios in Figure 61 because the non-linear dynamics of tipping points have not been fully accounted for. Global models project that mean species abundance will decrease during the first half of the century between 9% and 17% (Figure 60).

Specific results include:

- Using quantitative projections of changes in land use and climate from the four Millenium Ecosystem Assessment scenarios, results from van Vuuren et al. (2006) show that in tundra, boreal forests, and cool conifer forest, climate change is projected to be the major cause of biodiversity loss, varying from 5% to almost 15% species loss at equilibrium. Note, however, that for these biomes, land-use change has relatively low impact in comparison with other biomes. In contrast, land-use change is the main driver of biodiversity loss in temperate forests, warm mixed forests, savannah, and tropical forest, leading to a 7% to nearly a 25% species loss at equilibrium. The contribution of climate change for plant diversity loss in these ecosystems varies between 1% and 7% loss of species. After 2050, climate change will become increasingly important.

- In a study projecting extinctions of endemic species from global biodiversity hotspots, Malcolm et al. (2006) projected percent extinctions ranged from <1 to 43% of the endemic biota (average 11.6%), with biome specificity having the greatest influence on the estimates (i.e., narrowly or broadly defined), followed by the global vegetation model (i.e., either MAPSS or BIOME3) and then by migration and biome classification assumptions (2 x CO₂ vs. 1 x CO₂, where CO₂ is an undefined current level; 14 scenarios run with MAPSS and BIOME3 and seven GCMs). Using projections of species’ distributions for future climate scenarios (i.e., a climate-envelope model approach), Thomas et al. (2004) found minimum expected climate change scenarios for 2050 produce fewer projected “committed extinctions” (18%; average of three area methods and two dispersal

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2066 Verbatim from Robinson et al. (2008, p. 89). Robinson et al. cite Jensen et al. (2008) for information on the effects of increasing temperatures in the short-term, and Zöckler & Lysenko (2000) and Meltofte et al. (2007) for information on the effects of increasing temperature in the longer term.

2067 Verbatim from Leadley et al. (2010, p. 11)

2068 Nearly verbatim from Leadley et al. (2010, p. 14). Leadley et al. are referring to Figure 2 in the cited report for this information. Leadley et al. also refer the reader to the following sections of the cited report for additional information on tipping points.

2069 Verbatim from Leadley et al. (2010, p. 15). Leadley et al. refer the reader to Figure 5A in the cited report for this information.

2070 Nearly verbatim from van Vuuren et al. (2006, p. 33)

2071 Verbatim from van Vuuren et al. (2006, p. 33)

2072 Verbatim from van Vuuren et al. (2006, p. 33)

2073 Verbatim from van Vuuren et al. (2006, p. 33)

2074 Nearly verbatim from van Vuuren et al. (2006, p. 25)

scenarios, universal and no dispersal; \(\text{CO}_2 = 500\) ppm by volume, ppmv) than mid-range projections (24%; \(\text{CO}_2 = 500\text{-}550\) ppmv), and about half of those predicted under maximum expected climate change (35%; \(\text{CO}_2 > 550\) ppmv).\(^{2076}\) It should also be kept in mind that most models project the proportion of species that are “committed to extinction” at some future time because their habitat or range size shrinks, but the lag time between becoming “committed to extinction” and actually going extinct may range from decades to many millennia.\(^{2077}\)

In both studies, (i.e., Malcolm et al. 2006 and Thomas et al. 2004) extinction risks were higher when species were modeled under limited dispersal scenarios, situations that reflect both the inherent biological constraints of many organisms and the ways in which habitat fragmentation may impede species dispersal.\(^{2078}\) van Vuuren et al. (2006) found that land-use change rather than climate change is likely a more dominant driver of biodiversity loss in the next fifty years, consistent with the qualitative assessment of Sala et al. (2000), but inconsistent with the results of Thomas et al. (2004).\(^{2079}\)

In an assessment of climate-induced change in the geographic ranges of 2,954 species of birds, mammals, and amphibians in the Western Hemisphere (2071-2100 vs. 1961-1990; 30 AOGCMs run with B1 and A2), although all three taxonomic groups (birds, mammals, amphibians) were predicted to experience large changes at high northern latitudes, and in the Andes, Mexico, and Central America, amphibians were uniquely predicted to also undergo a high degree of turnover in the central and eastern United States.\(^{2080}\) The largest changes in fauna are predicted for the tundra, Central America, and the Andes Mountains where, assuming no dispersal constraints, specific areas are likely to experience over 90% turnover, so that faunal distributions in the future will bear little resemblance to those of today.\(^{2081}\)

