Chapter 9

Temperate forests

Emily Fusco[1], Jessica E. Halofsky[2], Matthew Reilly[3], Holly R. Prendeville[4] and Rita Sousa-Silva[5]

[1]U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Olympia, WA, United States, [2]Northwest Climate Hub and Western Wildland Environmental Threat Assessment Center, U.S. Department of Agriculture of Forest Service, Pacific Northwest Research Station, Olympia, WA, United States, [3]Western Wildland Environmental Threat Assessment Center, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Corvallis, OR, United States, [4]Northwest Climate Hub and Western Wildland Environmental Threat Assessment Center, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, United States, [5]Young Academy for Sustainability Research, Freiburg Institute for Advanced Studies, University of Freiburg, Freiburg im Breisgau, Baden-Württemberg, Germany

Introduction

Temperate forests make up approximately 16% of the world's forest biome (Hansen, Stehman, & Potapov, 2010), and areas of high human population density are found in the temperate biome. While climate change is an imminent threat to the continued health and utility of these forests, adaptation and mitigation actions can reduce the negative effects of climate change and help ensure the continued provision of ecosystem services. However, to effectively employ adaptation and mitigation options, we must first understand what shapes temperate forests and assess potential climate change impacts.

Temperate forest ecosystems encompass a range of climates globally but are generally characterized by a cyclical annual climate with well-defined seasons (Gilliam, 2016). They can be either coniferous- or broadleaf-dominated (Table 9.1) and are typically between 20° and 60° latitude (Gilliam, 2016). Most temperate forests are in the northern hemisphere; in the southern hemisphere, they are limited in geographic extent (Fig. 9.1) and tend to have maritime temperate climates (Gilliam, 2016). Recent historical temperatures (1850−1900) have significantly varied across temperate forest regions, with average minimum temperatures as low as 0 °C in western North America to average maximum temperatures as high as 18.7 °C in Australasia. Mean annual precipitation has also varied from an average of 2.1 mm day^{-1} in Europe to 5.4 mm day^{-1} in South America (Table 9.2).

Globally, dense settlements and villages make up approximately 21% and 28% of evergreen, and deciduous temperate forest biomes, respectively (Ellis, Klein Goldewijk, Siebert, Lightman, & Ramankutty, 2010), and societies around the world rely on the many ecosystem services temperate forests provide. Ecosystem services are broadly defined as the benefits people receive from the environment and include four broad categories: provisioning, regulating, cultural, and supporting (Millennium Ecosystem Assessment Program, 2005). Some ecosystem services provided by temperate forests include timber and nontimber goods (provisioning), carbon sequestration and flood regulation (regulating), recreation and indigenous connection to place (cultural), and soil formation (supporting) (Galicia & Zarco-Arista, 2014; Kovats et al., 2014; Vose et al., 2018; Xie et al., 2010). These ecosystem services have become a major consideration in forest management decisions (Millar & Stephenson, 2015).

This chapter aims to describe key climate change vulnerabilities in temperate forests, review the potential effects of climate change on ecosystem services provided by temperature forests, and highlight adaptation options to address climate change vulnerabilities. We do this by exploring the past climate and land use drivers of temperate forest distribution and composition, modern-day human and climate change impacts, and the potential future of temperate forests to the year 2100, under moderate future climate change scenarios. We focus on trees, as they are the defining vegetation of the forested biome.

Future Forests. DOI: https://doi.org/10.1016/B978-0-323-90430-8.00007-1
Copyright © 2024 Elsevier Inc. All rights reserved.
Jessica E. Halofsky, Matthew Reilly, Holly R. Prendeville's Contribution is in public domain.

TABLE 9.1 Prominent disturbance agents, land use legacies, and tree genera in temperate forest regions of the world.

Region	Major disturbance agents	Land use legacies	Dominant shade-intolerant genera	Dominant shade-tolerant genera
Inland Western NA	Fire, insects	Fire exclusion, logging	*Pinus, Juniperus, Larix, Populus*	*Abies, Tsuga, Psuedotsuga, Picea*
Coastal Western NA	Fire, wind, pathogens	Logging	*Pseudotsuga, Alnus, Acer*	*Picea, Thuja, Abies, Sequoia, Notholithocarpus*
Eastern NA	Fire, hurricanes, insects, acid rain	Fire exclusion, agriculture, logging	*Pinus, Quercus, Liriodendron, Betula, Prunus, Magnolia*	*Acer, Fagus, Fraxinus, Tsuga, Picea, Abies*
South America	Fire	Logging	*Nothofagus* spp.	
Europe	Fire, wind, insects, drought	Agriculture	*Quercus, Betula*	*Acer, Fagus, Ulmus, Picea, Abies*
Asia	Typhoons, insects, fire	Agriculture	*Quercus, Ulmus, Betula, Pinus*	*Tilia, Fraxinus, Castanopsis, Distylium, Acer, Abies, Larix, Sabina, Tsuga, Picea*
Australia/ Tasmania/New Zealand	Fire	Logging	*Eucalyptus, Acacia, Nothofagus*	

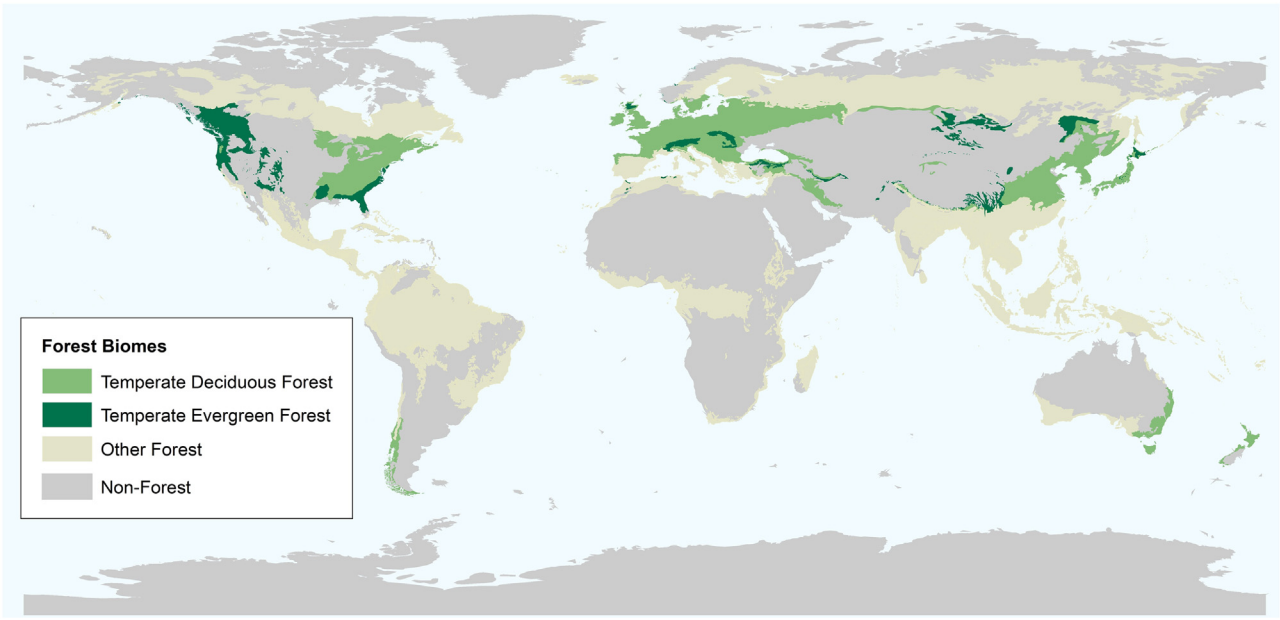

FIGURE 9.1 Evergreen and deciduous temperate forests are located across the globe. *Data from Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., . . . Kassem, K. R. (2001). Terrestrial ecoregions of the world: A new map of life on Earth.* Bioscience, 51*(11), 933–938.*

Past temperate forest development

The distribution and composition of contemporary temperate forests have been shaped by millennia of natural and anthropogenic influences. Our understanding of past forest ecosystems relies heavily on pollen, macrofossil, and

TABLE 9.2 Baseline climate (1850–1900) for temperate forests in six regions (Olson et al., 2001) based on CMIP6 (IPCC et al., 2021; Interactive Atlas. https://interactive-atlas.ipcc.ch/).

Region	Mean temperature (°C)	Maximum temperature (°C)	Minimum temperature (°C)	Average precipitation (mm day^{-1})
Western NA	3.8	8.8	0.0	3.0
Eastern NA	10.3	14.8	6.2	3.1
South America	7.1	10.8	5.9	5.4
Europe	7.7	11.5	3.7	2.1
Asia	5.1	9.4	0.1	2.7
Australasia	14.6	18.7	10.9	2.5

Temperatures are calculated as a mean of daily mean, maximum, and minimum near-surface air temperatures.

charcoal records, which can provide reconstructions of past plant species composition and fire regimes (Lindbladh, Fraver, Edvardsson, & Felton, 2013). Here we briefly discuss some abiotic influences and anthropogenic impacts to provide a foundation for understanding factors important in developing contemporary temperate forest landscapes.

Abiotic factors

Several natural disturbances and climatic forces have shaped temperate forest ecosystems. Over the last 120,000 years, the most recent glacial-interglacial cycle explains substantial fluctuations in the global distribution of temperate forests, with temperate forest expansion during warmer periods (Hoogakker et al., 2016). The Last Glacial Maximum (approximately 20,000 years ago) was the last time when the terrestrial surface was primarily covered in ice (Gilliam, 2016; Hoogakker et al., 2016), and the effects of past glacial events are still apparent in modern plant functional composition (Blonder et al., 2018).

Fire has also been a driving factor in temperate forests (Gilliam, 2016), and global fire regimes have varied with changing climate, human population density, and vegetation shifts (Power et al., 2008). Generally, fire has been more important in conifer-dominated than in most deciduous-dominated ecosystems (Gilliam, 2016). Significant disturbances, such as those resulting from fire, can lead to abrupt ecosystem conversion lasting thousands of years (Calder & Shuman, 2017).

In addition to past disturbances, climate factors, such as precipitation, can also be a major factor driving species composition (Zhu et al., 2010). For example, a study of vegetation dynamics in northern China during the Holocene, which began 12,000 years ago, suggested that changes in species composition were driven by monsoon development and differential responses of species to abiotic environmental changes (Liu, Yin, Hao, & Liu, 2014). Indeed, climate and disturbance together played a role in shaping ecosystems in many places. In eastern North America, combined influences from changing climate and fire likely led to changes in vegetation composition, from boreal species to hardwoods, over the past 8000 years (Payette, Pilon, Fregeau, Couillard, & Laflamme, 2021).

Anthropogenic influences

While climate and disturbances were the earliest drivers of temperate forest distribution and composition, an understanding of temperate forests must also incorporate more recent anthropogenic influences. Compared to other forested biomes (e.g., tropical and boreal), temperate forests have had a particularly long history of human land use and land cover conversion (Gilliam, 2016), with agriculture becoming an extensive land cover type in the temperate forest landscapes of Europe, Russia, and China long before North America or Australia (Gilliam, 2016; Stephens et al., 2019). These influences are so deeply embedded in ecological history that disentangling climate effects on forest composition can be difficult. For example, in Europe, periods of deforestation over the past 4000 years have been linked to anthropogenic influences (Novenko et al., 2019). In China, extensive forest alteration has been occurring for 6000 years (Gilliam, 2016).

Before European colonization, Indigenous peoples also managed temperate forest landscapes outside of Europe. One prominent example of Indigenous land management was the application of fire, which affected biodiversity, habitat heterogeneity, and fire regimes (Hoffman et al., 2021). Indigenous management had effects at both local and regional

scales. For example, the Hemish people managed the temperate ponderosa pine forests of southwestern North America near their settlements through fire and fuelwood collection, directly affecting local fire regimes for hundreds of years (Roos et al., 2021). Human impacts on fire regimes are also apparent before and after European colonization in eastern Canada (Blarquez et al., 2018). In the Pacific Northwest and northern California, indigenous burning affected regional-scale processes for thousands of years prior to European colonization, decoupling climate and fire, and maintaining culturally important species (e.g., *Quercus* species) (Crawford, Mensing, Lake, & Zimmerman, 2015; Walsh, Duke, & Haydon, 2018).

Indigenous land use impacts are not limited to those associated with fire. In the North American Pacific Northwest, forest gardens created and managed by Indigenous peoples were characterized by higher levels of plant diversity than surrounding unmanaged habitat more than 150 years after management, demonstrating a lasting positive effect of Indigenous land use on temperate forest biodiversity (Armstrong, Miller, McAlvay, Ritchie, & Lepofsky, 2021). The effects of Indigenous land management are less apparent in South America's temperate forests, where vegetation composition had been relatively stable for thousands of years until European colonization (Villa-Martínez & Moreno, 2021). Indigenous people still manage or have tenure rights over a substantial portion of temperate forest ecosystems (Garnett et al., 2018).

Contemporary temperate forests

While distinguishing between the effects of anthropogenic and natural disturbances has become increasingly difficult (Ghazoul, Burivalova, Garcia-Ulloa, & King, 2015), we focus here on understanding how recent anthropogenic land use is a key factor in determining the distribution and health of modern temperate forests. Thousands of years of human land use and management in temperate forests have shaped the template upon which decisions for future management will be based. This legacy of past management has left different landscapes better or maladapted for the future. Human land use impacts in temperate forests include clearing land for crops, pasture, or settlements, timber harvest, and recreation. These uses can result in the degradation of forest health and negatively affect ecosystem services.

Historically, temperate forest loss was often driven by agricultural use, and in some cases, forest cover and agricultural cover have directly opposed one another (Miao et al., 2013). This is evident when agricultural land is abandoned, resulting in forest regrowth (Barbier, Burgess, & Grainger, 2010). However, in recent years (2001−2015), global disturbance-driven temperate forest loss has been largely attributed to forest harvest, though this loss is typically not permanent (Curtis, Slay, Harris, Tyukavina, & Hansen, 2018). As we enter an era of climate change, we must consider how human land use shapes modern ecosystems. To provide this context, we describe a range of recent human land use impacts in three distinct temperate forest regions: New England, United States, Chile, and Japan.

In New England (northeastern United States), European colonization was extensive by the late 18th to mid-19th centuries, and the landscape experienced large-scale deforestation to clear land for agriculture (Fischer, Marshall, & Camp, 2013; Foster, 1992) (Fig. 9.2A). Most farms were abandoned by the late 19th century, and forest regeneration began

FIGURE 9.2 Temperate forests of New England (northeastern United States) were primarily cleared for agriculture by 1830 (A), followed by large-scale farm abandonment by 1850 (B). *All works are licensed for use under the Creative Commons attribution CC BY-ND. The license allows for redistribution, commercial and non-commercial, as long as it is passed along unchanged and in whole, with credit to Harvard Forest.*

(Fischer et al., 2013; Foster, 1992) (Fig. 9.2B). As a result, the forested landscape was largely homogenized, and most forested areas in New England are now secondary growth. Today, much of the region is forested. However, urbanization is a more recent driver of deforestation trends (Fischer et al., 2013), and some forested areas in northern New England are considered degraded for silviculture potential (e.g., commercial desirability) (Gunn, Ducey, & Belair, 2019).

Human land use impacts also include planting nonnative species for forest products. For example, in Chile, nonnative pine plantations were established during the mid-20th century (Toro & Gessel, 1999). Today, the conversion of native forests to plantations is a major driver of land use change (Zamorano-Elgueta, Benayas, Cayuela, Hantson, & Armenteras, 2015). Nonnative pines (e.g., *Pinus radiata*, *Pinus contorta*) have invasive potential, escaping plantations and establishing in nearby landscapes. Although they are most likely to invade grasslands and disturbed areas (Curtis, Pasquarella, & Bradley, 2019), they also impact native temperate forests, outcompeting native tree species (Peña, Hidalgo, Langdon, & Pauchard, 2008) and altering fire regimes by increasing vertical fuel continuity and fire severity (Cóbar-Carranza, García, Pauchard, & Peña, 2014). Today, nonnative pine plantations are extensive across southern Chile (Curtis et al., 2019; Zamorano-Elgueta et al., 2015). However, some native forest regeneration in abandoned agricultural areas has mitigated native forest loss (Zamorano-Elgueta et al., 2015).

