The impacts of climate change at Mount Rainier National Park

Photo credit: Larry Workman

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Summary

Past and future climate change

Average annual temperature in the Pacific Northwest has increased 0.83ºC (1.5ºF) since 1920 and is projected to increase an additional 2.0-4.0ºC (3.6-7.2ºF), or more, by the end of the century. In addition to higher temperatures, the region will likely experience wetter winters and drier summers, with a slight increase in annual precipitation. These alterations of the climate system are due in large part to human actions, namely the emission of greenhouse gasses. Below are some of the ways Mount Rainier National Park could be affected by these changes in climate.

Glaciers, debris flows and floods

The Park's glaciers have decreased in area and volume over the last century in association with increasing temperatures. The retreat of the glaciers has exposed large amounts of loose dirt that can be washed into river channels during heavy rain events. Once in the channel, this dirt mixes with water to form a fast moving slurry called a debris flow. These flows can be very powerful and dislodge large boulders or trees, and also destroy riverside buildings and roads. Much of the debris washed into the Park's rivers settles out at lower elevations and accumulates on the river bed. Some areas of the Park have experienced such high rates of accumulation that the beds of some stretches of river are actually above the surrounding landscape, making it more likely for waters to overtop river banks and flood large areas of land during intense rainstorms. For example, Longmire is 8.8m (29 feet) *below* the bed of the nearby Nisqually River. Future temperature increases will likely lead to greater retreat of the glaciers and perhaps increased risk of debris flows and flooding.

Air quality

Mount Rainier's location downwind of the Seattle-Tacoma metropolitan area can lead to high concentrations of air pollutants in the Park. In fact, high elevation sites such as Paradise typically have higher average ground-level ozone concentrations than Seattle. Ground-level ozone is an air pollutant that harms humans and other organisms. Higher temperatures tend to lead to higher concentrations of ground level ozone and other air pollutants. Therefore, future warming is expected to have a negative impact on the Park's air quality.

Forests

The abundances and distributions of the Park's tree species are strongly influenced by climate. Thus, climate change is expected to lead to shifts in the geographic ranges of tree species within the Park. But the long lifetimes of these trees suggest that climate change induced range shifts will likely be slow in the absence of major disturbances. However, background rates of tree mortality have increased in Pacific Northwest forests, a trend thought to be caused by higher temperatures and greater drought stress. This increased mortality could alter the structure, composition and carbon storage of Mount Rainier's forests. Also, the increased temperatures and decreased summer precipitation brought about by climate change would lead to drier conditions that could increase the frequency of forest fires. An increase in fire frequency could also lead to faster shifts in tree species ranges if fires kill adult members of cool-adapted species to allow seedlings of warm-adapted species to establish.

Subalpine and alpine meadows

The subalpine and alpine meadows of the Park are found at high elevations where temperatures are too cold or snow covers the ground for too long for trees to grow. Over the last century, ecologists have documented tree establishment in subalpine meadows throughout the Park in association with increased temperatures. Higher temperatures and longer snow free periods in the future will likely lead to the establishment of more trees in subalpine meadows and colonization of bare ground by alpine plants, leading to an overall upward movement of these meadows. This movement will probably result in a reduction of the area occupied by the meadows, because there is less land at higher elevations, which could lead to the loss of some subalpine and alpine plant species.

Whitebark pine

The whitebark pines at Mount Rainier have been victim to a non-native disease called the white pine blister rust that has killed many of these trees in the Park. Climate change exacerbates the problem of the blister rust. One of these threats is a potential increase in outbreaks of the mountain pine beetle (a bark-boring insect) which can cause widespread mortality amongst whitebark pines. Although the mountain pine beetle is native to the Park, the high elevation habitats of whitebark pine have historically been too cold for beetle populations to reach epidemic proportions in most years. Rising temperatures would lead to whitebark pine stands becoming more suitable for the beetle, which could, in turn, lead to more beetle outbreaks and reduced numbers of whitebark pines.