No-analog communities (communities that are compositionally unlike any found today) occurred frequently in the past and will develop in the greenhouse world of the future.\(^{2082}\) In climate simulations for the IPCC A2 and B1 emission scenarios (2080-2099 vs. 1980-1999), novel climates arise by 2100 AD, primarily in tropical and subtropical regions.\(^{2083}\) These future novel climates are warmer than any present climates globally, with spatially variable shifts in precipitation, and increase the risk of species reshuffling into future no-analog communities and other ecological surprises.\(^{2084}\) Individualistic species dynamics and the formation of no-analog communities can be explained by a niche-based conceptual framework (Figure 59).\(^{2085}\)

\(^{2076}\) Nearly verbatim from Thomas et al. (2004, p. 147)
\(^{2077}\) Verbatim from Leadley et al. (2010, p. 14). Leadley et al. cite Sala et al. (2005) for this information.
\(^{2078}\) Nearly verbatim from Staudt et al. (2012, p. 5-13)
\(^{2079}\) Verbatim from van Vuuren et al. (2006, p. 37)
\(^{2080}\) Nearly verbatim from Lawler et al. (2009, p. 592). Projected climate-induced faunal change in the Western Hemisphere.
\(^{2081}\) Verbatim from Lawler et al. (2009, p. 588)
\(^{2082}\) Verbatim from Williams & Jackson (2007, p. 475)
\(^{2083}\) Verbatim from Williams & Jackson (2007, p. 475)
\(^{2084}\) Verbatim from Williams & Jackson (2007, p. 475)
\(^{2085}\) Verbatim from Williams & Jackson (2007, p. 476). Williams & Jackson refer the reader to Figure 1 in the cited article for this information. Williams & Jackson also cite Jackson & Overpeck (2000) for this information.
**Figure 59.** A conceptual diagram showing how no-analog combinations of species arise in response to novel climates. The set of climates in existence at two periods, “present” and an arbitrary “time t”, are represented as open ellipses. The fundamental niches for three species are shown as colored ellipses. Associations between species can occur only when their fundamental niches overlap with one another and with the set of climates in existence at a particular time period. A present-day ecologist would therefore sometimes observe communities containing both Species 1 and 2, but would never observe co-occurrences of Species 2 and 3 (nor Species 1 and 3). If the right climates arise, however, Species 2 and 3 could co-occur, forming a “no-analog” community from the perspective of the present-day ecologist. Adapted from Figure 5 in Jackson and Overpeck (2000).

**Source:** Reproduced from Williams & Jackson (2007, Figure 1, p. 476) by authors of this report.

**Figure 60.** Observed changes and scenario projections to 2050 in abundance of terrestrial species. A) Modelled changes in terrestrial mean species abundance (MSA) using the GLOBIO model (Alkemade et al. 2009) for the GEO4 and GBO2 scenarios from 1970 to 2050. B) The Living Planet Index (LPI) for terrestrial species is based on observed changes in the population sizes of well-studied terrestrial vertebrates from 1970 to 2005 (Source: Jonathan Loh, WWF). These two indicators assess changes in species abundances, but are calculated differently so they are not directly comparable. Nevertheless, they suggest that species abundances have been declining globally, and will continue to do so in the examined scenarios. The scenario that has the least biodiversity loss is the one where effective protected areas are implemented and expanded globally.

**Source:** Reproduced from Leadley et al. (2010, Figure 5, p. 15) by authors of this report.

**Figure 61.** Historical extinction rates and scenario projections for the 21st century. Extinctions per million species years (E/MSY) for distant past, recent past and future. “Distant past” refers to the background extinction rate of mammals obtained from the fossil record (MA 2005). “Recent past” refers to documented extinctions registered in the 20th century, by the Red List — mammals (upper bound), amphibians (lower bound) and birds (in between) (Baillie et al. 2004). “Future” refers to projections of species “committed to extinction” according to different global scenarios: birds (Jetz et al. 2007, for the period of 2000–2050), vascular plants (van Vuuren et al. 2006 for the period 1995–2050) and various taxa (Thomas et al. 2004 for the period 2000–2050 and Malcolm et al. 2006 for the period 2000–2100). This figure shows that projected extinction rates have large uncertainties (both intra and inter-study), but are nonetheless higher than recent extinction rates.