In Japan, forest cover has remained relatively stable over the past 150 years at approximately 60% (Shoyama, 2008; Shoyama et al., 2019; Spake et al., 2019). However, modern management practices have affected the composition of Japan's temperate forests. After World War II, many of Japan's temperate deciduous forests were replanted as coniferous plantations to meet timber demand (Miyamoto & Sano, 2008). By the 21st century, two-thirds of Japan was still forested, but only about 17% of the total land area was considered natural forest (Shoyama et al., 2019). While old-growth forests are typically considered a conservation priority, management in second-growth and plantation forests can be conducted to enhance biodiversity and ecosystem services (Spake et al., 2019). As a result, today, most regional and national forest plans in Japan manage for both ecological and forestry priorities (Nagaike, 2020).

Modern land use impacts across temperate forest ecosystems have led to substantial changes in forest composition through uses, including agricultural clearing and farm abandonment, planting of native and nonnative timber plantations, and more recently, urbanization and recreation. In addition to these direct land use influences, people also affect temperate forest landscapes through anthropogenic climate change.

Early climate change impacts

Temperature and precipitation trends

Temperate forest ecosystems have experienced warming over the last several decades. As described in Chapter 3 (this volume), the mean annual temperature has increased by 0.21 °C per decade between 1961 and 2015 across temperate forest ecosystems (Iturbide et al., 2021). However, warming trends have varied geographically and seasonally. The most significant temperature increases in most regions have occurred in winter. Across the globe, the surface temperature increased by 1.09 °C in 2011−20 compared to 1850−1900, and heatwaves have become more frequent and intense with recent warming (IPCC, 2021).

Mean annual precipitation has increased slightly across temperate forests (by 0.003 mm day^{-1} decade^{-1} between 1961 and 2015) (Iturbide et al., 2021), and across areas for which there are sufficient data for analysis, heavy precipitation events have increased in frequency and intensity since the 1950s (IPCC et al., 2021). Precipitation trends vary by season and geographic region (see Chapter 3 for more detail). For example, temperate forests in Europe have seen slight increases in precipitation across seasons. In contrast, temperate forests in western North America have experienced slight declines in precipitation in all seasons except spring. However, slight increases in precipitation do not preclude drought, especially with temperature increases.

Observed effects of warming on phenology and species distribution

Plant species in ecosystems worldwide have begun to respond to warming over the last several decades through alteration of phenology, or seasonal timing of life history stages (Menzel et al., 2020; Parmesan, 2006; Piao et al., 2019; Root et al., 2003). Recent studies have shown an earlier onset of spring as well as delays in the end date of autumn, indicating that the growing season length is increasing (Menzel et al., 2020; Piao et al., 2019). For example, in Europe, a meta-analysis that included over 500 plant species showed significant advances in spring phenological events, while changes to autumn leaf coloring were less apparent (Menzel et al. 2006). If plants and animals respond differently to environmental cues with climate change (e.g., air temperature, winter chilling), there may be mismatches in the timing

of life-history events (Renner & Zohner, 2018). For example, shifts in leaf emergence in trees and shrubs and insect phenology could alter insect outbreak cycles in a warming climate. Although empirical evidence of phenological mismatches related to insects with recent climatic warming is limited (Renner & Zohner, 2018), phenological mismatches have been demonstrated for understory wildflowers in the northeast United States (Heberling, McDonough MacKenzie, Fridley, Kalisz, & Primack, 2019).

With warming over the last several decades, studies have documented latitudinal and elevational shifts in species distribution, some of which have involved movement to higher elevations or poleward (Boisvert-Marsh, Périé, & de Blois, 2014; Chen, Hill, Ohlemüller, Roy, & Thomas, 2011; Kelly & Goulden, 2008; Lenoir, Gégout, Marquet, De Ruffray, & Brisse, 2008; Parmesan & Yohe, 2003; Parmesan, 2006; Savage & Vellend, 2015). Some studies have also documented a shift of temperate forest ecosystems into the boreal zone (Evans & Brown, 2017). However, species responses have been complex, and other studies have documented species movement to lower elevations (or no shift) (Crimmins, Dobrowski, Greenberg, Abatzoglou, & Mynsberge, 2011; Evans & Brown, 2017).

Disturbance trends

Drought is a natural occurrence that plays a major role in limiting species' distributions worldwide and is a major disturbance in temperate forests. Droughts can occur slowly, after many months to years with no or extremely low precipitation, or can occur rapidly, after weeks of high temperatures and limited precipitation (flash drought) (Otkin et al., 2018). Ecological drought is the most relevant to temperate forests, as this disturbance pushes ecosystems and services beyond their adaptive capacity, resulting in socio-ecological feedback (Crausbay et al., 2017). Ecological drought is assessed by precipitation levels, soil moisture, evapotranspiration, and vegetation health (Crausbay et al., 2017; IPCC et al., 2021). In some regions, particularly areas with temperate forests such as western North America, much of Europe, East Asia, and southern Australia, climate change has resulted in increased observed ecological droughts due to increases in evapotranspiration with warmer temperatures (IPCC et al., 2021).

Tree mortality events have been linked to drought in temperate forests around the world (as summarized in Allen et al., 2010; Allen, Breshears, & McDowell, 2015), including temperate forests in South America (Suarez & Kitzberger, 2008) and in several different regions of Europe (e.g., Bréda, Huc, Granier, & Dreyer, 2006; Carnicer et al., 2011; Čater, 2015; Dobbertin et al., 2005; Schuldt et al., 2020; Senf, Buras, Zang, Rammig, & Seidl, 2020; Solberg, 2004). Drought-related tree mortality and the frequency of some drought-related disturbance events have increased in recent decades (Allen et al., 2010, 2015). However, natural variability accounts for most observed droughts (Williams et al., 2015). Extreme-duration drought has increased in the western United States over the last 40 years, with increases in dry intervals between precipitation events (Zhang et al., 2021). In addition to tree mortality, drought stress has been shown to reduce tree growth and result in the dieback of temperate forest species (Bréda et al., 2006; D'Orangeville et al., 2018), and drought events have been linked to decreases in net primary productivity globally (Zhao & Running, 2010) and regionally (Zhang et al., 2012).

Trees stressed by drought and higher temperatures (i.e., hotter droughts) are more susceptible to damage from some native and invasive insects and pathogens. For example, California's recent large-scale tree mortality event was attributed to severe drought and related insect damage (Young et al., 2017). Since 1990, western North America has experienced an extensive outbreak of mountain pine beetle (*Dendroctonus ponderosae*) across 20 million ha (Fig. 9.3A). This large outbreak has been attributed to warming temperatures, in combination with the susceptibility of large areas of older, low-vigor lodgepole pine (Bentz et al., 2010; Hicke, Logan, Powell, & Ojima, 2006; Logan, Régnière, & Powell, 2003), and it has also caused mortality in some ponderosa pine forests (Fettig, Gibson, Munson, & Negrón, 2014). In Europe, recent impacts from bark beetles have been linked to increases in drought and heat stress (Marini et al., 2017). Wind is also a significant disturbance in some temperate forests (Fig. 9.3B), and synchronous outbreaks of bark beetles in temperate forests of central Europe have been attributed to drought and wind events (Senf & Seidl, 2018). Overall, combined effects from disturbance will likely lead to increased tree stress and mortality in most temperate forest regions (Millar & Stephenson, 2015).

Recent trends in the amount of area burned vary among temperate forest regions (Andela et al. 2017; Hislop et al. 2020). Fire activity in forests of the western United States has increased since the early 1980s with increasing vapor deficits (Fig. 9.3C) (Higuera & Abatzoglou, 2021) and recently expanded in higher elevation forests due to warming (Alizadeh et al., 2021). Temperate rainforests in Australia, Patagonia, and the West Coast of the United States have all experienced large fires driven by extreme downslope winds in recent years (Abram et al., 2021; Higuera & Abatzoglou, 2021; McWethy, Garreaud, Holz, & Pederson, 2021). Trends in the area burned have been relatively stable in deciduous forests of Asia and central and northern Europe (Andela et al. 2017), although nonfire-prone areas in central and

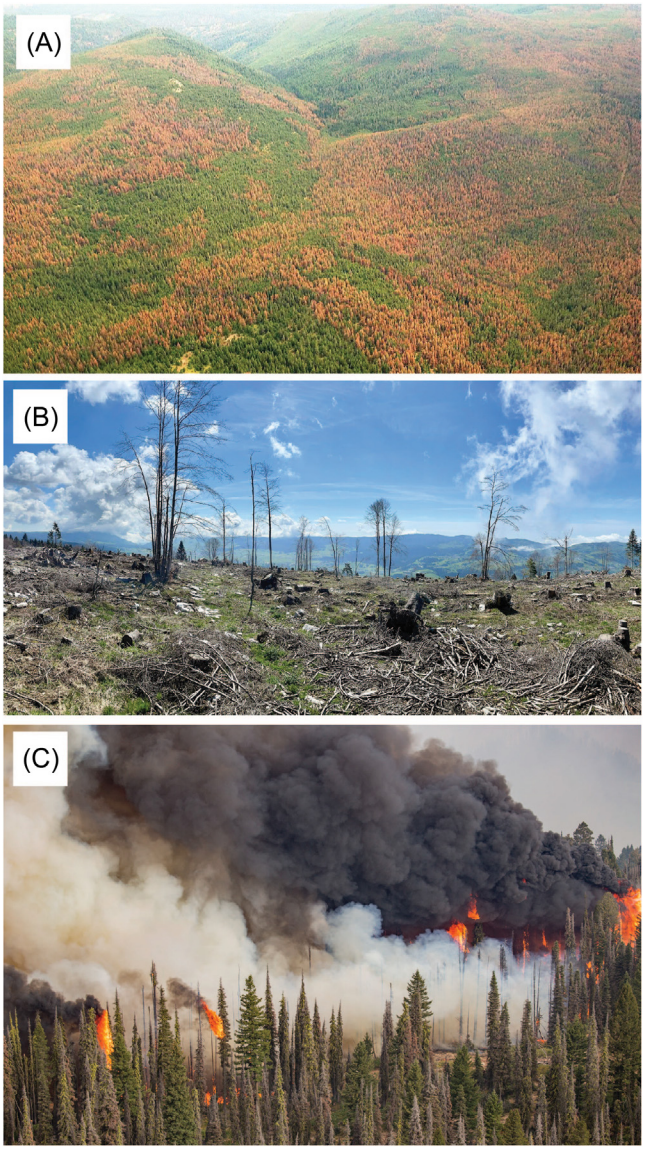

FIGURE 9.3 (A) Tree mortality from mountain pine beetle, indicated by the brown trees, is present in the Blue Mountains, Oregon, United States, in 2015. (B) Wind disturbance topples trees in Italy during the 2018 Vaia storm. (C) The Pioneer Fire in Boise National Forest, Idaho, United States, where low late-summer precipitation in 2016 facilitated fire spread to more than 25,000 ha. *(A): USDA Forest Service, Region 6, State and Private Forestry, Forest Health Protection, Central Oregon Insect and Disease Service Center by Rob Flowers. (B): Marco Mina. (C): Forest Service photo by Kari Greer.*

northern Europe have seen more fire in recent decades (European Environment Agency, 2021). Despite some large fire years with exceptionally high area burned, Mediterranean portions of southern Europe have experienced a slightly decreasing trend in area burned between 1985 and 2011, primarily due to fire management and exclusion efforts (Turco et al., 2016). Similarly, the eastern United States has seen limited increases in wildfire activity, except for a few extensive fires in the Coastal Plain conifer forests and the 2016 wildfire event in mixed hardwood-conifer forests of the southern Appalachians, which was driven by severe drought in late fall (Williams et al., 2017).

Projected effects of climate change on temperate forest ecosystems

Projected changes in temperature and precipitation

There is high confidence that climate change will result in increased global temperatures (IPCC et al., 2021). It is likely that global warming of 1 °C−2 °C will occur during the 21st century without significant greenhouse gas mitigation in the next several decades. Under a very high greenhouse gas emissions scenario (SSP5-8.5), average global surface temperatures may increase by 3.3 °C−5.7 °C by the end of the century (compared to 1850−1900) (IPCC et al., 2021). In temperate forest regions, Europe and West Central Asia are projected to warm the most by the end of the century, with

increases in temperature of 5.6 °C and 6.2 °C, respectively, under the SSP3-7.0 emissions scenario. Central Asia is expected to warm the most by the end of the century, warming by 6.2 °C. South America is projected to warm the least by the end of the century (3.7 °C under the SSP3-7.0 emissions scenario) (Fig. 9.4). With temperature increases, heat extremes and heatwaves will likely increase in frequency and intensity, as will heavy precipitation events and ecological droughts (IPCC et al., 2021).

Precipitation changes are more uncertain than those for temperature because of uncertainty in projecting changes in the large-scale circulation that affects the formation of clouds and precipitation (Shepherd, 2014). At a broad scale, precipitation is projected to increase for North America, Europe, and Central Asia, and precipitation decreases are projected for South America and Australia (relative to the 1850−1900 baseline; see Chapter 3), but projections vary regionally. South America is projected to have the most significant percent decrease in precipitation (−11.4%). However, across much of the temperate forest biome (even in many areas projected to receive more precipitation), soil moisture is projected to decrease with increased temperatures and increased evapotranspiration (IPCC et al., 2021).

Disturbances

Drought

Drought severity, frequency, and duration are projected to increase with higher temperatures. As a result, ecological drought is projected to increase in areas with temperate forests, including western and central North America, southwestern South America, western and central Europe, the Mediterranean, and eastern and southern Australia (IPCC et al., 2021). Climate projections indicate that droughts will occur in conjunction with higher temperatures, resulting in hotter droughts. Hotter droughts are expected to have greater direct and indirect impacts on forests than historically cooler droughts (Allen et al., 2015; Millar & Stephenson, 2015). Even with above-normal precipitation, temperature increases will result in an exponential increase in atmospheric water demand and vapor pressure deficit (a key metric of forest drought stress) (Breshears et al., 2013; Williams et al., 2013).

In temperate forests, drought impacts are not consistent. Drought vulnerability varies among species (Blackman, Brodribb, & Jordan, 2009; Camarero, Colangelo, Gazol, & Azorín-Molina, 2021; Nardini, Battistuzzo, & Savi, 2013; Negret, Pérez, Markesteijn, Castillo, & Armesto, 2013), and generally, deciduous trees are more sensitive to drought than conifers (Choat et al., 2012). In Mediterranean forests, the sensitivity of tree species to drought located in the same region

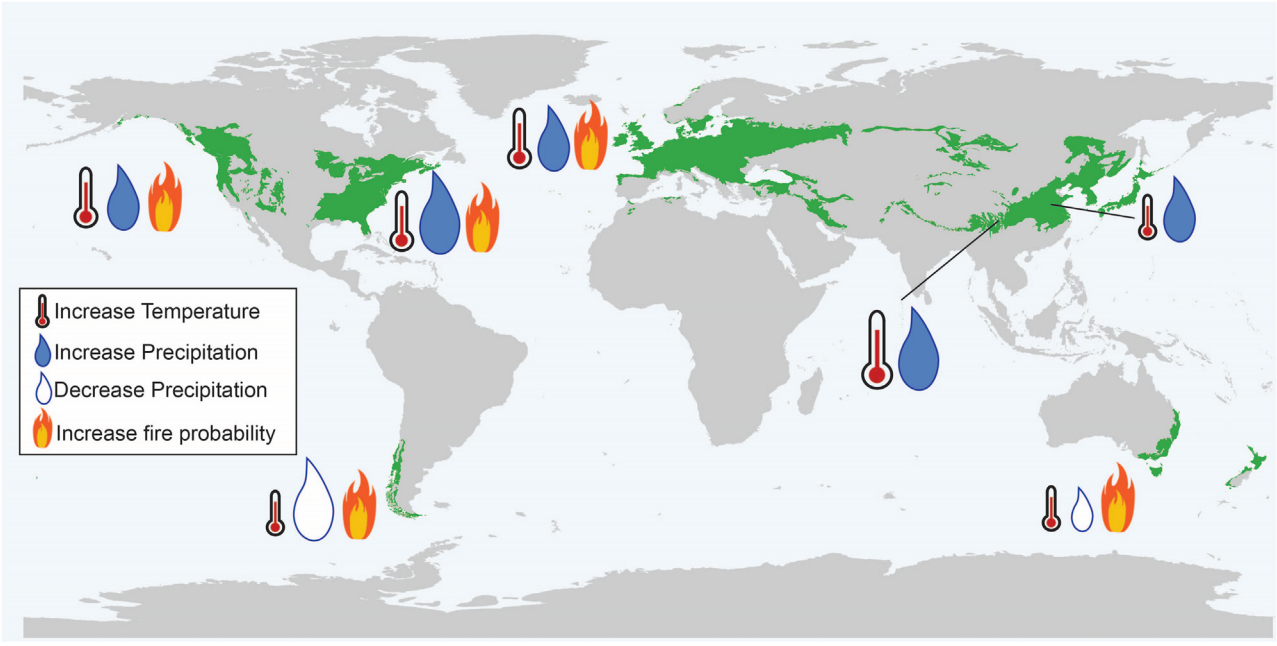

FIGURE 9.4 Projections for temperature, precipitation, and fire changes vary across temperate forests (green). Temperature and precipitation indicate projected percent change from an 1850−1900 baseline scenario (see Chapter 3). Fire projections are based on published studies included in this chapter (but there were too few studies from China to include a projection for fire). The size of each symbol indicates how much that climate factor will change relative to other regions.

was dependent on microclimates, with trees on dry sites being more sensitive than those in wet sites (Gazol et al., 2020). Similarly, there was greater mortality after an extreme drought in California in hotter and drier areas (Young et al. 2017). Droughts may also negatively affect the ability of forest microclimates to provide buffers to extreme climatic events in cases where soil moisture is reduced (Davis, Dobrowski, Holden, Higuera, & Abatzoglou, 2019).