The American pika

The American pika is a small mammal found at high elevations in the Park. The animal is sensitive to high temperatures and could be negatively affected by warming in parts of its range. Consistent with this expectation are observations in the Great Basin region of the Southwestern US that 10 out of 25 pika populations documented in the 20^{th} century have apparently disappeared, and that the extinct populations were in warmer locations than surviving populations. However, pikas currently occupy locations with a wide range of average temperatures, suggesting that a large portion of the species' habitat will continue to experience suitable temperatures even with substantial warming. Pikas have also been known to adjust their behavior to cope with high temperatures by resting inside shady boulder fields during hot weather and shifting their foraging to cooler times of day. Thus, the pika will likely face threats from climate change, but may be well suited to cope with these threats.

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Introduction

"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."

-Intergovernmental Panel on Climate Change (IPCC), 2007

Average annual temperature in the Pacific Northwest has increased 0.83ºC (1.5ºF) since 1920 and is projected to increase an additional 2.0-4.0ºC (3.6-7.2ºF), or more, by the end of the century. In addition to higher temperatures, the region will likely experience wetter winters and drier summers, with a slight increase in annual precipitation (Mote and Salathé 2009). The scientific consensus is that these changes in climate are due in large part to human actions, namely the emission of greenhouse gasses from burning fossil fuels, deforestation and agriculture (IPCC 2007, Mote and Salathé 2009). The purpose of this report is to review how these ongoing changes are affecting some of the most valued resources at Mount Rainier National Park and what these changes mean for the future of the Park. It appears that a number of these resources are vulnerable to large changes in climate and that the Park will face unprecedented challenges in conserving the resources it is mandated to protect.

Glaciers, debris flows and floods

Mount Rainier's glaciers are the largest single-mountain glacier system in the contiguous 48 states (91 square kilometers or 35 square miles), represent 25% of the total ice area in the contiguous 48 states and contain as much ice (by volume) as all the other Cascade volcanoes combined (NPS 2001, Nylen 2004). However, these glaciers shrank 22% by area and 25% by volume between 1913 and 1994 in conjunction with rising temperatures (Nylen 2004). The most recent studies of Park glaciers have shown that monitored glaciers are continuing to retreat (NPS 2009a). Beyond Mount Rainier, there has been a general trend of glaciers shrinking across western North America (Moore et al. 2009) and the globe (Lemke et al. 2007) over the last century, in association with increasing temperatures.

This shrinking not only diminishes the Park's iconic glaciers, but also increases the risk of geologic hazards. As the glaciers recede, they expose and de-buttress large amounts of sediment that is easily washed into river channels during heavy rain events (Figure 1). During especially intense rain events, this large amount of sediment can mix with water in river channels to form a fast-moving slurry called a *debris flow*, which is similar in appearance to wet concrete. The mass of the sediment adds momentum to the river's flow and makes it much more powerful than it would be with water alone. As a result, the debris flow can dislodge large boulders, old-growth trees and other large objects in its path as it moves down steep slopes, leading to a snowball effect where the flow becomes more powerful and mobilizes even more debris (Ballantyne 2002). These debris flows pose a threat to human infrastructure in the Park, and can easily destroy riverside buildings and roads.

As the debris flows travel down river and reach the Park's lower elevations, the slope of the river's course becomes less steep and the river's flow slows down. As this happens, the sediment, rocks and other objects in the debris flow settle out and begin to accumulate in the riverbed, increasing the height of the channel in a process called *aggradation*. Because of the large amount of loose sediment exposed by glacial recession in the Park, substantial aggradation occurs even during periods of normal river flow. However, aggradation is especially rapid during debris flows spawned by heavy rains. For example, the background rate of aggradation is 15 – 36 cm (6-14 inches) per decade in the Park's braided rivers, but around 1.8m (6 feet) of material was deposited along a section of the Nisqually River during a single debris flow. In other words, around 30 – 70 years worth of background aggradation occurred in the span of a few days (Beason and Kennard 2007).

Figure 1. The Nisqually Glacier, situated on the South side of Mount Rainier, has receded over the last century and exposed a large amount of unstable sediment. Destructive debris flows have originated from these recently exposed areas (photo credit: wikimedia.org).

High rates of aggradation can raise river channels to elevations above the nearby landscape, so that one actually has to walk *up*hill to reach the river. For instance, the bed of the White River is as much as 4.8m (16 feet) above the adjacent landscape which includes State Route 410 (an important highway for Park workers and visitors), while the bed of the Nisqually River is 8.8m (29 feet) above Longmire (one of the largest developed areas in the Park containing lodging, offices and facilities for workers and visitors). Because of the elevated of river channels, floods tend to be more severe because water can more easily spill over river banks and down onto the surrounding landscape during high rainfall events (Beason and Kennard 2007).