**Source:** Reproduced from Leadley et al. (2010, Figure 2, p. 12) by authors of this report.
Western North America

Increasing temperatures will alter competitive interactions between deciduous and evergreen species by allowing increased rates of photosynthesis by evergreen species during winter months.\textsuperscript{2086} In a study of tree species richness using climate envelope modeling of 130 tree species, all of the AOGCMs project substantial reductions in climate envelope richness across the eastern half of the United States, gains in climate envelope richness for much of Canada, and relatively little change across much of the mountainous regions of the United States (Figure 62; 2071-2100 vs. 1971-2000 run with CGCM2, CGCM3.1, CSIRO-mk2, CSIRO-mk3.5, PCM, and CCSM3.0 under A2).\textsuperscript{2087} These maps only indicate where suitable climatic conditions will exist for the 130 tree species under study; the extent to which trees will actually shift with climate is of course highly uncertain.\textsuperscript{2088}

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Species of unusual specialized habitats (for example, archaeabacteri and mollusks in hot springs, ferns (for example, Kruckeberg’s hollyfern, mountain holly fern) restricted to ultrabasic bedrock, and subterranean cave species) are more likely to persist—as long as their special habitats

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\textsuperscript{2086} Nearly verbatim from Shafer et al. (2011, p. 212)
\textsuperscript{2087} Nearly verbatim from McKenney et al. (2011, p. 2726). Revisiting projected shifts in the climate envelopes of North American trees using updated general circulation models.
\textsuperscript{2088} Nearly verbatim from McKenney et al. (2011, p. 2726)
continue to exist. The Grand Canyon of the Stikine, the ultrabasic bedrock of the Shulaps Range, hot springs, coastal dunes, karst on Vancouver Island and Haida Gwaii, and spray zones of waterfalls will continue to support some sort of regionally unusual biota almost regardless of how much the climate changes. In addition, British Columbia species that live at the edge of their range as peripheral populations (for example, burrowing owl), and species that harbor genetically distinct and reproductively isolated populations as cryptic species (for example, seaside juniper), will be important genetic resources in the future.

Pacific Northwest

For information on implications for species, populations, and communities in the Pacific Northwest, please see Chapters VI (habitats) and VIII (mammals, birds, invertebrates, and lichens and mosses).

Northwest California

Of 25 global hotspots analyzed, the California Floristic Province (i.e., most of northern and central CA) was identified to be one of the areas most vulnerable to climate change (2 x CO₂ vs. 1 x CO₂; CO₂ is an undefined current level; 14 scenarios run with MAPSS and BIOME3 global vegetation models and 7 GCMs).

Klausmeyer et al. (2011) estimated the vulnerability of biodiversity to climate change impacts across broad areas using landscape-scale indicators. After combining the stress metrics for precipitation and temperature to estimate climate stress, areas with the highest stress include the Klamath Basin, the Modoc, the Sacramento Valley, and various locations in the Mojave and Sonoran Deserts. Areas with the highest exposure (i.e., landscape exposure) include the flatter inland portions of the state, portions of the Mojave and Sonoran Deserts, and the Imperial Valley, while the coastal mountain ranges have the lowest exposure. Adaptive constraints are significant in the coastal ecoregions and portions of the Klamath and Sierra Nevada mountains.

Regions of California that show the greatest decline of species richness of California native plants by the end of the century (2071-2100 vs. 1971-2000) include the Coast and Transverse ranges, as well as the transition zone between the Central Valley and the high Sierra (Figure 63) (GFDL and PCM, A2).