Fire

Future increases in fire activity (e.g., area burned, fire size) are anticipated in many temperate forest regions as climatic conditions warm, and droughts become more common (Clark, Mills, Brown, Harris, & Abatzoglou, 2021; De Rigo, Libertà, Durrant, Vivancos, & San-Miguel-Ayanz, 2017; Gao et al., 2021; Krawchuk, Moritz, Parisien, Van Dorn, & Hayhoe, 2009; Liu, Stanturf, & Goodrick, 2010). Most studies rely on statistical models of recent fire activity, and project changes in different aspects of fire or the fire environment at global or regional scales. These studies assume that the primary pathway to change will be based on climate alteration of fuel aridity as the relationships among climate, fuel, and fire activity are well established by studies of recent fires. However, changes in these relationships, and variation across scales, may lead to differing short- and long-term effects on fire regimes (Kennedy, Bart, Tague, & Choate, 2021). In addition, changes in ignition sources, suppression efforts, and characteristics of fuel and vegetation are less certain but will play an essential role in future fire activity (Syphard, Sheehan, Rustigian-Romsos, & Ferschweiler, 2018). Projections for future fire severity are also less specific, as most studies do not include changes in fuel amount or potential shifts in vegetation that may result in alteration of recent fire regimes.

Seasonally dry forests of the western United States and Mediterranean regions of southern Europe are projected to experience the most significant increases in fire activity. Dry conifer forests of the inland western United States are projected to experience an increase in area burned (Littell, McKenzie, Wan, & Cushman, 2018), along with a 300% to 600% increase in the potential for wildfires larger than 5000 ha (Barbero, Abatzoglou, Larkin, Kolden, & Stocks, 2015). Also, in the western United States, warmer and drier conditions have contributed to an increase in area burned at high severity (Parks & Abatzoglou, 2020). However, live fuel is often a better predictor of fire severity in these regions than weather and climate (Parks et al., 2018). In Mediterranean parts of southern Europe, greater seasonal drought effects on fuel moisture and increased weather-driven forest fire danger is projected under RCP8.5 (De Rigo et al., 2017), along with a greater likelihood of heat-induced fires (Ruffault et al., 2020). In Greece, model results project risk of large wildfires that escape initial attack will increase under the A1B scenario (Kalabokidis et al., 2015). In Portugal, projections with the B1 scenario project an increase of 7% to 11% in the burned area by the middle and end of the 21st century, respectively (Pereira, Calado, DaCamara, & Calheiros, 2013).

Temperate rainforests in Australia, the Pacific Northwest, and western Patagonia are all expected to experience an increase in climatic conditions conducive to more fire activity in the future. The area burned in moist forests of the Pacific Northwest is projected to increase by 300%−500% (Mote et al., 2014), and mean fire return intervals are projected to decrease from 150 to 60 years under RCP8.5 (Gao et al., 2021). Results from a Dynamic Global Vegetation Model (MC2) agree on increases in fire frequency, and also suggest increased fire severity in moist forests of the Pacific Northwest (Rogers et al., 2011). In southeastern Australia and Tasmania, the Fire Weather Danger Index (FFDI) is projected to increase with longer fire seasons by 2100 under the A1 scenario (Clarke, Smith, & Pitman, 2011; Fox-Hughes, Harris, Lee, Grose, & Bindoff, 2014). A more recent study using RCP8.5 projected a 10%−20% increase in the FFDI with longer fire seasons in southeastern Australia (Clark et al., 2021). Future projections of fire activity in Patagonia are limited. However, wildfire activity is expected to increase based on projected changes in drought (González, Gómez-González, Lara, Garreaud, & Díaz-Hormazábal, 2018), which may be amplified by interactions among sea surface temperatures and regional wind patterns (Holz et al., 2017).

Temperate forests in eastern North America, northern Europe, and China have experienced less fire than those in other regions, and projections for the future vary. Gao et al. (2021) project a 75% to >125% increase in the probability of fire in the eastern U.S. under RCP8.5 due primarily to warmer temperatures. Conifer forests in the Coastal Plain of the southeastern U.S. are projected to experience a 500% increase in the potential for wildfires larger than 5000 ha. In comparison, forests of the southern Appalachians are expected to experience an increase of 75%−100% (Barbero et al., 2015). Moderate increases in fire danger are projected in central Europe compared to those in the southern Mediterranean parts of Europe, with little change in northern Europe under RCP8.5 (De Rigo et al., 2017). Projections of fire occurrence probability agree between RCP2.6 and 8.5, and show little change in the coming century, except for cooler mixed forests in northern Europe (Wu et al., 2020).

Invasive plants, insects, and pathogens

Invasive plants, insects, and pathogens are a significant disturbance in temperate forest ecosystems. Climate change will interact with these species by facilitating new species introductions, geographic range shifts, and altering species impacts and native ecosystem susceptibility. Temperate ecosystems may be disproportionately impacted by invasives

relative to tropical ecosystems, as they are primarily located in the global north and tend to be recipients of nonnative species, partly due to high imports (Turbelin, Malamud, & Francis, 2017). Furthermore, cold-limited tropical and subtropical species introduced to temperate biomes may be able to establish and spread as the climate warms, exacerbating existing invasions and prompting new invasions (McGlone, Walker, Hay, & Christie, 2010; Spear, Walsh, Ricciardi, & Zanden, 2021). Here we discuss the potential arrival of new invaders, expected trends for range shifts, and changes to impacts for invasive plants, insects, and pathogens in a changing climate.

Globally, the rate of invasive species introductions has not slowed (Seebens et al., 2017), suggesting the potential for new invasions remains high. Invasive plants are introduced both intentionally and unintentionally, with intentional insect and pathogen introductions being less common. Some climate change mitigation strategies may prompt the intentional introduction of nonnative species. For example, candidate species for biofuels include nonnative grasses capable of invading temperate forests (Canavan et al., 2019). Unintentional introductions of "hitchhiking" species may occur as a reduction in sea ice opens new shipping routes, offering more direct and rapid transport of nonnative species to new ecosystems (Pyke et al., 2008). Climate change may also alter travel patterns (Hellmann, Byers, Bierwagen, & Dukes, 2008), and unintentional introductions in places with high levels of international travel, such as Europe, may see a rise in new species introductions (Kovats et al., 2014).

Invasive species may shift their geographic ranges to track a changing climate. Projecting range shifts for invasive plants have mainly relied on species distribution models (SDMs). One analysis using species distribution models for nearly 900 terrestrial invasive plant species found that in the United States, 80% of invasive plant species' distributions would remain stable under climate change through 2050, while the remaining 20% would see northward shifts, including many species moving into northeastern temperate forests (Allen & Bradley, 2016). In Europe, it is also likely that invasive species will expand their ranges (Kovats et al., 2014). Globally, suitable climate for the 100 worst invasive species is expected to increase more in temperate forests than in other biomes (Bellard et al., 2013). Although the utility of species distribution models can be limited due to their tendencies to over/under-predict potential ranges (Sinclair, White, & Newell, 2010; Velazco, Ribeiro, Laureto, & Júnior, 2020), they are nevertheless a valuable tool for conservation planning (Sofaer et al., 2019).

Due to climate change, some invasive forest insects are also expected to shift their ranges. For example, increasing temperatures may result in decreased winter mortality and expanded northern range limits for the invasive insect hemlock wooly adelgid (McAvoy, Régnière, St-Amant, Schneeberger, & Salom, 2017; Vose et al., 2018). Warmer temperatures have also facilitated the movement of bark beetles to more northern latitudes and higher altitudes, resulting in outbreaks in forests in which they have been historically rare (Logan & Powell, 2001; Logan, Macfarlane, & Willcox, 2010). However, mismatches in host and insect and pathogen range shifts could decrease invasive species abundance, even if the climate becomes more suitable (Dudney et al., 2021).

Climate change may alter invasive species impacts by changing both the invader's competitive ability and the recipient ecosystem's susceptibility. For example, increased competitive ability due to higher temperatures and atmospheric CO_2 (Sorte et al., 2013), combined with disturbances such as fire, may allow some nonnative grasses to invade temperate forest ecosystems, providing potential for ecosystem conversion (e.g., *Ventanata dubia* in the northwest United States; Kerns et al., 2020). Invasive plant impacts may also change, as they are more likely than natives to experience phenological changes to track a changing climate (Finch et al., 2021; Wolkovich et al., 2013). However, direct impacts from climate change are likely dependent on the invasive species and recipient ecosystem. Therefore, it is difficult to assess whether climate change will benefit invasives more than native species (Finch et al., 2021).

Climate change effects on invasive insects and pathogen impacts are difficult to predict (Dukes et al., 2009; Tobin, Parry, & Aukema, 2014; Vose et al., 2018). Most work in temperate forests focuses on a relatively small subset of species. Warming temperatures are expected to benefit some invasive insects directly (Finch et al., 2021), particularly wood-boring insects, if longer warm seasons increase brood numbers (Tobin et al., 2014). In addition, changes in precipitation are projected to affect pathogens. For example, in Iowa (central United States), increases in bur oak blight may result from increased spring precipitation levels (Harrington & McNew, 2016). However, pathogens in many places may be limited by drought conditions (Dukes et al., 2009). Regardless of direct climate impacts on invasive insects and pathogens, temperature- and drought-stressed trees will generally be more susceptible to damage (Jactel et al., 2012; Millar & Stephenson, 2015).

Ecosystem effects

Shifts in spatial distribution

Globally, the temperate forest biome is highly vulnerable to vegetation shifts due to climate change (Gonzalez, Neilson, Lenihan, & Drapek, 2010). These shifts can be catalyzed by the disturbance events described above (Allen et al., 2015).

The distribution of temperate forest species is generally expected to shift poleward and to higher elevations as the climate warms. For temperate forests in the northern hemisphere, these shifts would involve species moving into the southern portions of the current boreal zone. In North America, undeveloped areas that connect the temperate and boreal forests are still largely intact, providing ample opportunity for species migration relative to Europe and Asia, where human land use has resulted in more fragmented landscapes (Evans & Brown, 2017; Goldblum & Rigg, 2010; Venter et al., 2016).

Despite high levels of forest connectivity in eastern North America, projections suggest that temperate species will still face difficulty moving into current boreal zones (Vissault, Talluto, Boulangeat, & Gravel, 2020), creating a lag between boreal retraction and temperate species expansion (Taylor et al., 2017). However, as temperate species have more time to move into open niches left by retracting northern hardwood and boreal species, range shifts may become more apparent by 2300 (Wang, He, Thompson, Fraser, & Dijak, 2017). It is important to note that even without climate change, some species would still shift their ranges (Thom et al., 2017). Other factors driving the distribution of species include biotic interactions (e.g., herbivory, seed predation, competition), edaphic constraints, disturbance, and land use history. In some cases, nonclimatic factors may slow species' response to climate change (Brown & Vellend, 2014), or even drive counter-intuitive distribution shifts (Foster & D'Amato, 2015).

Unlike in the northern hemisphere, temperate forests in South America and Australia already extend to the edge of their terrestrial range (Fig. 9.1). However, species in these forests are expected to follow the same trends in geographic shifts. In Australia, models (to 2085) projected temperate eucalypt species would shift southward (Butt, Pollock, & Mcalpine, 2013), unlike tropical, subtropical, and desert species, which were projected to shift eastward and westward to track changing precipitation (Butt et al., 2013). Similar shifts are expected in South America, where mountainous north-south oriented forests provide promising opportunities for species to shift their ranges into more suitable climates (Alarcón & Cavieres, 2018). Modeling studies to 2050 projected substantial southward shifts for *Nothofagus* species, although ground and epiphytic ferns were less likely to follow this pattern (Alarcón & Cavieres, 2018).

Considering microclimates in projections for understory and other nontree species like ferns will be important for understanding climate change effects on these vegetation communities (De Frenne et al., 2021; Landuyt et al., 2018). Although individual species are projected to shift to track a changing climate, differing species responses to a changing climate will make entire forested ecosystem shifts unlikely. Some species may persist within their current distributions, while others may reach their climatic limits (Walentowski et al., 2017), leading to changes in ecosystem composition. Additionally, microclimates in temperate forests may provide climate refugia, particularly for understory species, allowing them to persist in their current ranges (Lenoir, Hattab, & Pierre, 2017). Differences in species' need and ability to shift their ranges will lead to new ecosystem assemblages. Existing assemblages may be reshaped if species dominance changes with altered competitive ability under new environmental conditions (Ammer, 2019). Disturbances will likely be the catalysts for shifts in species composition.

Phenological shifts

Climate change is expected to result in shifts in temperate forest phenology, and changes in phenology may produce climate change feedbacks, such as changes in CO_2 uptake or albedo (Peñuelas, Rutishauser, & Filella, 2009). Plant phenology is typically driven by photoperiod, chilling days, and warming days. While all cues are important for both spring budburst and leaf out, chilling is most important for budburst, and warm-temperature thermal forcing and photoperiod are most important for leaf out (Flynn & Wolkovich, 2018; Polgar & Primack, 2011).

Projected climate change impacts are often determined based on modeling studies and experiments that expose plants to novel temperature and photoperiod conditions (Polgar & Primack, 2011). In addition to modeling and experimental work, observational studies that use anomalously warm years can also lend insight into potential changes to phenology (Friedl et al., 2014). For example, a modeling study using moderate climate-warming scenarios in the United States projected that budburst would be an average of 8.3 days earlier by 2100, with the largest changes observed at northern latitudes (Jeong, Medvigy, Shevliakova, & Malyshev, 2013). These changes to early-season phenology, such as budburst, are also good indicators of climate effects on late-season phenological events (Ettinger, Gee, & Wolkovich, 2018; Zani, Crowther, Mo, Renner, & Zohner, 2020). These general projections are consistent with the Pacific Northwest region of the United States, where models projected that huckleberry would flower on average 21 days earlier and would fruit on average 23 days earlier by 2100 (Prevéy, Parker, Harrington, Lamb, & Proctor, 2020). While a longer growing season may be advantageous to plants in some regards, cold events late in spring may damage plants that shift to earlier spring leaf out or flowering (Xie, Ahmed, Allen, Wilson, & Silander, 2015).

Although phenological changes are expected, projections for future phenology are challenging due to complex interactions with precipitation, photoperiod, and potential decreases in days that meet a chilling requirement (Hijioka et al., 2014). Mild warming that leads to reductions in an adequate number of chilling days could lead to later spring green-up (Chmura et al., 2011; Hijioka et al., 2014; Xie et al., 2015), and effects may vary for species across latitudes and elevations. For example, models suggested that coastal Douglas-fir in the Pacific Northwest would track climate warming at higher elevations but not lower elevations, likely due to a loss of chilling days at lower elevations (Ford, Harrington, Bansal, Gould, & St. Clair, 2016).