Mount Rainier experienced how damaging these hazards can be in November 2006 when a major storm produced 46cm (18 inches) of rainfall in just 36 hours (NPS 2009b). The debris flows and floods that ensued caused widespread damage throughout the Park, including destroyed roads, trails, campgrounds, buildings and utility systems (NPS 2009b) (Figure 2). The damage forced the Park to close for 6 months and total recovery costs have been estimated at over $27 million (NPS 2009b). Although extraordinarily high rainfall set off the debris flows and flooding, receding glaciers probably made these hazards more destructive than they would have been otherwise (Beason and Kennard 2007).

Heavy rainfall is not the only force that can spark these debris flows and floods. As glaciers melt, large lakes can form on top of or within the glaciers, held in place by ice dams. These ice dams can eventually fail, releasing large amounts of water in a *glacial outburst flood* (also known by the Icelandic term, *jökulhlaup*). Ice dam failures can be brought about by periods of high rainfall or high temperatures when a large amount of meltwater is produced (Walder and Driedger 1993). These floods can then spawn debris flows, creating serious threats to downstream locations. Glacial outburst floods have occurred repeatedly within a number of the glacier fed streams and rivers of Mount Rainier (Walder and Driedger 1993). A similar phenomenon can occur when lakes form behind the terminal moraine of a receding glacier. The moraines, which serve as dams for the lakes, can fail and unleash large outburst floods that lead to debris flows downstream. These types of floods have occurred in several valleys that have experienced glacial recession in western North America (Moore et al. 2009).

As the climate continues to warm, the glaciers of Mount Rainier will likely continue to recede. This would lead to more unstable sediment becoming exposed, likely increasing the frequency and intensity of debris flows (O'Connor and Costa 1993, Evans and Clague 1994). In addition, the newly exposed sediment will probably lead to greater increases in the rate of aggradation within Park rivers, further increasing the risk of flooding (Beason and Kennard 2007). Thus, climate change poses a serious threat to the glaciers, rivers, infrastructure (including buildings and roads that are part of the Mount Rainier National Historic Landmark District) and people of Mount Rainier.