Information Gaps

Basic information on species and population traits ranging from physiology to behavior, life history characteristics, current distributions, dispersal abilities, and ecological relationships is needed to

2089 Nearly verbatim from Pojar (2010, p. 28)
2090 Nearly verbatim from Pojar (2010, p. 28)
2091 Nearly verbatim from Pojar (2010, p. 38)
2093 Nearly verbatim from Klausmeyer et al. (2011, p.1)
2094 Verbatim from Klausmeyer et al. (2011, p.10). Klausmeyer et al. refer the reader to Figure 4A in the cited article for a map of climate stress.
2095 Nearly verbatim from Klausmeyer et al. (2011, p.10)
2096 Verbatim from Klausmeyer et al. (2011, p.12)
2097 Nearly verbatim from Hannah et al. (2012, p. 14)
understand why some species and populations are able to adjust to the impacts of climate change (while others decline), and will be critical for building better models to forecast future biological responses and vulnerabilities. Additional experimental and field research is needed to improve our abilities to detect, attribute, and predict changes in these relationships (i.e. trophic mismatches) as well as the emergence of novel interactions and species assemblages. Further, there is a need for experimental, observational, and modeling studies to identify the conditions under which such shifts (i.e., climate-driven regime shifts) are likely and the mechanisms through which they may occur. There is also an incomplete knowledge of the impact of connections between ecosystems and their responses to climate and other global environmental challenges. Although species gains and losses occur simultaneously in many communities, there is still a dearth of knowledge about the net consequences of the two processes occurring in tandem for terrestrial ecosystems functioning. The advancement of this topic will require studies that explicitly consider both species invasion and extinction, as well as their interactions, environmental drivers, and temporal dynamics.

A critical barrier to investigating how multiple stressors interact is the lack of national data networks that combine climate, biological, and stressor information, including explicit data on population structure and abundance for invasive, rare, threatened, endangered, and other key species. Such data networks would allow researchers to combine information on projected climate changes with species biological data to understand possible future range shifts, and also to consider how other environmental stressors can influence future species distributions.

Most ecological models are at least partially parameterized from modern observations and so may fail to accurately predict ecological responses to these novel climates. Important drivers that are currently missing or only partially treated in current models include invasive species and overexploitation in terrestrial systems; dam construction, pollution and invasive species in freshwater systems; and, habitat degradation and pollution in coastal and marine systems. Predicting where mitigation and adaptation responses will occur, and how they will impact biodiversity will also be a critical step in developing credible future climate change impact scenarios. Although many tools for forecasting climate change impacts on ecosystem services exist, fewer methods for anticipating how people will respond to those impacts have been developed or incorporated into projected impacts on biodiversity.

2099 Nearly verbatim from Staudinger et al. (2012, p. 2-40)
2100 Nearly verbatim from Anderson-Teixeira et al. (2013, p. 16)
2101 Nearly verbatim from Grimm et al. (2012, p. 3-37)
2102 Nearly verbatim from Wardle et al. (2011, p. 1277)
2103 Nearly verbatim from Wardle et al. (2011, p. 1277)
2104 Verbatim from Staudt et al. (2012, p. 5-24)
2105 Verbatim from Staudt et al. (2012, p. 5-24)
2106 Verbatim from Williams & Jackson (2007, p. 475)
2107 Verbatim from Leadley et al. (2010, p. 36)
2108 Nearly verbatim from Staudinger et al. (2012, p. 2-40)
2109 Verbatim from Staudinger et al. (2012, p. 2-40). Staudinger et al. cite Kareiva & others (2011) for information on the many tools for forecasting climate change impacts on ecosystem services.
**Figure 63.** Projected changes in California native plant species richness. (top) Modeled Native Species Richness for 2071-2100. (bottom) Change in Modeled Species Richness from Current Climate (1971-2000) to 2071-2100. 
*Source: Reproduced from Hannah et al. (2012, Figures 1.10 and 1.11, p. 15) by authors of this report.*
5. Altered interaction with invasive & non-native plant and animal species

The impact of introduced species on ecosystems is influenced by such climatic factors as temperature, drought, and cloud cover. Introduced species can affect forests through herbivory, predation, habitat change, competition, alteration of gene pools via hybridization with natives, and disease (as either pathogens or vectors). Introduced species can alter the diversity, nutrient cycles, forest succession, and fire frequency and intensity of some ecosystems. Further, developmental rates will be modified by temperature change. In general, one might expect a larger fraction of survivors when the climate is warmer; introduced species comprise a far larger fraction of the biota in the warmer areas of the United States.