The timing of warming may also play a role in phenological outcomes, especially when considered with other phenological drivers. For example, mismatches in temperature and photoperiod for Australian eucalypt species were problematic when temperature thresholds were reached before day length requirements (Rawal, Kasel, Keatley, & Nitschke, 2015). Phenological responses also vary based on species, growth form, and latitude (Flynn & Wolkovich, 2018; Jeong et al., 2013; Xie et al., 2015), further complicating robust projections on phenological effects.

Changes in forest productivity

Effects of climate change on forest productivity will likely vary by forest type and elevation, and with changes in disturbance regimes (Reyer et al., 2017). In water-limited forests where soil water availability is often low during the growing season (e.g., many Australian eucalypt forests, *Nothofagus* forests of South America, low-elevation forests in the western United States, and southern European forests), tree growth will likely decrease in a warmer climate (Bowman, Williamson, Keenan, & Prior, 2014; Latta, Temesgen, Adams, & Barrett, 2010; Venegas-González, Juñent, Gutiérrez, & Filho, 2018). Conversely, in energy-limited forests where the growing season is restricted by snow and cold temperatures (e.g., most forests in the eastern United States and Canada, northern European forests, and high-elevation temperate forests), tree growth will likely increase in a warmer climate (Latta et al., 2010; Marcinkowski, Peterson, & Ettl, 2015; Wang et al., 2017). However, drought and extreme temperatures could limit growth increases in energy-limited forests by causing water-related and/or heat-related stress on forests (Anderegg et al., 2015; Hember, Kurz, & Coops, 2017).

Increased levels of CO_2 in the atmosphere can increase tree growth through carbon fertilization (e.g., Norby et al., 2002). However, nutrient and water limitations can limit or negate growth increases (Norby, Warren, Iversen, Medlyn, & McMurtrie, 2010; Oren et al., 2001). In addition, it is unclear if fertilization effects will continue as forests age (Norby et al., 2010). Air pollutants (e.g., ground-level ozone) may also negate CO_2 fertilization where concentrations are sufficiently high to be toxic to plants, such as near urban areas (Pan, Birdsey, Hom, & McCullough, 2009). Warming and increased atmospheric CO_2 may also affect belowground biogeochemical processes, such as carbon and nitrogen cycling (Melillo et al., 2017), thereby affecting forest productivity (Campbell et al., 2009).

Effects of climate change on temperate forest ecosystem services

Ecosystem services are the benefits that ecosystems provide to people and these services vary across ecosystems (Millennium Ecosystem Assessment Program, 2005). Here we have chosen to focus on climate impacts on timber, water quality and quantity, recreation, and carbon storage, as these have been identified among the major services provided by temperate forest ecosystems (Gonzalez et al., 2005). As a result, they have become a significant consideration in temperate forest management decisions (Millar & Stephenson, 2015).

Timber

With increased temperatures and atmospheric CO_2, forest productivity and biomass accumulation may increase (Tian, Sohngen, Kim, Ohrel, & Cole, 2016), leading to increases in timber production in some locations (e.g., at higher elevations and latitudes; Fig. 9.5). However, moisture limitations, ecological disturbances, and their interactions may reduce forest growth in other locations (e.g., low elevations). Climate change will likely increase wildfire area burned (Krawchuk et al., 2009), drought severity (IPCC et al. 2021), and insect outbreaks (Millar & Stephenson, 2015). These disturbances are often associated with significant tree mortality and decreases in forest growth (e.g., Reyer et al., 2017). These disturbances also have variable effects on tree recruitment events. For example, severe fire may promote unnaturally dense ponderosa pine stands (Savage & Mast, 2005), and drought may decrease ponderosa pine regeneration by the end of the century (Petrie et al., 2017).

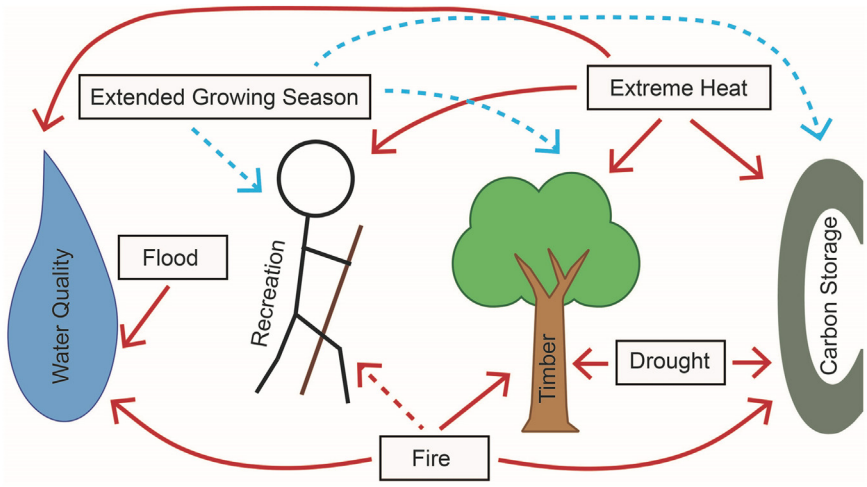

FIGURE 9.5 Climate change effects, in white boxes, have variable projected effects on ecosystem services. Blue arrows indicate a positive effect, while red arrows indicate a negative effect. Dotted lines indicate less certainty about the effect.

Though harvests can increase in the short term through the salvage of dead and dying trees (Tian et al., 2016), long-term timber availability will likely decrease in locations that experience increased moisture limitations and/or more frequent disturbance (Warziniack et al., 2018). Over decades, soil moisture deficits and changing disturbance regimes may cause the location of some desirable timber species to shift. For example, valuable European timber species may decrease in abundance with climate change (Hanewinkel, Cullmann, Schelhaas, Nabuurs, & Zimmermann, 2013). Warmer winters and associated freezing and thawing may also increase forest road erosion and landslides, making winter harvest more difficult and expensive, and potentially reducing timber supply (Karl, Melillo, Peterson, & Hassol, 2009). However, adaptation in timber and wood product markets may offset the potentially harmful effects of climate change (Tian et al., 2016).

Water quality and quantity

Forested watersheds provide water for municipalities, agriculture, power generation, recreation, spiritual values, and in-stream flows for aquatic biota. In a warming climate, water quality and quantity will be affected by increased temperatures, disturbance, and changes in snow (amount, timing, and melt). In watersheds affected by snow, earlier and lower spring peak flows result in lower streamflows later in the summer (Stewart, Cayan, & Dettinger, 2005). As a result, summer surface water shortages are likely in dry years in some locations (Li, Wrzesien, Durand, Adam, & Lettenmaier, 2017).

Stream temperatures are expected to increase in response to increased air temperature and lower summer streamflows (Isaak et al., 2016). Stream temperatures affect water solubility and biogeochemical cycles, which determine the organisms that can survive in water, potentially increasing municipal water treatment costs (Warziniack et al., 2018). In places where burned area increases with climate change, more sediment deposition and debris in streams, lakes, and reservoirs will negatively affect water quality (Fig. 9.5; Luce et al., 2012). In addition, extreme weather and a higher rain: snow ratio may increase runoff from agricultural fields and add pesticides and fertilizers to streams. These changes in water quality will likely decrease the availability and increase the cost of accessing clean water in some temperate forest regions.

Recreation

Warming temperatures with climate change will likely increase overall participation in outdoor recreation in temperate forest ecosystems (Fig. 9.5; Bowker et al., 2013). However, the length and quality of the winter recreation season will likely be reduced with climate change (e.g., Burakowski et al., 2022). Lower-elevation sites may become unsuitable for snow-based recreation with warming, and high-elevation sites will likely experience more variability in season length (Hand & Lawson, 2017).

In contrast, climate change is expected to result in a more extended season for warm-weather activities. Snow and ice will melt earlier, making some sites accessible earlier in the spring, and temperatures will be higher during the autumn and spring "shoulder" seasons, making warm-weather activities more attractive (Hand & Lawson, 2017; Hewer,

Scott, & Fenech, 2016). Extreme summer temperatures can reduce participation during the hottest weeks of the year (Fig. 9.5; Bowker et al., 2012; Hewer et al., 2016), shifting demand to cooler weeks or to alternative sites less exposed to extreme temperatures (e.g., lakes and streams), though cooler forest microclimates may still be amenable at these times. Wildfire activity may reduce demand in some years because of degraded site desirability, impaired air quality from smoke, and limited site access. Heavy rainfall, landslides, and rockfall caused by melting ice could damage infrastructure (e.g., roads, trails, bridges), potentially causing safety risks and reducing the quality of visitor experiences (Pröebstl-Haider, Höedl, Ginner, & Borgwardt, 2021). Recreation visits to sites with highly valued natural characteristics (e.g., glaciers and charismatic wildlife species) may also decrease in the future if the quality of those sites is threatened (Scott, Jones, & Konopek, 2007).

Overall, the adaptive capacity among recreationists is high as they can switch to alternative sites, alter the timing of visits, and alter capital investments (e.g., gear). Thus, recreational use will likely continue to be high in temperate forest ecosystems, although shifts in the timing and type of recreation activities will likely be necessary for some recreationists.

Carbon storage

Climate change may decrease carbon storage in many temperate forests due to higher temperatures, increasing water stress, and disturbances such as fire and insect outbreaks (Fig. 9.5; Kurz et al., 2008; Pugh, Arneth, Kautz, Poulter, & Smith, 2019; Seidl, Schelhaas, Rammer, & Verkerk, 2014). Forest productivity is one of many determinants of forest carbon storage capacity (McCarthy, Oren, Finzi, & Johnsen, 2006). As discussed above, forest productivity may increase in some forests due to longer growing seasons or CO_2 fertilization, but those increases may be offset by nutrient limitations, drought, and other disturbances (Norby et al., 2010).

Globally, disturbances, such as fire and wind, are negatively associated with carbon storage (Thom & Seidl, 2016), and the type, extent, frequency, and severity of disturbance are likely to be key in determining the future of carbon in forests under changing climate (Williams, Gu, MacLean, Masek, & Collatz, 2016). Severe disturbances, such as some wildfires, often result in the release of carbon into the atmosphere, reduced stand productivity, transfer of carbon from live to dead pools, and increased decomposition (Williams et al., 2016). Forest regrowth after disturbance results in carbon uptake. However, even if growth rates rise in a changing climate, increases in carbon storage in biomass will likely be small compared to losses that occur with increased disturbance (Kurz et al., 2008; Pugh et al., 2019; Seidl et al., 2014; Wear & Coulston, 2015).

Land use decisions also influence forest-based carbon storage, with the conversion of forestland contributing to CO_2 emissions. It is unclear whether emissions from deforestation will outweigh increased carbon storage from afforestation in the future (Coulston, Wear, & Vose, 2015). Overall, U.S. and European forests are expected to continue to store carbon at declining rates because of land use and lower CO_2 uptake in aging forests (Nabuurs et al., 2013; Oswalt, Smith, Miles, & Pugh, 2014; Seidl et al., 2014; Wear & Coulston, 2015).

Adaptation to climate change

Adaptation overview

Adaptation, "the process of adjustment to actual or expected climate and its effects" (Noble, Huq, & Anokhin, 2014), is critical to maintain resilient ecosystems and sustain natural resources into the future. The process of climate change adaptation consists of four general steps (Peterson et al., 2011), including (1) synthesis and review of current climate change science and integration of this information with local management and social conditions and contextual factors (review); (2) evaluation of climate change sensitivities, future climate exposure, and adaptive capacities for key ecosystems or natural resource areas (evaluate); (3) development and implementation of adaptation options (resolve); and (4) monitoring the effectiveness of adaptation actions (observe) and adjust as needed.

Information from the first two steps is typically integrated into climate change vulnerability assessments that describe the exposure, sensitivity, and adaptive capacity of specific resource areas, ecosystems, or species to climate change stressors. Vulnerability assessments must account for an uncertain future climate and consider many aspects of sustainable forest management (Williamson, Campagna, & Ogden, 2012). Assessments facilitate adaptation options and can also facilitate engagement in the adaptation process by raising awareness of possible climate change risks (Halofsky, Andrews-Key, et al., 2018).

The third step is to develop climate change adaptation strategies and tactics. Adaptation options vary in scope and specificity; adaptation strategies describe how they can be employed, but they are still broad and general in their application across ecosystems. Tactics are more specific adaptation responses and can provide prescriptive directions for

actions to be applied on the ground. At the broadest level, climate change adaptation strategies can be differentiated into four main types: (1) resistance, (2) resilience, (3) response, and (4) realignment (Millar, Stephenson, & Stephens, 2007). The resistance strategy includes tactics that forestall impacts to protect highly valued resources. Resistance strategies are only a short-term solution, but often describe the intensive and localized management of rare and isolated species (Heller & Zavaleta, 2009). The resilience strategy includes tactics that improve the capacity of systems to return to desired conditions after disturbance. The response strategy employs tactics to facilitate the transition of systems from current to new desired conditions. Finally, the realignment strategy uses restoration practices to ensure the persistence of ecosystem processes and functions in a changing climate.

The fourth step in the adaptation process is to monitor effectiveness and adjust if needed. Because of the complexity and uncertainty associated with climate change, an iterative implementation, monitoring, and modification (or adaptive management) will likely result in the most effective adaptation (Littell, Peterson, Millar, & O'Halloran, 2012; Millar et al., 2007; Peterson et al., 2011).

Adaptation options in temperate forests

There has been increasing focus on adaptation to climate change in forests over the last 10−15 years, and there are many options to adapt temperate forest management to a changing climate. Promoting biological diversity, including species, genetic, age, structural, and landscape diversity, is a frequently suggested adaptation strategy to increase forest resilience to climate change (Halofsky, Andrews-Key, et al., 2018; Messier, Puettmann, & Coates, 2013; Seidl, Spies, Peterson, Stephens, & Hicke, 2016). Areas with high species and genetic diversity are more likely to have species that can respond to or rebound after a range of disturbances, thereby allowing the ecosystem as a whole to better maintain functions in a changing climate (Dymond et al., 2014; Messier et al., 2019). Increasing the diversity of functional traits, such as shade tolerance, tree height, seed size, specific leaf area, ability to resprout, and bark thickness has also been proposed to give forests the ability to withstand or adapt to disturbances in a changing climate (Grossiord, 2020; Jactel et al., 2017; Messier et al., 2019).

Forest managers may want to consider planting tree species and genotypes that can survive in current and future projected climates and related disturbances (Sáenz-Romero, O'Neill, Aitken, & Lindig-Cisneros, 2021). Although this is an often-suggested adaptation strategy, forest managers need specific information on appropriate genotypes and species to introduce different tree species (Sousa-Silva et al., 2018). Tools such as the Seedlot Selection Tool (https://seedlotselectiontool.org/sst/) have been developed to help to identify a seedling stock that will be best adapted to a given site in the future. Managers may also want to increase seed collection and ensure that adequate nursery stock adapted to future climate conditions is available for postdisturbance planting (Halofsky et al., 2011). Changing the timing of planting to coincide with precipitation patterns to increase establishment and planting seedlings in cooler, wetter microsites will also likely help to increase survival (Rother, Veblen, & Furman, 2015).

In drought-prone temperate forests (e.g., ponderosa pine and dry mixed conifer forests in the American West, forests in central and southern Europe), reducing forest density can increase resistance and resilience to drought (Clark et al., 2016; Sohn, Saha, & Bauhus, 2016). Even in wetter forest types, reducing stand density with thinning can increase water availability, tree growth, and tree vigor by reducing competition (Roberts & Harrington, 2008). However, decreases in canopy cover can affect forest microclimate regulation and increase ground-level temperatures (Blumröder, May, Härdtle, & Ibisch, 2021).

Decreased forest stand density and hazardous fuel treatments can also increase forest resilience to wildfire in dry, fire-prone forest types (Agee & Skinner, 2005; Hessburg et al., 2015). Thinning and prescribed fire can reduce forest density and promote disturbance-resilient species (Spies et al., 2010). However, these treatments must be maintained over time to remain effective (Agee & Skinner, 2005), especially in productive forest types.