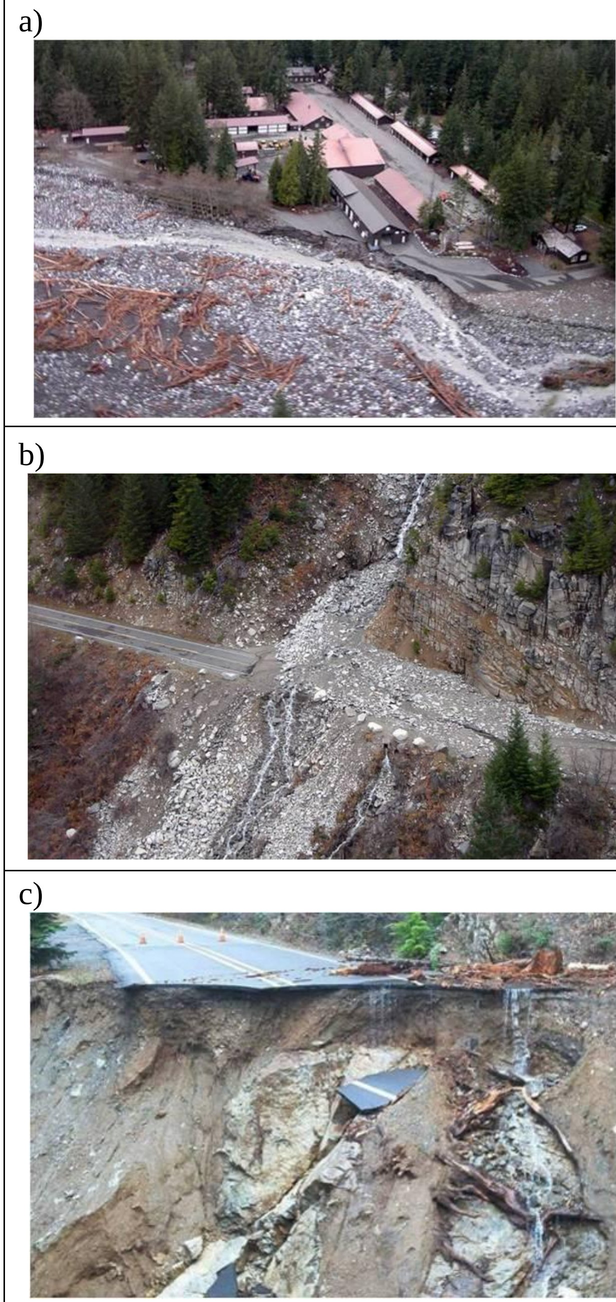

Figure 2. Photos from Mount Rainier National Park illustrating the impacts of the 2006 flood; a) The Nisqually River at Longmire; b) Stevens Canyon Road; c) State Route 123. Photo credits: (NPS 2009b).

Air quality

Mount Rainier National Park is a mandatory class 1 air quality area as defined by the Clean Air Act, which means the Park receives the highest level of air quality protection. Air pollution mostly comes from outside Park boundaries, particularly from the Seattle-Tacoma metropolitan area. Air pollutants that have been noted as a concern for the Park include ground-level ozone, sulfates, nitrates and fine particulates (NPS 2001). The concentration of some of these pollutants may be altered by climate change.

Ground-level ozone

Although ozone in the stratosphere is important for protecting humans and other organisms from damaging ultraviolet radiation, ozone produced near the surface of the Earth can have negative impacts on human health and ecosystem function. For humans, high concentrations of ozone can cause both short and long term declines in lung function (Bernard et al. 2001). Individuals working and exercising outside as well as those with respiratory illnesses are especially at risk (Bernard et al. 2001). In addition, ground-level ozone is thought to be responsible for over 90% of the damage to vegetation caused by air pollution because it disrupts photosynthesis (Felzer et al. 2004).

Ground-level ozone is formed in the atmosphere by the reaction of nitrogen oxides with volatile organic compounds in the presence of sunlight. Nitrogen oxides are emitted from natural sources such as lightning and biological processes in the soil, as well as from human sources, mostly the combustion of fossil fuels. Similarly, volatile organic compounds come from natural sources such as vegetation, and from human sources including gasoline, refineries, chemical plants, factories and various commercial products (e.g. paint, cleaning supplies, pesticides) (Bernard et al. 2001). Thus, although ground-level ozone is produced in natural environments, it reaches far higher concentrations because of industrial activities.

In the past few decades, elevated ozone concentrations have been recorded within the Park, particularly at high elevation sites such as Paradise (NPS 2001, Brace and Peterson 1998, Peterson et al. 1999). In fact, high elevation sites at Mount Rainier typically have greater average concentrations of ozone than the Seattle-Tacoma metropolitan area and have experienced some of the highest average concentrations of ozone in western Washington. These high concentrations are thought to result from prevailing winds carrying ozone and its precursors from urban areas in the Puget Sound Region to Mount Rainier (Peterson et al. 1999, Cooper and Peterson 2000). Although the Pacific Northwest does not have the highest levels of ozone pollution in the country (EPA 2006), recent decades have seen ozone levels in the region rise above standards set by the US Environmental Protection Agency (EPA) (Barna et al. 2000). Several species of plants in the Park have been shown to be sensitive to ozone pollution (Brace et al. 1999) (Figure 3) and vegetation within the Park, particularly at high elevations, is thought to be at risk of ozone damage given current concentrations (Brace and Peterson 1998).

a) Low ozone exposure | b) High ozone exposure

Figure 3. Photographs of specimens of broad-leaf lupine experimentally exposed to (a) low and (b) high levels of ozone (Brace et al. 1999).

Climate change is expected to increase concentrations of ground-level ozone in the Pacific Northwest and other regions because high concentrations of ozone are correlated with high temperatures (Peterson et al. 1999, Bernard et al. 2001, Confalonieri et al. 2007, Jackson et al. 2009, Chen et al. 2009) (Figure 4). This correlation exists because higher temperatures increase the rates at which nitrogen oxides and volatile organic compounds react in the atmosphere to form ozone, and also increase natural emissions of nitrogen oxides (from the soil) and volatile organic compounds (from vegetation) (Bernard et al. 2001).