Climate change will modify the distributions of many introduced species. Rather than simply enhancing invasion risk, climate change may also reduce invasive plant competitiveness if conditions become climatically unsuitable. The great majority of introduced species do not survive. Many fail because the climate is unsuitable at their points of arrival. In some areas, currently invaded lands may also become climatically unsuitable, creating potential retreat areas which may provide opportunities for ecological restoration. Further, although community and ecosystem impacts of invasive plants may be initially strong because of their novel traits and strengthen through selection, they may not be sustained in the longer term as decomposers, herbivores, and pathogens in the invaded range adapt. Thus, a changed climate will lead to a different mix of surviving and failing species. Plants with C3 photosynthetic biochemistry that grow in habitats that are dominated by plants with C4 biochemistry may gain a competitive advantage with an increase in CO2, even though there is no clear link between CO2-responsiveness and invasiveness.

Key Terms in this Section

Eradication: complete removal of all individuals of a distinct population

Introduced species or population: a species or population that arrives at a specific location with intentional or accidental human assistance

Invasive species or population: an introduced species or population that spreads and maintains itself without human assistance

Sources: Simberloff et al. (2012)

2111 Verbatim from Dale et al. (2008, p. 727)
2112 Verbatim from Dale et al. (2008, p. 727)
2113 Verbatim from Dale et al. (2008, p. 727)
2115 Verbatim from Dale et al. (2008, p. 727)
2116 Verbatim from Bradley et al. (2009, p. 1511). Climate change and plant invasions: restoration opportunities ahead?
2118 Verbatim from Dale et al. (2008, p. 728)
2119 Verbatim from Bradley et al. (2009, p. 1512). Bradley et al. refer the reader to Figure 1c in the cited article for this information.
2120 Verbatim from Wardle et al. (2011, p. 1273, 1275). Terrestrial ecosystem responses to species gains and losses. Wardle et al. cite Lankau et al. (2009) for this information.
2121 Verbatim from Dale et al. (2008, p. 728)
Observed Trends

Western North America

Eurasian forbs in the genus *Centaurea* are the most abundant invasive plants in the western U.S., covering over 17 million acres (7 million hectares, ha) (7 million acres, or 3 million ha in California). Collectively known as knapweeds and star-thistles, 12 *Centaurea* species are listed as noxious in at least one U.S. state (5 species account for most of the damage). Although these species are usually associated with grasslands, they also affect forest ecosystems, particularly in open areas and after fire or other disturbances.

Yellow star-thistle became established in western North America in the mid-1800s and now infests more than 9.9 million acres (4 million ha), primarily in California, Oregon, Idaho, and Washington. Yellow star-thistle infests annual and perennial grasslands, shrub steppe, oak savannas, open woodlands, and modified habitats such as pastures, hayfields, orchards, and vineyards. Climatically suitable habitat currently includes much of California, eastern Oregon, and parts of eastern Washington. Analysis indicates the distribution of yellow star-thistle in the western United States is most constrained by summer precipitation, spring precipitation, winter minimum temperature, and spring minimum temperature. Yellow star-thistle has a strong growth and competitive response to elevated carbon dioxide. In one study, its aboveground biomass increased more than sixfold in response to elevated CO₂, which allowed it to compete aggressively with native species, although supplemental precipitation reduced its establishment in the field.

Southcentral and Southeast Alaska

A beetle induced die-off of white spruce trees in the Copper River Basin, improved habitat for some birds but reduced the densities of the ruby-crowned kinglets and red squirrels.

Alaskan forests are becoming increasingly susceptible to non-native plant invasions as the climate warms and the amount of land disturbance (anthropogenic and natural) increases, which could collectively promote the establishment of invasive plant species into remote regions of Alaska. The rate of new introductions of exotic plant taxa has increased from roughly one to three species per year (1941–1968 and 1968–2006, respectively). Table 30 provides additional information on invasive plant species in.

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2123 Verbatim from Ryan et al. (2012, Box 2.5, p. 30)
2124 Verbatim from Ryan et al. (2012, Box 2.5, p. 30)
2125 Verbatim from Ryan et al. (2012, Box 2.5, p. 30)
2127 Verbatim from Roché & Thill (2001, p. 439)
2128 Verbatim from Bradley et al. (2009, p. 1514). Bradley et al. refer the reader to Figure 2a in the cited article for this information.
2129 Verbatim from Bradley et al. (2009, p. 1514)
2130 Verbatim from Ryan et al. (2012, Box 2.5, p. 30). Ryan et al. cite Dukes et al. (2011) for this information.
2131 Verbatim from Ryan et al. (2012, Box 2.5, p. 30). Ryan et al. cite Dukes et al. (2011) for this information.
2132 Verbatim from Kelly et al. (2007, p. 54). Kelly et al. cite Matsuoka et al. (2001) for this information.
2133 Verbatim from Wolken et al. (2011, p. 3). Wolken et al. cite Villano & Mulder (2008) for this information.
2134 Verbatim from Wolken et al. (2011, p. 3). Wolken et al. cite Carlson & Shephard (2007) for this information.
Alaska’s coastal temperate rainforest region and ecological implications expected to increase with projected changes in climate.