Forest management may also affect the mitigation potential of forests. Nabuurs et al. (2017) suggest that changes in forest management in European forests could provide additional carbon sequestration benefits of up to 172 Mt CO_2 per year by the mid-century. These changes in forest management could include thinning of stands to increase growth, planting more site-adapted species, and planting faster-growing species (Nabuurs et al., 2017). Forest reserves have also been proposed to increase carbon sequestration.

Temperate forests and an uncertain future

There are several areas of uncertainty associated with the future of temperate forest ecosystems. These can be considered in three broad categories: uncertainty in climate change projections, ecosystem response, and the use of adaptation strategies.

Climatic changes

While the certainty behind the cause and general impacts of anthropogenic climate change is high (IPCC et al., 2021), greater uncertainty remains in the degree to which those impacts will be realized. In particular, precipitation changes have a higher uncertainty due to the complex circulation processes that must be included when modeling future change (Shepherd, 2014). However, more variable precipitation is expected in many areas, and this, combined with the high certainty around temperature increases, suggests that drought is more likely (IPCC et al., 2021).

Another uncertainty in climate change projections is the difficulty in climate change attribution, which determines the degree to which anthropogenic climate change contributes to climate-related events. While the field of climate change attribution is rapidly developing, limitations remain in model reliability (Bellprat, Guemas, Doblas-Reyes, & Donat, 2019). In particular, extreme events remain difficult to predict, and these events will likely have some of the largest ecosystem effects (Bellprat et al., 2019).

Finally, the degree to which the climate will change relies mainly on future emissions. However, significant uncertainty exists surrounding the social and political contexts under which emissions might be reduced, and climate change impacts mitigated. Here, we chose to discuss the future of forests using moderate emissions scenarios unless otherwise noted. However, the degree to which climate change impacts temperate forests will depend mainly on the degree to which future emissions can be mitigated.

Ecosystem response

Another factor impacting uncertainty around climate change impacts is our understanding of ecosystem response. For example, many studies assessing the potential for species range shifts rely on species distribution models, which focus on climatic limitations and do not consider important factors such as biotic interactions or dispersal ability (Keenan, 2015). While these models can be helpful for conservation planning (Sofaer et al., 2019), these limitations reduce the certainty of future species ranges, which is a significant consideration for determining climate change impacts on temperate forests.

Our understanding of climate change impacts on ecosystem response is also stymied by the difficulty of untangling multiple stressors and a lack of monitoring. For example, in 2019, Australia experienced its hottest and driest year on record and unprecedented wildfires (Abram et al., 2021). While the drought led to massive canopy dieback and hydraulic failure in eucalypt forests, tree mortality was unclear because of the potential for the trees to resprout after significant disturbance (Nolan et al., 2021). In addition, limited forest monitoring and the life history of these trees have made it difficult to determine whether widespread tree mortality was due to recent droughts or subsequent fires. Further empirical understanding of long-term trajectories of species persistence versus vegetation shifts following drought-driven mortality remains very limited (Batllori et al., 2020).

Use of adaptation strategies

The future of temperate forest ecosystems is intricately intertwined with anthropogenic land use and management. Decisions about whether and how we should implement adaptation strategies are mainly dependent on social, cultural, and economic values, making the implementation of climate change adaptation strategies an area of uncertainty. There are a growing number of examples of the implementation of climate change adaptation options in temperate forests (e.g., Aguiar et al., 2018; Halofsky, Peterson, & Prendeville, 2018; Nagel et al., 2017). However, despite increasing recognition of climate change as an issue in temperate forests, implementation of adaptation actions has been slow (Ameztegui et al., 2018; Halofsky, Andrews-Key, et al., 2018; Sousa-Silva et al., 2018). Barriers to climate change adaptation include managers and landowners perceiving climate change as complex and uncertain (Nelson, Williamson, Macaulay, & Mahony, 2016; Sousa-Silva et al., 2018), lack of time or resources (Aguiar et al., 2018; Timberlake & Schultz, 2017), lack of mandates or guidelines by government agencies or organizations to incorporate climate change in management (Halofsky, Andrews-Key, et al., 2018), and a lack of information at scales relevant for planning and management (Nagel et al., 2017). These barriers need to be addressed to promote the implementation of adaptation options and the continued provision of ecosystem services by temperate forests.

Conclusions

Climate change will affect temperate forests worldwide, raising temperatures and changing precipitation patterns. However, the magnitude and degree of these effects on ecosystems will vary by geography and ecosystem composition.

This chapter focused on projections generated using moderate greenhouse gas concentration pathways when possible. However, in most cases, higher concentration pathways will lead to more extreme ecosystem effects. Ecosystem response will also play out on a complex backdrop of differing land use legacies and disturbance regimes. Varying outcomes in the continued provisioning of ecosystem services will inevitably require different adaptation strategies and management approaches.

Temperate forests are expected to respond directly to changing temperature and precipitation regimes, resulting in shifting phenology, species distributions, and ecosystem processes. Geographic shifts will likely include species' movement poleward and upward elevation. Although these changes have already been observed in some temperate forests, most species have not been able to migrate as quickly as the climate has changed. Some species may be dispersal limited because they exist in fragmented landscapes, and some may experience high levels of competition, limiting their ability to shift in range. The individualistic response of species to climatic changes will ultimately result in novel ecosystem assemblages.

Although temperate forests are expected to respond directly to changes in temperature and precipitation, these responses will be moderate compared to those due to changes in disturbance regimes, which can result in large-scale and abrupt ecosystem shifts. Drought is the most ubiquitous disturbance expected to occur in temperate forest ecosystems. Drought alone or in concert with other disturbances, including fire, insects, and pathogens, can result in tree mortality and negatively affect ecosystem services (Allen et al., 2010, 2015; Batllori et al., 2020; Millar & Stephenson, 2015).

Temperate forests are unique among forest biomes because of their extensive use by and connection to human societies (Gilliam, 2016); we rely heavily on ecosystem services provided by these forests. In general, climate change will negatively impact the ability of temperate forest ecosystems to provide these services. For example, increased disturbance leading to broad-scale tree mortality will negatively impact water quality and timber production (Millar & Stephenson, 2015). The availability of ecosystem services will also likely shift geographically and seasonally. For example, optimal sites for timber harvest may move to higher elevations or latitudes in a warming climate. In addition, cultural ecosystem services (e.g., availability of culturally important foods) may shift in location or be reduced due to increased disturbance. Climate change will also affect recreation, requiring people to alter the type and seasonality of their outdoor activities. Regardless of specific impacts on ecosystem services, we can expect profound changes that will require societies to rethink their current practices and employ climate change adaptation strategies to mitigate impacts where possible.

Acknowledgments

This research was supported in part by appointment to the United States Forest Service (USFS) Research Participation Program administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy (DOE) and the U.S. Department of Agriculture (USDA). ORISE is managed by ORAU under DOE contract number DE-SC0014664. All opinions expressed in this paper are the authors' and do not necessarily reflect the policies and views of USDA, DOE, or ORAU/ORISE.

References

Abram, N. J., Henley, B. J., Gupta, A. S., Lippmann, T. J., Clarke, H., Dowdy, A. J., ... Boer, M. M. (2021). Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment*, *2*(1), 1–17.

Agee, J. K., & Skinner, C. N. (2005). Basic principles of forest fuel reduction treatments. *Forest Ecology and Management*, *211*(1-2), 83–96.

Aguiar, F. C., Bentz, J., Silva, J. M., Fonseca, A. L., Swart, R., Santos, F. D., & Penha-Lopes, G. (2018). Adaptation to climate change at local level in Europe: An overview. *Environmental Science & Policy*, *86*, 38–63.

Alarcón, D., & Cavieres, L. A. (2018). Relationships between ecological niche and expected shifts in elevation and latitude due to climate change in South American temperate forest plants. *Journal of Biogeography*, *45*(10), 2272–2287.

Alizadeh, M. R., Abatzoglou, J. T., Luce, C. H., Adamowski, J. F., Farid, A., & Sadegh, M. (2021). Warming enabled upslope advance in western US forest fires. *Proceedings of the National Academy of Sciences*, *118*(22).

Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, *6*(8), 1–55.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., . . . Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, *259*(4), 660–684.

Allen, J. M., & Bradley, B. A. (2016). Out of the weeds? Reduced plant invasion risk with climate change in the continental United States. *Biological Conservation*, *203*, 306–312.

Ameztegui, A., Solarik, K. A., Parkins, J. R., Houle, D., Messier, C., & Gravel, D. (2018). Perceptions of climate change across the Canadian forest sector: The key factors of institutional and geographical environment. *PLoS One*, *13*(6), e0197689.

Ammer, C. (2019). Diversity and forest productivity in a changing climate. *New Phytologist*, *221*(1), 50−66.

Andela, N., Morton, D. C., Giglio, L., Chen, Y., van der Werf, G. R., Kasibhatla, P. S., … Randerson, J. T. (2017). A human-driven decline in global burned area. *Science*, *356*(6345), 1356−1362.

Anderegg, W. R., Schwalm, C., Biondi, F., Camarero, J. J., Koch, G., Litvak, M., … Pacala, S. (2015). Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science*, *349*(6247), 528−532.

Armstrong, C. G., Miller, J. E., McAlvay, A. C., Ritchie, P. M., & Lepofsky, D. (2021). Historical Indigenous land-use explains plant functional trait diversity. *Ecology and Society*, *26*(2), 6.

Barbero, R., Abatzoglou, J. T., Larkin, N. K., Kolden, C. A., & Stocks, B. (2015). Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*, *24*(7), 892−899.

Barbier, E. B., Burgess, J. C., & Grainger, A. (2010). The forest transition: Towards a more comprehensive theoretical framework. *Land Use Policy*, *27*(2), 98−107.

Batllori, E., Lloret, F., Aakala, T., Anderegg, W. R., Aynekulu, E., Bendixsen, D. P., … Zeeman, B. (2020). Forest and woodland replacement patterns following drought-related mortality. *Proceedings of the National Academy of Sciences*, *117*(47), 29720−29729.

Bellard, C., Thuiller, W., Leroy, B., Genovesi, P., Bakkenes, M., & Courchamp, F. (2013). Will climate change promote future invasions? *Global Change Biology*, *19*(12), 3740−3748.

Bellprat, O., Guemas, V., Doblas-Reyes, F., & Donat, M. G. (2019). Towards reliable extreme weather and climate event attribution. *Nature Communications*, *10*(1).

Bentz, B. J., Régnière, J., Fettig, C. J., Hansen, E. M., Hayes, J. L., Hicke, J. A., … Seybold, S. J. (2010). Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience*, *60*(8), 602−613.

Blackman, C. J., Brodribb, T. J., & Jordan, G. J. (2009). Leaf hydraulics and drought stress: Response, recovery and survivorship in four woody temperate plant species. *Plant, Cell & Environment*, *32*(11), 1584−1595.

Blarquez, O., Talbot, J., Paillard, J., Lapointe-Elmrabti, L., Pelletier, N., & Gates St-Pierre, C. (2018). Late Holocene influence of societies on the fire regime in southern Québec temperate forests. *Quaternary Science Reviews*, *180*, 63−74.

Blonder, B., Enquist, B. J., Graae, B. J., Kattge, J., Maitner, B. S., Morueta-Holme, N., … Violle, C. (2018). Late Quaternary climate legacies in contemporary plant functional composition. *Global Change Biology*, *24*(10), 4827−4840.

Blumröder, J. S., May, F., Härdtle, W., & Ibisch, P. L. (2021). Forestry contributed to warming of forest ecosystems in northern Germany during the extreme summers of 2018 and 2019. *Ecological Solutions and Evidence*, *2*(3), e12087.

Boisvert-Marsh, L., Périé, C., & de Blois, S. (2014). Shifting with climate? Evidence for recent changes in tree species distribution at high latitudes. *Ecosphere*, *5*(7), 1−33.

Bowker, J. M., Askew, A. E., Poudyal, N., Zarnoch, S. J., Seymour, L., & Cordell, H. K. (2013). Climate change and outdoor recreation participation in the Southern United States. In J. M. Vose, & K. D. Klepzig (Eds.), *Climate change adaptation and mitigation management options: A guide for natural resource managers in southern forest ecosystems* (pp. 421−450). Boca Raton, FL: CRC Press.

Bowker, J.W., Askew, A.E., Cordell, H.K., Betz, C.J., Zarnoch, S.J., & Seymour, L. (2012). *Outdoor recreation participation in the United States—projections to 2060: A technical document supporting the forest service 2010 RPA assessment*. General Technical Report: GTR-SRS-160. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station.

Bowman, D. M. J. S., Williamson, G. J., Keenan, R. J., & Prior, L. D. (2014). A warmer world will reduce tree growth in evergreen broadleaf forests: Evidence from Australian temperate and subtropical eucalypt forests. *Global Ecology and Biogeography*, *23*(8), 925−934.

Bréda, N., Huc, R., Granier, A., & Dreyer, E. (2006). Temperate forest trees and stands under severe drought: A review of ecophysiological responses, adaptation processes and long-term consequences. *Annals of Forest Science*, *63*(6), 625−644.

Breshears, D. D., Adams, H. D., Eamus, D., McDowell, N., Law, D. J., Will, R. E., … Zou, C. B. (2013). The critical amplifying role of increasing atmospheric moisture demand on tree mortality and associated regional die-off. *Frontiers in Plant Science*, *4*, 266.

Brown, C. D., & Vellend, M. (2014). Non-climatic constraints on upper elevational plant range expansion under climate change. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1794), 20141779.

Burakowski, E. A., Contosta, A. R., Grogan, D., Nelson, S. J., Garlick, S., & Casson, N. (2022). Future of winter in Northeastern North America: Climate indicators portray warming and S89now loss that will impact ecosystems and communities. *Northeastern Naturalist*, *28*(sp11), 180−207.

Butt, N., Pollock, L. J., & Mcalpine, C. A. (2013). Eucalypts face increasing climate stress. *Ecology and Evolution*, *3*(15), 5011−5022.

Calder, W. J., & Shuman, B. (2017). Extensive wildfires, climate change, and an abrupt state change in subalpine ribbon forests, Colorado. *Ecology*, *98*(10), 2585−2600.

Camarero, J. J., Colangelo, M., Gazol, A., & Azorín-Molina, C. (2021). Drought and cold spells trigger dieback of temperate oak and beech forests in northern Spain. *Dendrochronologia*, *66*, 125812.

Campbell, J. L., Rustad, L. E., Boyer, E. W., Christopher, S. F., Driscoll, C. T., Fernandez, I. J., … Ollinger, S. V. (2009). Consequences of climate change for biogeochemical cycling in forests of northeastern North America. *Canadian Journal of Forest Research*, *39*(2), 264−284.

Canavan, S., Meyerson, L. A., Packer, J. G., Pyšek, P., Maurel, N., Lozano, V., … Wilson, J. R. U. (2019). Tall-statured grasses: A useful functional group for invasion science. *Biological Invasions*, *21*(1), 37−58.

Carnicer, J., Coll, M., Ninyerola, M., Pons, X., Sanchez, G., & Penuelas, J. (2011). Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. *Proceedings of the National Academy of Sciences*, *108*(4), 1474−1478.