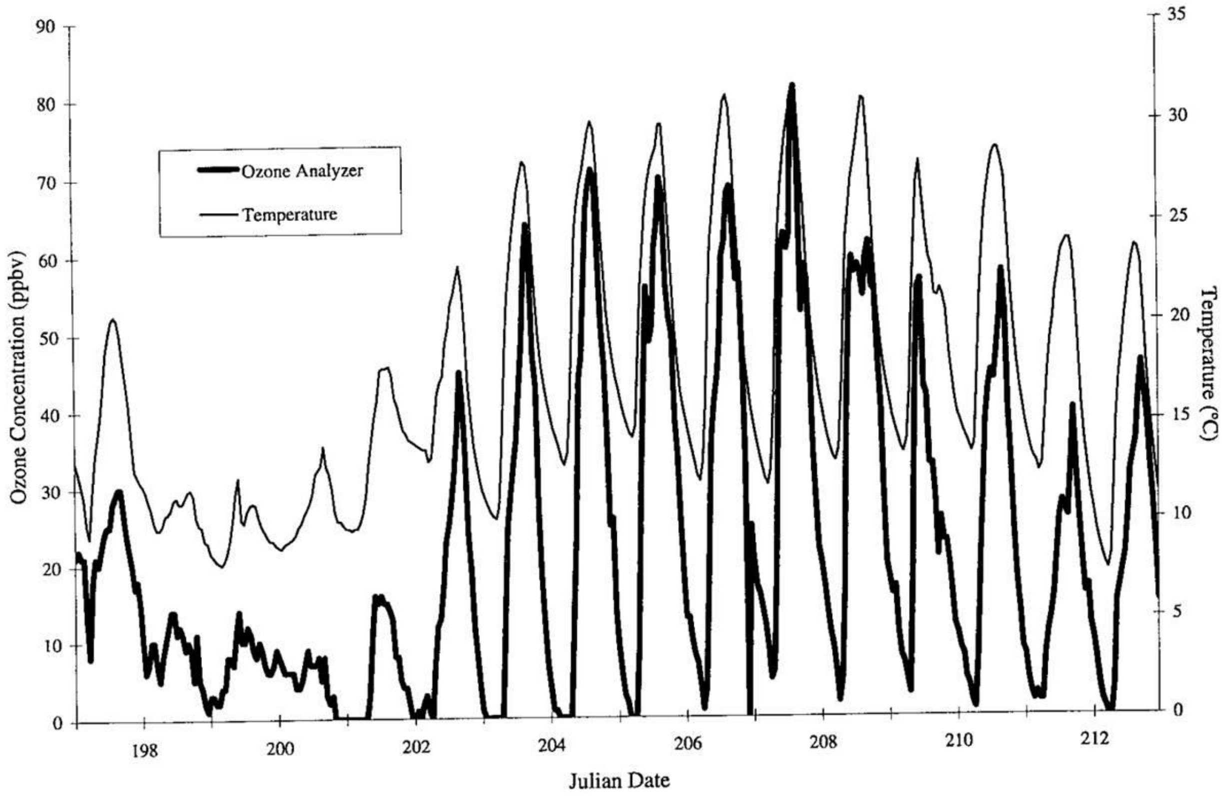

Figure 4. Atmospheric ozone concentration and temperature data from Tahoma Woods (near Mount Rainier National Park) during July 1996. Ozone concentrations tend to be high when temperatures are high (Peterson et al. 1999).

However, it should be noted that regional ozone concentrations have declined in the last decade (Jackson et al. 2009) and more stringent air quality standards regarding ground-level ozone have been imposed (EPA 2008). But climate change, growing human populations and expanded industrial activity may detract from or override these improvements. For example, ground-level ozone pollution has been projected to increase by 28% by mid century in King County Washington (based on the IPCC A2 emissions scenario, which assumes high rates of greenhouse gas emissions) (Jackson et al. 2009). Changes in pollutant emissions in nearby metropolitan areas have the potential to impact air quality in the Park since ozone and its precursor pollutants can travel hundreds of kilometers from their source and most of the Park's air pollution comes from the Puget Sound region (NPS 2001, Bernard et al. 2001). Thus, although predicting future levels of ground-level ozone is difficult, climate change will likely tend to increase the problem of ozone pollution.