**Western British Columbia**

The 18 or so species of European earthworms invading B.C.’s forests, which since Pleistocene glaciation have retained a very few native species of earthworms, show how introduced species can profoundly change ecosystems.2135 These earthworms have changed the way nutrients cycle, leading to a change in community composition and reducing abundance of understory plants.2136 For more information on earthworms and climate change, please see Chapter VIII.3.

**Western Washington**

*Information needed.*

**Western Oregon**

Several non-native, mammalian species have become widespread in uplands in the Willamette Valley.2137 Eastern gray-squirrels and the house mouse have been reported to occur primarily in urban areas, whereas the eastern cottontail and Virginia opossum are common throughout the Willamette Valley, particularly in shrubby vegetation, including within oak and prairie habitats.2138 Non-native bird species that commonly occur in prairie and oak habitats of the Willamette Valley include wild turkey, ring-necked pheasant, and European starling.2139 Nonnative plants make up more than half of the total vegetation in the riparian zone of the Willamette River mainstem.2140

Comparing native and non-native plant growth, Hebel et al. (2009) investigated the chemical and biotic factors associated with severely burned ‘‘red’’ soil and less severely burned ‘‘black’’ soil from a recently burned forest on the eastern slope of the Cascade Range in Oregon.2141 The study revealed red soils were highly nutrient-limited and exhibited reduced microbial abundance, arbuscular mycorrhizal (AM) fungal propagules, and plant growth.2142 The findings suggest that some native species may out-compete non-native species in low-resource environments, such as severely burned red soil, where organic matter, soil nutrients and soil microbes are reduced by severe soil heating.2143 For additional information on nutrient limitation and microbial abundance, please see Chapter V.2.

2137 Verbatim from Vesely & Rosenberg (2010, p. 16)
2139 Verbatim from Vesely & Rosenberg (2010, p. 18)
2141 Nearly verbatim from Hebel et al. (2009, p. 150)
2142 Nearly verbatim from Hebel et al. (2009, p. 158)
2143 Verbatim from Hebel et al. (2009, p. 150)
Northwest California

Yellow star thistle is an annual forb that dominates California grasslands and has become a serious agricultural pest, particularly due to its use of water resources.\textsuperscript{2144} Yellow star thistle was accidentally introduced as a seed contaminant in the mid-1800s.\textsuperscript{2145}

Future Projections

Western North America

Predictive models project various changes in the range of Centaurea species (i.e., knapweeds and star-thistles) in a warmer climate.\textsuperscript{2146} Broennimann and Guisan (2008) projected a northern shift and reduced invasion extent for spotted knapweed by 2080 using the hot, dry HadCM-A1FI scenario (baseline not provided), but Bradley et al. (2009) suggested that the distribution of yellow-star thistle was likely to increase in a warming West.\textsuperscript{2147} Specific results from Bradley et al. (2009) include:

- **Invasion risk and restoration potential:** Climate change is likely to expand invasion risk from yellow star-thistle to include more of California and Nevada (2090-2100 vs. 1970-2000 run with 10 AOGCMs under A1B).\textsuperscript{2148} Lands currently occupied by invasive populations of yellow star thistle in California, Oregon, and Washington have low potential for restoration (Figure 64).\textsuperscript{2149}

- **Climatic suitability of land for invasion:** Of the currently invaded lands, only 1% are no longer climatically suitable by 2100 in any of the 10 AOGCMs tested by Bradley et al. (2009).\textsuperscript{2150} Eighty-eight percent (88%) of currently invaded lands maintained climatic suitability in five or more of the 10 AOGCMs.\textsuperscript{2151}