Čater, M. (2015). A 20-year overview of *Quercus robur* L. mortality and crown conditions in Slovenia. *Forests*, *6*(3), 581–593.
Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science*, *333*(6045), 1024–1026.
Chmura, D. J., Anderson, P. D., Howe, G. T., Harrington, C. A., Halofsky, J. E., Peterson, D. L., … Clair, J. B. S. (2011). Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. *Forest Ecology and Management*, *261*(7), 1121–1142.
Choat, B., Jansen, S., Brodribb, T. J., Cochard, H., Delzon, S., Bhaskar, R., … Zanne, A. E. (2012). Global convergence in the vulnerability of forests to drought. *Nature*, *491*(7426), 752–755.
Clark, J. S., Iverson, L., Woodall, C. W., Allen, C. D., Bell, D. M., Bragg, D. C., … Zimmermann, N. E. (2016). The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology*, *22*(7), 2329–2352.
Clark, S., Mills, G., Brown, T., Harris, S., & Abatzoglou, J. T. (2021). Downscaled GCM climate projections of fire weather over Victoria, Australia. Part 2*: A multi-model ensemble of 21st century trends. *International Journal of Wildland Fire*, *30*(8), 596–610.
Clarke, H. G., Smith, P. L., & Pitman, A. J. (2011). Regional signatures of future fire weather over eastern Australia from global climate models. *International Journal of Wildland Fire*, *20*(4), 550–562.
Cóbar-Carranza, A. J., García, R. A., Pauchard, A., & Peña, E. (2014). Effect of *Pinus contorta* invasion on forest fuel properties and its potential implications on the fire regime of *Araucaria araucana* and *Nothofagus antarctica* forests. *Biological Invasions*, *16*(11), 2273–2291.
Coulston, J. W., Wear, D. N., & Vose, J. M. (2015). Complex forest dynamics indicate potential for slowing carbon accumulation in the southeastern United States. *Scientific Reports*, *5*(1), 1–6.
Crausbay, S. D., Ramirez, A. R., Carter, S. L., Cross, M. S., Hall, K. R., Bathke, D. J., … Sanford, T. (2017). Defining ecological drought for the twenty-first century. *Bulletin of the American Meteorological Society*, *98*(12), 2543–2550.
Crawford, J. N., Mensing, S. A., Lake, F. K., & Zimmerman, S. R. (2015). Late Holocene fire and vegetation reconstruction from the western Klamath Mountains, California, USA: A multi-disciplinary approach for examining potential human land-use impacts. *The Holocene*, *25*(8), 1341–1357.
Crimmins, S. M., Dobrowski, S. Z., Greenberg, J. A., Abatzoglou, J. T., & Mynsberge, A. R. (2011). Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. *Science*, *331*(6015), 324–327.
Curtis, C. A., Pasquarella, V. J., & Bradley, B. A. (2019). Landscape characteristics of non-native pine plantations and invasions in Southern Chile. *Austral Ecology*, *44*(7), 1213–1224.
Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. *Science*, *361*, 1108–1111.
Davis, K. T., Dobrowski, S. Z., Holden, Z. A., Higuera, P. E., & Abatzoglou, J. T. (2019). Microclimatic buffering in forests of the future: The role of local water balance. *Ecography*, *42*(1), 1–11.
De Frenne, P., Lenoir, J., Luoto, M., Scheffers, B. R., Zellweger, F., Aalto, J., … Hylander, K. (2021). Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology*, *27*(11), 2279–2297.
De Rigo, D., Libertà, G., Durrant, T.H., Vivancos, T.A., & San-Miguel-Ayanz, J. (2017). *Forest fire danger extremes in Europe under climate change: Variability and uncertainty* (Research Report, Publications Office of the European Union). hal-02906196f.
Dobbertin, M., Mayer, P., Wohlgemuth, T., Feldmeyer-Christe, E., Graf, U., Zimmermann, N. E., & Rigling, A. (2005). The decline of *Pinus sylvestris* L. forests in the Swiss Rhone valley-a result of drought stress? *Phyton (Austria) Annales Rei Botanicae*, *45*(4), 153–156.
D'Orangeville, L., Maxwell, J., Kneeshaw, D., Pederson, N., Duchesne, L., Logan, T., … Phillips, R. P. (2018). Drought timing and local climate determine the sensitivity of eastern temperate forests to drought. *Global Change Biology*, *24*(6), 2339–2351.
Dudney, J., Willing, C. E., Das, A. J., Latimer, A. M., Nesmith, J. C. B., & Battles, J. J. (2021). Nonlinear shifts in infectious rust disease due to climate change. *Nature Communications*, *12*(1).
Dukes, J. S., Pontius, J., Orwig, D., Garnas, J. R., Rodgers, V. L., Brazee, N., … Ayres, M. (2009). Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Canadian Journal of Forest Research*, *39*(2), 231–248.
Dymond, C. C., Tedder, S., Spittlehouse, D. L., Raymer, B., Hopkins, K., McCallion, K., & Sandland, J. (2014). Diversifying managed forests to increase resilience. *Canadian Journal of Forest Research*, *44*(10), 1196–1205.
Ellis, E. C., Klein Goldewijk, K., Siebert, S., Lightman, D., & Ramankutty, N. (2010). Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*, *19*(5), 589–606.
Ettinger, A. K., Gee, S., & Wolkovich, E. M. (2018). Phenological sequences: How early-season events define those that follow. *American Journal of Botany*, *105*(10), 1771–1780.
European Environment Agency. (2021). *Forest fires in Europe*. <https://www.eea.europa.eu/data-and-maps/indicators/forest-fire-danger-4/assessment> Accessed 29.10.21.
Evans, P., & Brown, C. D. (2017). The boreal–temperate forest ecotone response to climate change. *Environmental Reviews*, *25*(4), 423–431.
Fettig, C. J., Gibson, K. E., Munson, A. S., & Negrón, J. F. (2014). Cultural practices for prevention and mitigation of mountain pine beetle infestations. *Forest Science*, *60*(3), 450–463.
Finch, D. M., Butler, J. L., Runyon, J. B., Fettig, C. J., Kilkenny, F. F., Jose, S., … Amelon, S. K. (2021). Effects of climate change on invasive species. In T. M. Poland, et al. (Eds.), *Invasive species in forests and rangelands of the United States* (pp. 57–83). Springer International Publishing. Available from https://doi.org/10.1007/978-3-030-45367-1_4.
Fischer, A., Marshall, P., & Camp, A. (2013). Disturbances in deciduous temperate forest ecosystems of the northern hemisphere: Their effects on both recent and future forest development. *Biodiversity and Conservation*, *22*(9), 1863–1893.

Flynn, D. F. B., & Wolkovich, E. M. (2018). Temperature and photoperiod drive spring phenology across all species in a temperate forest community. *New Phytologist*, *219*(4), 1353−1362.

Ford, K. R., Harrington, C. A., Bansal, S., Gould, P. J., & St. Clair, J. B. (2016). Will changes in phenology track climate change? A study of growth initiation timing in coast Douglas-fir. *Global Change Biology*, *22*(11), 3712−3723.

Foster, D. R. (1992). Land-use history (1730-1990) and vegetation dynamics in central New England, USA. *Journal of Ecology*, *80*, 753−771.

Foster, J. R., & D'Amato, A. W. (2015). Montane forest ecotones moved downslope in northeastern USA in spite of warming between 1984 and 2011. *Global Change Biology*, *21*(12), 4497−4507.

Fox-Hughes, P., Harris, R., Lee, G., Grose, M., & Bindoff, N. (2014). Future fire danger climatology for Tasmania, Australia, using a dynamically downscaled regional climate model. *International Journal of Wildland Fire*, *23*(3), 309−321.

Friedl, M. A., Gray, J. M., Melaas, E. K., Richardson, A. D., Hufkens, K., Keenan, T. F., . . . O'Keefe, J. (2014). A tale of two springs: Using recent climate anomalies to characterize the sensitivity of temperate forest phenology to climate change. *Environmental Research Letters*, *9*(5).

Galicia, L., & Zarco-Arista, A. E. (2014). Multiple ecosystem services, possible trade-offs and synergies in a temperate forest ecosystem in Mexico: A review. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *10*(4), 275−288.

Gao, P., Terando, A. J., Kupfer, J. A., Varner, J. M., Stambaugh, M. C., Lei, T. L., & Hiers, J. K. (2021). Robust projections of future fire probability for the conterminous United States. *Science of the Total Environment*, *789*, 147872.

Garnett, S. T., Burgess, N. D., Fa, J. E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C. J., . . . Leiper, I. (2018). A spatial overview of the global importance of Indigenous lands for conservation. *Nature Sustainability*, *1*(7), 369−374.

Gazol, A., Camarero, J. J., Sangüesa-Barreda, G., Serra-Maluquer, X., Sánchez-Salguero, R., Coll, L., & Casals, P. (2020). Tree species are differently impacted by cumulative drought stress and present higher growth synchrony in dry places. *Frontiers in Forests and Global Change*, *3*, 128.

Ghazoul, J., Burivalova, Z., Garcia-Ulloa, J., & King, L. A. (2015). Conceptualizing forest degradation. *Trends in Ecology & Evolution*, *30*(10), 622−632.

Gilliam, F. S. (2016). Forest ecosystems of temperate climatic regions: from ancient use to climate change. *New Phytologist*, *212*(4), 871−887.

Goldblum, D., & Rigg, L. S. (2010). The deciduous forest−boreal forest ecotone. *Geography Compass*, *4*(7), 701−717.

González, M. E., Gómez-González, S., Lara, A., Garreaud, R., & Díaz-Hormazábal, I. (2018). The 2010−2015 Megadrought and its influence on the fire regime in central and south-central Chile. *Ecosphere*, *9*(8), e02300.

Gonzalez, P., Hassan, R., McCallum, I., Nilsson, S., Pulhin, J., & Scholes, B. (2005). Forest and woodland systems. In A. Shvidenko, C. V. Barber, K. A. O'Halloran, & R. Persson (Eds.), *Millennium ecosystem assessment*. Island Press.

Gonzalez, P., Neilson, R. P., Lenihan, J. M., & Drapek, R. J. (2010). Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography*, *19*(6), 755−768.

Grossiord, C. (2020). Having the right neighbors: How tree species diversity modulates drought impacts on forests. *New Phytologist*, *228*(1), 42−49.

Gunn, J. S., Ducey, M. J., & Belair, E. (2019). Evaluating degradation in a North American temperate forest. *Forest Ecology and Management*, *432*, 415−426.

Halofsky, J. E., Andrews-Key, S. A., Edwards, J. E., Johnston, M. H., Nelson, H. W., Peterson, D. L., . . . Williamson, T. B. (2018). *Adapting forest management to climate change: The state of science and applications in Canada and the United States*, . *Forest Ecology and Management* (421, pp. 84−97). .

Halofsky, J. E., Peterson, D. L., & Prendeville, H. R. (2018). Assessing vulnerabilities and adapting to climate change in northwestern US forests. *Climatic Change*, *146*(1), 89−102.

Halofsky, J. E., Peterson, D. L., Aubry, C., Dowling, C., & Acker, S. A. (2011). Climate change and vegetation management at Olympic National Forest and Olympic National Park. In J. E. Halofsky, D. L. Peterson, K. A. O'Halloran, & C. Hawkins Hoffman (Eds.), *Adapting to climate change at Olympic National Forest and Olympic National Park* (pp. 61−90). Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, *General Technical Report PNW-GTR-844*.

Hand, M. S., & Lawson, M. (2017). Effects of climate change on recreation in the Northern Rockies. In J. E. Halofsky, & D. L. Peterson (Eds.), Climate change and rocky mountain ecosystems. Advances in global change research (Volume 63, pp. 169−188). Cham, Switzerland: Springer International Publishing.

Hanewinkel, M., Cullmann, D. A., Schelhaas, M. J., Nabuurs, G. J., & Zimmermann, N. E. (2013). Climate change may cause severe loss in the economic value of European forest land. *Nature Climate Change*, *3*(3), 203−207.

Hansen, M. C., Stehman, S. V., & Potapov, P. V. (2010). Quantification of global gross forest cover loss. *Proceedings of the National Academy of Sciences*, *107*(19), 8650−8655.

Harrington, T.C., & McNew, D.L. (2016). *Distribution and Intensification of Bur Oak Blight in Iowa and the Midwest* (Project NC-EM-B-10-01). General Technical Report: SRS 213. USDA Forest Service, Southern Research Station.

Heberling, J. M., McDonough MacKenzie, C., Fridley, J. D., Kalisz, S., & Primack, R. B. (2019). Phenological mismatch with trees reduces wildflower carbon budgets. *Ecology Letters*, *22*(4), 616−623.

Heller, N. E., & Zavaleta, E. S. (2009). Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, *142*(1), 14−32.

Hellmann, J. J., Byers, J. E., Bierwagen, B. G., & Dukes, J. S. (2008). Five potential consequences of climate change for invasive species. *Conservation Biology*, *22*(3), 534−543.

Hember, R. A., Kurz, W. A., & Coops, N. C. (2017). Relationships between individual-tree mortality and water-balance variables indicate positive trends in water stress-induced tree mortality across North America. *Global Change Biology*, *23*(4), 1691−1710.

Hessburg, P. F., Churchill, D. J., Larson, A. J., Haugo, R. D., Miller, C., Spies, T. A., ... Reeves, G. H. (2015). Restoring fire-prone Inland Pacific landscapes: Seven core principles. *Landscape Ecology*, *30*(10), 1805–1835.

Hewer, M., Scott, D., & Fenech, A. (2016). Seasonal weather sensitivity, temperature thresholds, and climate change impacts for park visitation. *Tourism Geographies*, *18*(3), 297–321.

Hicke, J. A., Logan, J. A., Powell, J., & Ojima, D. S. (2006). Changing temperatures influence suitability for modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States. *Journal of Geophysical Research: Biogeosciences*, *111*(G2), 1–12.

Higuera, P. E., & Abatzoglou, J. T. (2021). Record-setting climate enabled the extraordinary 2020 fire season in the western United States. *Global Change Biology*, *27*, 1–2.

Hijioka, Y., Lin, E., Pereira, J. J., Corlett, R., Cui, X., Insarov, G., ... Surjan, A. (2014). Asia. In V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate *Change*. United Kingdom and New York, NY: Cambridge.

Hislop, S., Haywood, A., Jones, S., Soto-Berelov, M., Skidmore, A., & Nguyen, T. H. (2020). A satellite data driven approach to monitoring and reporting fire disturbance and recovery across boreal and temperate forests. *International Journal of Applied Earth Observation and Geoinformation*, *87*, 102034.

Hoffman, K. M., Davis, E. L., Wickham, S. B., Schang, K., Johnson, A., Larking, T., ... Trant, A. J. (2021). Conservation of Earth's biodiversity is embedded in Indigenous fire stewardship. *Proceedings of the National Academy of Science*, *118*(2).

Holz, A., Paritsis, J., Mundo, I. A., Veblen, T. T., Kitzberger, T., Williamson, G. J., ... Quezada, J. M. (2017). Southern Annular Mode drives multicentury wildfire activity in southern South America. *Proceedings of the National Academy of Sciences*, *114*(36), 9552–9557.

Hoogakker, B. A. A., Smith, R. S., Singarayer, J. S., Marchant, R., Prentice, I. C., Allen, J. R. M., ... Tzedakis, C. (2016). Terrestrial biosphere changes over the last 120 kyr. *Climate of the Past*, *12*(1), 51–73.

IPCC. (2021). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, ... B. Zhou (Eds.), *Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, In press.

Isaak, D. J., Young, M. K., Luce, C. H., Hostetler, S. W., Wenger, S. J., Peterson, E. E., ... Nagel, D. E. (2016). Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. *Proceedings of the National Academy of Sciences*, *113*(16), 4374–4379.

Iturbide, M., Fernandez, M., Gutierrez, J., Bedia, J.M., Cimadevilla, J., Diez-Sierra, E., ... Yelekci, O. (2021). *IPCC-WG1/Atlas: Repository supporting the implementation of FAIR principles in the IPCC-WGI Atlas*. Retrieved from https://github.com/IPCC-WG1/Atlas.

Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., ... Brockerhoff, E. G. (2017). Tree diversity drives forest stand resistance to natural disturbances. *Current Forestry Reports*, *3*(3), 223–243.

Jactel, H., Petit, J., Desprez-Loustau, M. L., Delzon, S., Piou, D., Battisti, A., & Koricheva, J. (2012). Drought effects on damage by forest insects and pathogens: A meta-analysis. *Global Change Biology*, *18*(1), 267–276.

Jeong, S. J., Medvigy, D., Shevliakova, E., & Malyshev, S. (2013). Predicting changes in temperate forest budburst using continental-scale observations and models. *Geophysical Research Letters*, *40*(2), 359–364.

Kalabokidis, K., Palaiologou, P., Gerasopoulos, E., Giannakopoulos, C., Kostopoulou, E., & Zerefos, C. (2015). Effect of climate change projections on forest fire behavior and values-at-risk in southwestern Greece. *Forests*, *6*(6), 2214–2240.

Karl, T. R., Melillo, J. M., Peterson, T. C., & Hassol, S. J. (Eds.), (2009). *Global climate change impacts in the United States*. Cambridge University Press.