Southcentral and Southeast Alaska

Projected increases in temperature in boreal forests in southcentral and Kenai Peninsula, Alaska will likely increase the probability of establishment of invasive plant species.\textsuperscript{2152} Several invasive plant species in the coastal temperate forest region of Alaska could reduce the growth and density of native species via competition and alter forest structure and function, and salmon habitat (Table 30).\textsuperscript{2153}

\begin{itemize}
  \item Verbatim from Bradley et al. (2009, p. 1512). Bradley et al. cite DiTomaso (2000) and Pitcairn et al. (2006) for this information.
  \item Verbatim from Bradley et al. (2009, p. 1512)
  \item Nearly verbatim from Ryan et al. (2012, Box 2.5, p. 30)
  \item Nearly verbatim from Ryan et al. (2012, Box 2.5, p. 30)
  \item Verbatim from Bradley et al. (2009, p. 1514). Bradley et al. refer the reader to Figure 2b in the cited article for this information. Note: The 10 AOGCMs used in the study are CCCMA-CGCM3.1, CNRM-CM3, GFDL-CM2.1, GISS-AOM, INM-CM3, IPSL-CM4, MIROC3.2(hi-res), MPI-ECHAM5, NCAR-CCSM3, and UKMO-HadCM3.
  \item Verbatim from Bradley et al. (2009, p. 1514-1515). Bradley et al. refer the reader to Figure 2c in the cited article for this information.
  \item Nearly verbatim from Bradley et al. (2009, p. 1515)
  \item Nearly verbatim from Bradley et al. (2009, p. 1515). Bradley et al. refer the reader to Table 1 in the cited article for this information.
  \item Verbatim from Staudt et al. (2012, p. 5-15). Staudt et al. cite Wolken & others (2011) for this information.
  \item Nearly verbatim from Wolken et al. (2011, p. 18). Wolken et al. refer the reader to Table 3 in the cited article for this information.
\end{itemize}
Western British Columbia

Information needed.

Western Washington

Information needed.

Western Oregon

Information needed.

Northwest California

Information needed.

Information Gaps

Invasion biology is not yet adept at forecasting impacts of invasions.\textsuperscript{2154} The complex interactions among introduced species, native communities, managed and intensely harvested forests, and climate change compound this forecasting problem.\textsuperscript{2155}

\textsuperscript{2154} Verbatim from Dale et al. (2008, p. 727). Dale et al. cite Williamson (1999) for this information.

\textsuperscript{2155} Verbatim from Dale et al. (2008, p. 727). Dale et al. cite Simberloff (2000) for this information.
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Table 30. Invasive plant species in Alaska’s coastal temperate forest region and ecological implications expected to increase with projected changes in climate.

<table>
<thead>
<tr>
<th>Invasive Plant</th>
<th>Ecological implications</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garlic mustard</td>
<td>Invades urban forest understory; could eliminate native species through competition and/or allelopathy (i.e., chemical inhibition of one plant by another through the release of germination or growth inhibitors)</td>
<td>Meekins &amp; McCarthy (1999), Prati &amp; Bossdorf (2004), Lamb &amp; Shepard (2007)</td>
</tr>
<tr>
<td>Knotweed complex</td>
<td>Found along roadsides, stream banks, and beach meadows; reduces nutrient quality of litter input to aquatic habitats; could depress cover and density of native species and change forest structure and function of riparian forests and aquatic habitats</td>
<td>Lamb &amp; Shepard (2007), Urgenson et al. (2009)</td>
</tr>
<tr>
<td>Orange hawkweed*</td>
<td>Spreads vegetatively and by seed; forms monospecific stands and displaces native vegetation; currently spreading into meadows and open areas where it has escaped cultivation</td>
<td>Lapina &amp; Carlson (2004), IWAC (2006)</td>
</tr>
<tr>
<td>White sweetclover*</td>
<td>Spreads aggressively; invades heavily burned areas; decreases survival and pollination of native plants; alters primary succession on glacial floodplains by modifying nitrogen status</td>
<td>Cortes-Burns et al. (2008), Conn et al. (2008), Spellman (2008), Villano &amp; Mulder (2008)</td>
</tr>
<tr>
<td>European mountain ash</td>
<td>Escaped from ornamental plantings; now a dominant species of coastal rainforest plant communities</td>
<td>Dickinson &amp; Campbell (1991), Rapp (2006)</td>
</tr>
</tbody>
</table>

*Orange hawkweed is also found in the southcentral boreal forest region of Alaska. White sweetclover is also found in the interior boreal and southcentral boreal forest regions of Alaska.

Source: Modified from Wolken et al. (2011, Table 3, p. 14) by authors of this report.