Keenan, R. J. (2015). Climate change impacts and adaptation in forest management: A review. *Annals of Forest Science*, *72*(2), 145–167.

Kelly, A. E., & Goulden, M. L. (2008). Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Sciences*, *105*(33), 11823–11826.

Kennedy, M. C., Bart, R. R., Tague, C. L., & Choate, J. S. (2021). Does hot and dry equal more wildfire? Contrasting short-and long-term climate effects on fire in the Sierra Nevada, CA. *Ecosphere*, *12*(7), e03657.

Kerns, B. K., Tortorelli, C., Day, M. A., Nietupski, T., Barros, A. M., Kim, J. B., & Krawchuk, M. A. (2020). Invasive grasses: A new perfect storm for forested ecosystems? *Forest Ecology and Management*, *463*, 117985.

Kovats, S. R., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., ... White, L. (2014). Europe. In V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), *Contribution of Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York, NY: Cambridge.

Krawchuk, M. A., Moritz, M. A., Parisien, M. A., Van Dorn, J., & Hayhoe, K. (2009). Global pyrogeography: The current and future distribution of wildfire. *PLoS One*, *4*(4), e5102.

Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., ... Safranyik, L. (2008). Mountain pine beetle and forest carbon feedback to climate change. *Nature*, *452*(7190), 987–990.

Landuyt, D., Perring, M. P., Seidl, R., Taubert, F., Verbeeck, H., & Verheyen, K. (2018). Modelling understorey dynamics in temperate forests under global change—challenges and perspectives. *Perspectives in Plant Ecology, Evolution and Systematics*, *31*, 44–54.

Latta, G., Temesgen, H., Adams, D., & Barrett, T. (2010). Analysis of potential impacts of climate change on forests of the United States Pacific Northwest. *Forest Ecology and Management*, *259*, 720–729.

Lenoir, J., Gégout, J. C., Marquet, P. A., De Ruffray, P., & Brisse, H. (2008). A significant upward shift in plant species optimum elevation during the 20th century. *Science*, *320*, 1768–1771.

Lenoir, J., Hattab, T., & Pierre, G. (2017). Climatic microrefugia under anthropogenic climate change: Implications for species redistribution. *Ecography*, *40*(2), 253–266.

Li, D., Wrzesien, M. L., Durand, M., Adam, J., & Lettenmaier, D. P. (2017). How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters*, *44*(12), 6163–6172.

Lindbladh, M., Fraver, S., Edvardsson, J., & Felton, A. (2013). Past forest composition, structures and processes—how paleoecology can contribute to forest conservation. *Biological Conservation*, *168*, 116–127.

Littell, J. S., McKenzie, D., Wan, H. Y., & Cushman, S. A. (2018). Climate change and future wildfire in the western United States: An ecological approach to nonstationarity. *Earth's Future*, *6*(8), 1097–1111.

Littell, J. S., Peterson, D. L., Millar, C. I., & O'Halloran, K. A. (2012). US National Forests adapt to climate change through Science—management partnerships. *Climatic Change*, *110*(1), 269–296.

Liu, H., Yin, Y., Hao, Q., & Liu, G. (2014). Sensitivity of temperate vegetation to Holocene development of East Asian monsoon. *Quaternary Science Reviews*, *98*, 126–134. Available from https://doi.org/10.1016/j.quascirev.2014.06.006.

Liu, Y., Stanturf, J., & Goodrick, S. (2010). Trends in global wildfire potential in a changing climate. *Forest Ecology and Management*, *259*(4), 685–697.

Logan, J. A., & Powell, J. A. (2001). Ghost forests, global warming, and the mountain pine beetle (Coleoptera: Scolytidae). *American Entomologist*, *47*(3), 160–173.

Logan, J. A., Macfarlane, W. W., & Willcox, L. (2010). Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the Greater Yellowstone Ecosystem. *Ecological Applications*, *20*(4), 895–902.

Logan, J. A., Régnière, J., & Powell, J. A. (2003). Assessing the impacts of global warming on forest pest dynamics. *Frontiers in Ecology and the Environment*, *1*(3), 130–137.

Luce, C., Morgan, P., Dwire, K., Isaak, D., Holden, Z., & Rieman, B. (2012). *Climate change, forests, fire, water, and fish: Building resilient landscapes, streams, and managers* (pp. 207). General Technical Report: RMRS-GTR-290. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Marcinkowski, K., Peterson, D. L., & Ettl, G. J. (2015). Nonstationary temporal response of mountain hemlock growth to climatic variability in the North Cascade Range, Washington, USA. *Canadian Journal of Forest Research*, *45*(6), 676–688.

Marini, L., Økland, B., Jönsson, A. M., Bentz, B., Carroll, A., Forster, B., … Schroeder, M. (2017). Climate drivers of bark beetle outbreak dynamics in Norway spruce forests. *Ecography*, *40*(12), 1426–1435.

McAvoy, T., Régnière, J., St-Amant, R., Schneeberger, N. F., & Salom, S. M. (2017). Mortality and recovery of hemlock woolly adelgid (*Adelges tsugae*) in response to winter temperatures and predictions for the future. *Forests*, *8*(12), 497.

McCarthy, H. R., Oren, R., Finzi, A. C., & Johnsen, K. H. (2006). Canopy leaf area constrains [CO_2]-induced enhancement of productivity and partitioning among aboveground carbon pools. *Proceedings of the National Academy of Sciences*, *103*(51), 19356–19361.

McGlone, M., Walker, S., Hay, R., & Christie, J. (2010). Climate change, natural systems, and their conservation in New Zealand. In A. Richard, C. Nottage, D. S. Wratt, J. F. Bomman, & K. Jones (Eds.), *Climate change adaptation in New Zealand* (pp. 82–100). Wellington, New Zealand: New Zealand Climate Change Centre.

McWethy, D. B., Garreaud, R. D., Holz, A., & Pederson, G. T. (2021). Broad-Scale surface and atmospheric conditions during large fires in South-Central Chile. *Fire*, *4*(2), 28.

Melillo, J. M., Frey, S. D., DeAngelis, K. M., Werner, W. J., Bernard, M. J., Bowles, F. P., … Grandy, A. S. (2017). Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. *Science*, *358*(6359), 101–105.

Menzel, A., Sparks, T. H., Estrella, N., Koch, E., Aaasa, A., Ahas, R., … Zust, A. (2006). European phenological response to climate change matches the warming pattern. *Global Change Biology*, *12*(10), 1969–1976.

Menzel, A., Yuan, Y., Matiu, M., Sparks, T., Scheifinger, H., Gehrig, R., & Estrella, N. (2020). Climate change fingerprints in recent European plant phenology. *Global Change Biology*, *26*(4), 2599–2612.

Messier, C., Puettmann, K. J., & Coates, K. D. (2013). *Managing forests as complex adaptive systems: Building resilience to the challenge of global change*. New York: Routledge.

Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., … Puettmann, K. (2019). The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, *6*(1), 1–16.

Miao, L., Zhu, F., He, B., Ferrat, M., Liu, Q., Cao, X., & Cui, X. (2013). Synthesis of China's land use in the past 300 years. *Global and Planetary Change*, *100*, 224–233.

Millar, C. I., & Stephenson, N. L. (2015). Temperate forest health in an era of emerging megadisturbance. *Science*, *349*(6250), 823–826.

Millar, C. I., Stephenson, N. L., & Stephens, S. L. (2007). Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications*, *17*(8), 2145–2151.

Millennium Ecosystem Assessment (Program). (2005). *Ecosystems and human well-being: synthesis*. Island Press.

Miyamoto, A., & Sano, M. (2008). The influence of forest management on landscape structure in the cool-temperate forest region of central Japan. *Landscape and Urban Planning*, *86*(3–4), 248–256.

Mote, P., Snover, A. K., Capalbo, S., Eigenbrode, S. D., Glick, P., Littlel, J., … Reeder, S. (2014). Northwest. Climate change impacts in the United States. In J. M. Melillo, T. C. Richmond, & G. W. Yohe (Eds.), *The third national climate assessment* (pp. 487–513). US Global Change Research Program.

Nabuurs, G. J., Delacote, P., Ellison, D., Hanewinkel, M., Hetemäki, L., & Lindner, M. (2017). By 2050 the mitigation effects of EU forests could nearly double through climate smart forestry. *Forests*, *8*(12), 484.

Nabuurs, G. J., Lindner, M., Verkerk, P. J., Gunia, K., Deda, P., Michalak, R., & Grassi, G. (2013). First signs of carbon sink saturation in European forest biomass. *Nature Climate Change*, *3*(9), 792–796.

Nagaike, T. (2020). The role of biodiversity concerns in regional and nationwide forest management plans of Japan-Do forest plans promote conservation? *Forest Policy and Economics*, *118*, 102250.

Nagel, L. M., Palik, B. J., Battaglia, M. A., D'Amato, A. W., Guldin, J. M., Swanston, C. W., … Roske, M. R. (2017). Adaptive silviculture for climate change: A national experiment in manager-scientist partnerships to apply an adaptation framework. *Journal of Forestry*, *115*(3), 167–178.

Nardini, A., Battistuzzo, M., & Savi, T. (2013). Shoot desiccation and hydraulic failure in temperate woody angiosperms during an extreme summer drought. *New Phytologist*, *200*(2), 322–329.

Negret, B. S., Pérez, F., Markesteijn, L., Castillo, M. J., & Armesto, J. J. (2013). Diverging drought-tolerance strategies explain tree species distribution along a fog-dependent moisture gradient in a temperate rain forest. *Oecologia*, *173*(3), 625–635.

Nelson, H. W., Williamson, T. B., Macaulay, C., & Mahony, C. (2016). Assessing the potential for forest management practitioner participation in climate change adaptation. *Forest Ecology and Management*, *360*, 388–399.

Noble, I. R., Huq, S., Anokhin, Y. A., et al. (2014). Adaptation needs and options. In C. B. Field, V. R. Barros, & D. J. Dokken (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate Change* (pp. 833–868). Cambridge, UK and New York, NY: Cambridge University Press.

Nolan, R. H., Gauthey, A., Losso, A., Medlyn, B. E., Smith, R., Chhajed, S. S., … Choat, B. (2021). Hydraulic failure and tree size linked with canopy die-back in eucalypt forest during extreme drought. *New Phytologist*, *230*(4), 1354–1365.

Norby, R. J., Hanson, P. J., O'Neill, E. G., Tschaplinski, T. J., Weltzin, J. F., Hansen, R. A., … Johnson, D. W. (2002). Net primary productivity of a CO2-enriched deciduous forest and the implications for carbon storage. *Ecological Applications*, *12*(5), 1261–1266.

Norby, R. J., Warren, J. M., Iversen, C. M., Medlyn, B. E., & McMurtrie, R. E. (2010). CO2 enhancement of forest productivity constrained by limited nitrogen availability. *Proceedings of the National Academy of Sciences*, *107*(45), 19368–19373.

Novenko, E. Y., Tsyganov, A. N., Mazei, N. G., Kupriyanov, D. A., Rudenko, O. V., Bobrovsky, M. V., … Nizovtsev, V. A. (2019). Palaeoecological evidence for climatic and human impacts on vegetation in the temperate deciduous forest zone of European Russia during the last 4200 years: A case study from the Kaluzhskiye Zaseki Nature Reserve. *Quaternary International*, *516*, 58–69.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., … Kassem, K. R. (2001). Terrestrial ecoregions of the world: A new map of life on Earth. *Bioscience*, *51*(11), 933–938.

Oren, R., Ellsworth, D. S., Johnsen, K. H., Phillips, N., Ewers, B. E., Maier, C., et al. (2001). Soil fertility limits carbon sequestration by forest ecosystems in a CO 2-enriched atmosphere. *Nature*, *411*(6836), 469.

Oswalt, S.N., Smith, W.B., Miles, P.D., & Pugh, S.A. (2014). *Forest resources of the United States, 2012: A technical document supporting the forest service 2010 update of the RPA assessment* (pp. 218). General Technical Report: WO-91. Washington, DC: USDA, Forest Service, Washington Office. https://srs.fs.usda.gov/pubs/47322.

Otkin, J. A., Svoboda, M., Hunt, E. D., Ford, T. W., Anderson, M. C., Hain, C., & Basara, J. B. (2018). Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, *99*(5), 911–919.

Pan, Y., Birdsey, R., Hom, J., & McCullough, K. (2009). Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of US Mid-Atlantic temperate forests. *Forest Ecology and Management*, *259*(2), 151–164.

Parks, S. A., & Abatzoglou, J. T. (2020). Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, *47*(22), e2020GL089858.

Parks, S. A., Holsinger, L. M., Panunto, M. H., Jolly, W. M., Dobrowski, S. Z., & Dillon, G. K. (2018). High-severity fire: Evaluating its key drivers and mapping its probability across western US forests. *Environmental Research Letters*, *13*(4), 044037.

Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, *37*, 637–669.

Parmesan, C., & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, *421*(6918), 37–42.

Payette, S., Pilon, V., Fregeau, M., Couillard, P. L., & Laflamme, J. (2021). Post-glacial climate–fire interactions control tree composition of mesic temperate forests in Eastern North America. *Ecosystems*, 1–22.

Peña, E., Hidalgo, M., Langdon, B., & Pauchard, A. (2008). Patterns of spread of *Pinus contorta* Dougl. ex Loud. invasion in a Natural Reserve in southern South America. *Forest Ecology and Management*, *256*(5), 1049–1054.

Peñuelas, J., Rutishauser, T., & Filella, I. (2009). Phenology feedbacks on climate change. *Science*, *324*(5929), 887–888.

Pereira, M. G., Calado, T. J., DaCamara, C. C., & Calheiros, T. (2013). Effects of regional climate change on rural fires in Portugal. *Climate Research*, *57*(3), 187–200.

Peterson, D.L., Millar, C.I., Joyce, L.A., Furniss, M.J., Halofsky, J.E., Neilson, R.P., & Morelli, T.L. (2011). *Responding to climate change in national forests: A guidebook for developing adaptation options* (pp. 109). General Technical Report: PNW-GTR-855. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Petrie, M. D., Bradford, J. B., Hubbard, R. M., Lauenroth, W. K., Andrews, C. M., & Schlaepfer, D. R. (2017). Climate change may restrict dryland forest regeneration in the 21st century. *Ecology*, *98*(6), 1548–1559.

Piao, S., Liu, Q., Chen, A., Janssens, I. A., Fu, Y., Dai, J., … Zhu, X. (2019). Plant phenology and global climate change: Current progresses and challenges. *Global Change Biology*, *25*(6), 1922–1940.

Polgar, C. A., & Primack, R. B. (2011). Leaf-out phenology of temperate woody plants: From trees to ecosystems. *New Phytologist*, *191*(4), 926−941.

Power, M. J., Marlon, J., Ortiz, N., Bartlein, P. J., Harrison, S. P., Mayle, F. E., … Zhang, J. H. (2008). Changes in fire regimes since the Last Glacial Maximum: An assessment based on a global synthesis and analysis of charcoal data. *Climate Dynamics*, *30*(7-8), 887−907.

Prevéy, J. S., Parker, L. E., Harrington, C. A., Lamb, C. T., & Proctor, M. F. (2020). Climate change shifts in habitat suitability and phenology of huckleberry (Vaccinium membranaceum). *Agricultural and Forest Meteorology*, *280*, 107803.

Pröebstl-Haider, U., Höedl, C., Ginner, K., & Borgwardt, F. (2021). Climate change: Impacts on outdoor activities in the summer and shoulder seasons. *Journal of Outdoor Recreation and Tourism*, *34*, 100344.

Pugh, T. A., Arneth, A., Kautz, M., Poulter, B., & Smith, B. (2019). Important role of forest disturbances in the global biomass turnover and carbon sinks. *Nature Geoscience*, *12*(9), 730−735.

Pyke, C. R., Thomas, R., Porter, R. D., Hellmann, J. J., Dukes, J. S., Lodge, D. M., & Chavarria, G. (2008). Current practices and future opportunities for policy on climate change and invasive species. *Conservation Biology*, *22*(3), 585−592.

Rawal, D. S., Kasel, S., Keatley, M. R., & Nitschke, C. R. (2015). Climatic and photoperiodic effects on flowering phenology of select eucalypts from south-eastern Australia. *Agricultural and Forest Meteorology*, *214*, 231−242.

Renner, S. S., & Zohner, C. M. (2018). Climate change and phenological mismatch in trophic interactions among plants, insects, and vertebrates. *Annual Review of Ecology, Evolution, and Systematics*, *49*, 165−182.

Reyer, C. P., Bathgate, S., Blennow, K., Borges, J. G., Bugmann, H., Delzon, S., … Hanewinkel, M. (2017). Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? *Environmental Research Letters*, *12*(3), 034027.

Roberts, S. D., & Harrington, C. A. (2008). Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. *Forest Ecology and Management*, *255*(7), 2771−2781.

Rogers, B. M., Neilson, R. P., Drapek, R., Lenihan, J. M., Wells, J. R., Bachelet, D., & Law, B. E. (2011). Impacts of climate change on fire regimes and carbon stocks of the US Pacific Northwest. *Journal of Geophysical Research: Biogeosciences*, *116*(G3).

Roos, C., Swetnam, T. W., Ferguson, T. J., Liebmann, M. J., Loehman, R. A., Welch, J. R., … Kiahtipes, C. A. (2021). Native American fire management at an ancientwildland−urban interface in the Southwest United States. *Proceedings of the National Academy of Sciences*, *118*(4), 1−11.

Root, T. L., Price, J. T., Hall, K. R., Schneider, S. H., Rosenzweig, C., & Pounds, J. A. (2003). Fingerprints of global warming on wild animals and plants. *Nature*, *421*(6918), 57−60.

Rother, M. T., Veblen, T. T., & Furman, L. G. (2015). A field experiment informs expected patterns of conifer regeneration after disturbance under changing climate conditions. *Canadian Journal of Forest Research*, *45*(11), 1607−1616.

Ruffault, J., Curt, T., Moron, V., Trigo, R. M., Mouillot, F., Koutsias, N., … Belhadj-Khedher, C. (2020). Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. *Scientific Reports*, *10*(1), 1−9.

Sáenz-Romero, C., O'Neill, G., Aitken, S. N., & Lindig-Cisneros, R. (2021). Assisted migration field tests in Canada and Mexico: Lessons, limitations, and challenges. *Forests*, *12*(1), 9.

Savage, J., & Vellend, M. (2015). Elevational shifts, biotic homogenization and time lags in vegetation change during 40 years of climate warming. *Ecography*, *38*(6), 546−555.

Savage, M., & Mast, J. N. (2005). How resilient are southwestern ponderosa pine forests after crown fires? *Canadian Journal of Forest Research*, *35*(4), 967−977.

Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., … Kahmen, A. (2020). A first assessment of the impact of the extreme 2018 summer drought on Central European forests. *Basic and Applied Ecology*, *45*, 86−103.

Scott, D., Jones, B., & Konopek, J. (2007). Implications of climate and environmental change for nature-based tourism in the Canadian Rocky Mountains: A case study of Waterton Lakes National Park. *Tourism Management*, *28*(2), 570−579.

Seebens, H., Blackburn, T. M., Dyer, E. E., Genovesi, P., Hulme, P. E., Jeschke, J. M., … Essl, F. (2017). No saturation in the accumulation of alien species worldwide. *Nature Communications*, *8*(1), 1−9.

Seidl, R., Schelhaas, M. J., Rammer, W., & Verkerk, P. J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. *Nature Climate Change*, *4*(9), 806−810.

Seidl, R., Spies, T. A., Peterson, D. L., Stephens, S. L., & Hicke, J. A. (2016). Searching for resilience: Addressing the impacts of changing disturbance regimes on forest ecosystem services. *Journal of Applied Ecology*, *53*(1), 120−129.

Senf, C., & Seidl, R. (2018). Natural disturbances are spatially diverse but temporally synchronized across temperate forest landscapes in Europe. *Global Change Biology*, *24*(3), 1201−1211.

Senf, C., Buras, A., Zang, C. S., Rammig, A., & Seidl, R. (2020). Excess forest mortality is consistently linked to drought across Europe. *Nature Communications*, *11*(1), 1−8.

Shepherd, T. G. (2014). Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geoscience*, *7*, 703−708.

Shoyama, K. (2008). Reforestation of abandoned pasture on Hokkaido, northern Japan: Effect of plantations on the recovery of conifer-broadleaved mixed forest. *Landscape and Ecological Engineering*, *4*(1), 11−23.

Shoyama, K., Matsui, T., Hashimoto, S., Kabaya, K., Oono, A., & Saito, O. (2019). Development of land-use scenarios using vegetation inventories in Japan. *Sustainability Science*, *14*(1), 39−52.

Sinclair, S. J., White, M. D., & Newell, G. R. (2010). How useful are species distribution models for managing biodiversity under future climates? *Ecology and Society*, *15*(1).

Sofaer, H. R., Jarnevich, C. S., Pearse, I. S., Smyth, R. L., Auer, S., Cook, G. L., … Hamilton, H. (2019). Development and delivery of species distribution models to inform decision-making. *BioScience*, *69*(7), 544−557.

Sohn, J. A., Saha, S., & Bauhus, J. (2016). Potential of forest thinning to mitigate drought stress: A meta-analysis. *Forest Ecology and Management*, *380*, 261–273.

Solberg, S. (2004). Summer drought: A driver for crown condition and mortality of Norway spruce in Norway. *Forest Pathology*, *34*(2), 93–104.

Sorte, C. J. B., Ibáñez, I., Blumenthal, D. M., Molinari, N. A., Miller, L. P., Grosholz, E. D., … Dukes, J. S. (2013). Poised to prosper? A cross-system comparison of climate change effects on native and non-native species performance. *Ecology Letters*, *16*(2), 261–270.

Sousa-Silva, R., Verbist, B., Lomba, Â., Valent, P., Suškevičs, M., Picard, O., … Muys, B. (2018). *Adapting forest management to climate change in Europe: Linking perceptions to adaptive responses*, . *Forest Policy and Economics* (90, pp. 22–30). .

Spake, R., Yanou, S., Yamaura, Y., Kawamura, K., Kitayama, K., & Doncaster, C. P. (2019). Meta-analysis of management effects on biodiversity in plantation and secondary forests of Japan. *Conservation Science and Practice*, *1*(3), e14.

Spear, M. J., Walsh, J. R., Ricciardi, A., & Zanden, M. J. Vander (2021). The invasion ecology of sleeper populations: Prevalence, persistence, and abrupt shifts. *BioScience*, *71*(4), 357–369.

Spies, T. A., Giesen, T. W., Swanson, F. J., Franklin, J. F., Lach, D., & Johnson, K. N. (2010). Climate change adaptation strategies for federal forests of the Pacific Northwest, USA: Ecological, policy, and socio-economic perspectives. *Landscape Ecology*, *25*(8), 1185–1199.

Stephens, L., Fuller, D., Boivin, N., Rick, T., Gauthier, N., Kay, A., & Ellis, E. (2019). Archaeological assessment reveals Earth's early transformation through land use. *Science*, *365*(6456), 897–902.

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*, *18*(8), 1136–1155.

Suarez, M. L., & Kitzberger, T. (2008). Recruitment patterns following a severe drought: Long-term compositional shifts in Patagonian forests. *Canadian Journal of Forest Research*, *38*(12), 3002–3010.

Syphard, A. D., Sheehan, T., Rustigian-Romsos, H., & Ferschweiler, K. (2018). Mapping future fire probability under climate change: Does vegetation matter? *PLoS One*, *13*(8), e0201680.

Taylor, A. R., Boulanger, Y., Price, D. T., Cyr, D., McGarrigle, E., Rammer, W., & Kershaw, J. A. (2017). Rapid 21st century climate change projected to shift composition and growth of Canada's Acadian Forest Region. *Forest Ecology and Management*, *405*, 284–294.

Thom, D., & Seidl, R. (2016). Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biological Reviews of the Cambridge Philosophical Society*, *91*(3), 760–781.

Thom, D., Rammer, W., Dirnböck, T., Müller, J., Kobler, J., Katzensteiner, K., … Seidl, R. (2017). The impacts of climate change and disturbance on spatio-temporal trajectories of biodiversity in a temperate forest landscape. *Journal of Applied Ecology*, *54*(1), 28–38.

Tian, X., Sohngen, B., Kim, J. B., Ohrel, S., & Cole, J. (2016). Global climate change impacts on forests and markets. *Environmental Research Letters*, *11*(3), 035011.

Timberlake, T. J., & Schultz, C. A. (2017). Policy, practice, and partnerships for climate change adaptation on US national forests. *Climatic Change*, *144*(2), 257–269.

Tobin, P. C., Parry, D., & Aukema, B. H. (2014). The influence of climate change on insect invasions in temperate forest ecosystems. In T. Fenning (Ed.), *Challenges and opportunities for the world's forests in the 21st century* (pp. 267–293). Dordrecht: Springer.

Toro, J., & Gessel, S. (1999). Radiata pine plantations in Chile. *New Forests*, *18*, 33–44.

Turbelin, A. J., Malamud, B. D., & Francis, R. A. (2017). Mapping the global state of invasive alien species: Patterns of invasion and policy responses. *Global Ecology and Biogeography*, *26*(1), 78–92.

Turco, M., Bedia, J., Di Liberto, F., Fiorucci, P., Von Hardenberg, J., Koutsias, N., … Provenzale, A. (2016). Decreasing fires in Mediterranean Europe. *PLoS One*, *11*(3), e0150663.

Velazco, S. J. E., Ribeiro, B. R., Laureto, L. M. O., & Júnior, P. D. M. (2020). Overprediction of species distribution models in conservation planning: A still neglected issue with strong effects. *Biological Conservation*, *252*, 108822.

Venegas-González, A., Juñent, F. R., Gutiérrez, A. G., & Filho, M. T. (2018). Recent radial growth decline in response to increased drought conditions in the northernmost *Nothofagus* populations from South America. *Forest Ecology and Management*, *409*, 94–104.

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K. R., … Watson, J. E. (2016). Global terrestrial Human Footprint maps for 1993 and 2009. *Scientific Data*, *3*(1), 1–10.

Villa-Martínez, R., & Moreno, P. I. (2021). Development and resilience of deciduous Nothofag*us* forests since the Last Glacial Termination and deglaciation of the central Patagonian Andes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *574*, 110459.

Vissault, S., Talluto, M. V., Boulangeat, I., & Gravel, D. (2020). Slow demography and limited dispersal constrain the expansion of north-eastern temperate forests under climate change. *Journal of Biogeography*, *47*(12), 2645–2656.

Vose, J. M., Peterson, D. L., Domke, G. M., Fettig, C. J., Joyce, L. A., Keane, R. E., … Halofsky, J. E. (2018). Forests. In D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, & B. C. Stewart (Eds.), *Impacts, risks, and adaptation in the United States: Fourth national climate assessment* (Vol. II, pp. 232–267). Washington, DC: U.S. Global Change Research Program.

Walentowski, H., Falk, W., Mette, T., Kunz, J., Bräuning, A., Meinardus, C., … Leuschner, C. (2017). Assessing future suitability of tree species under climate change by multiple methods: A case study in southern Germany. *Annals of Forest Research*, *60*(1), 101–126.

Walsh, M. K., Duke, H. J., & Haydon, K. C. (2018). Toward a better understanding of climate and human impacts on late Holocene fire regimes in the Pacific Northwest, USA. *Progress in Physical Geography: Earth and Environment*, *42*(4), 478–512.

Wang, W. J., He, H. S., Thompson, F. R., Fraser, J. S., & Dijak, W. D. (2017). Changes in forest biomass and tree species distribution under climate change in the northeastern United States. *Landscape Ecology*, *32*(7), 1399–1413.

Warziniack, T.W., Elmer, M.J., Miller, C.J., Dante-Wood, S.K., Woodall, C.W., Nichols, M.C., . . . Borchers, A.M.. (2018). Chapter 13: effects of climate change on ecosystem services. In: Halofsky, J.E., Peterson, D.L., Ho, J.J., Little, N., J., & Joyce, L.A. (Eds.), *Climate change vulnerability and adaptation in the Intermountain Region [Part 2]* (pp. 376−403). General Technical Report: RMRS-GTR-375. Fort Collins, Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Wear, D. N., & Coulston, J. W. (2015). From sink to source: Regional variation in US forest carbon futures. *Scientific Reports*, *5*(1), 1−11.

Williams, A. P., Allen, C. D., Macalady, A. K., Griffin, D., Woodhouse, C. A., Meko, D. M., . . . McDowell, N. G. (2013). Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, *3*(3), 292−297.

Williams, A. P., Seager, R., Abatzoglou, J. T., Cook, B. I., Smerdon, J. E., & Cook, E. R. (2015). Contribution of anthropogenic warming to California drought during 2012−2014. *Geophysical Research Letters*, *42*(16), 6819−6828.

Williams, C. A., Gu, H., MacLean, R., Masek, J. G., & Collatz, G. J. (2016). Disturbance and the carbon balance of US forests: A quantitative review of impacts from harvests, fires, insects, and droughts. *Global and Planetary Change*, *143*, 66−80.

Williams, P. A., Cook, B. I., Smerdon, J. E., Bishop, D. A., Seager, R., & Mankin, J. S. (2017). The 2016 southeastern US drought: An extreme departure from centennial wetting and cooling. *Journal of Geophysical Research: Atmospheres*, *122*(20), 10−888.

Williamson, T. B., Campagna, M. A., & Ogden, A. E. (2012). *Adapting sustainable forest management to climate change: A framework for assessing vulnerability and mainstreaming adaptation into decision making*. Canadian Council of Forest Ministers.

Wolkovich, E. M., Jonathan Davies, T., Schaefer, H., Cleland, E. E., Cook, B. I., Travers, S. E., . . . Davis, C. C. (2013). Temperature-dependent shifts in phenology contribute to the success of exotic species with climate change. *American Journal of Botany*, *100*(7), 1407−1421.

Wu, Z., He, H. S., Keane, R. E., Zhu, Z., Wang, Y., & Shan, Y. (2020). Current and future patterns of forest fire occurrence in China. *International Journal of Wildland Fire*, *29*(2), 104−119.

Xie, G., Li, W., Xiao, Y., Zhang, B., Lu, C., An, K., . . . Wang, J. (2010). Forest ecosystem services and their values in Beijing. *Chinese Geographical Science*, *20*(1), 51−58.

Xie, Y., Ahmed, K. F., Allen, J. M., Wilson, A. M., & Silander, J. A. (2015). Green-up of deciduous forest communities of northeastern North America in response to climate variation and climate change. *Landscape Ecology*, *30*(1), 109−123.

Young, D. J., Stevens, J. T., Earles, J. M., Moore, J., Ellis, A., Jirka, A. L., & Latimer, A. M. (2017). Long-term climate and competition explain forest mortality patterns under extreme drought. *Ecology Letters*, *20*(1), 78−86.

Zamorano-Elgueta, C., Benayas, J. M. R., Cayuela, L., Hantson, S., & Armenteras, D. (2015). Native forest replacement by exotic plantations in southern Chile (1985−2011) and partial compensation by natural regeneration. *Forest Ecology and Management*, *345*, 10−20.

Zani, D., Crowther, T. W., Mo, L., Renner, S. S., & Zohner, C. M. (2020). Increased growing-season productivity drives earlier autumn leaf senescence in temperate trees. *Science*, *370*(6520), 1066−1071.

Zhang, F., Biederman, J. A., Dannenberg, M. P., Yan, D., Reed, S. C., & Smith, W. K. (2021). Five decades of observed daily precipitation reveal longer and more variable drought events across much of the western United States. *Geophysical Research Letters*, *48*(7), e2020GL092293.

Zhang, L., Xiao, J., Li, J., Wang, K., Lei, L., & Guo, H. (2012). The 2010 spring drought reduced primary productivity in southwestern China. *Environmental Research Letters*, *7*(4), 045706.

Zhao, M., & Running, S. W. (2010). Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, *329* (5994), 940−943.

Zhu, C., Ma, C., Yu, S. Y., Tang, L., Zhang, W., & Lu, X. (2010). A detailed pollen record of vegetation and climate changes in Central China during the past 16 000 years. *Boreas*, *39*(1), 69−76.