Sulfates, nitrates and acid deposition

Levels of sulfates and nitrates are of concern to the Park because they are associated with deposition of sulfuric and nitric acids, pollutants that increase the acidity of terrestrial and aquatic environments. Increased acidity in terrestrial ecosystems can disrupt soil chemistry and decrease plant growth and vigor, while increased acidity in aquatic systems can lead to reductions in populations of fish and other organisms (Miller 2002). Past measurements at Mount

Rainier have found high sulfate levels relative to other Parks in the Pacific Northwest and increasing levels of nitrates (NPS 2001). In fact, some of the lowest pH (highest acidity) readings in the state have been observed at Paradise (NPS 2001).

Acid deposition is driven mostly by the combustion of fossil fuels, which results in the emission of sulfur dioxide and nitrogen oxides into the atmosphere (though there are smaller, natural sources of sulfur dioxide and nitrogen oxides) (Bernard et al. 2001). In the atmosphere, the sulfur dioxide and nitrogen oxides react with oxygen and water vapor to form sulfuric and nitric acids (which contain sulfates and nitrates, respectively). These acids and their precursors can be transported hundreds of kilometers from their sources (Miller 2002).

Climate change is expected to increase rates of acid deposition because rising temperatures will tend to accelerate the rates at which sulfur dioxide and nitrogen oxides are converted to sulfuric and nitric acids which will increase the potential for acid deposition (Bernard et al. 2001). However, there are many factors that affect acid deposition (including economic and regulatory trends), which makes predicting the direction and magnitude of changes in acid deposition difficult.

Fine particulates

Fine particulates are of concern to the Park because they decrease visibility (NPS 2001) and have the potential to harm human health by negatively impacting the respiratory system (Bernard et al. 2001). However, there is limited evidence available about the effects of climate change on fine particulates, preventing any clear conclusions about how climate change may impact fine particulate concentrations in the Park (Jackson et al. 2009).

Forests

Forests occupy about 60% of Mount Rainier National Park and span an elevational range from about 500m (1640 ft) to about 1800m (5900 ft) (Franklin et al. 1988). However, the species of trees that make up these forests differs drastically at different elevations. Lower elevation forests are dominated by Douglas fir, western hemlock and western red cedar, while higher elevation forests are mainly composed of Pacific silver fir, mountain hemlock and Alaska yellow cedar (Franklin et al. 1988). The elevational stratification of tree species likely exists because species that perform better in cooler environments dominate high elevation sites, while species that perform better in warmer environments dominate low elevation sites, as species abundance tends to vary predictably with temperature (Figure 5). Thus, one would expect the area of land occupied by Mount Rainier's tree species (the *ranges* of these species) to shift upwards with warming.

This expectation of upward range shifts is supported by a study that reconstructed the last 6000 years of forest history at three sites at Mount Rainier by examining pollen and tree macrofossil samples deposited in pond sediments (Dunwiddie 1986). The study indicates that lower elevation species were more abundant during warmer periods while higher elevation species were more abundant during cooler periods, suggesting that the ranges of tree species at Mount Rainier are sensitive to changes in climate. In addition, recent decades have seen an increase in the background rates of tree mortality in Pacific Northwest forests, a trend thought to be caused by higher temperatures and greater drought stress (van Mantgem et al. 2009). This increased mortality has the potential to alter the structure, composition and carbon storage of Mount Rainier's forests. However, there was little change in the structure and composition of mature forest stands between the mid-1970s and the mid-1990s, despite changes in climate (Acker et al. 2006). This is not surprising, though, given the long lifetimes of the tree species in the Park. Thus, climate change induced range shifts could be substantial but will likely be very slow in the absence of major disturbances. In addition, a study of how climate affects tree growth at Mount Rainier found that patterns in growth were well correlated with patterns in climate at the highest elevations (near treeline) but not lower elevations, where tree growth was apparently more strongly dictated by other factors (Ettinger et al. 2011). This could make responses of trees to climate change fairly idiosyncratic and difficult to predict.

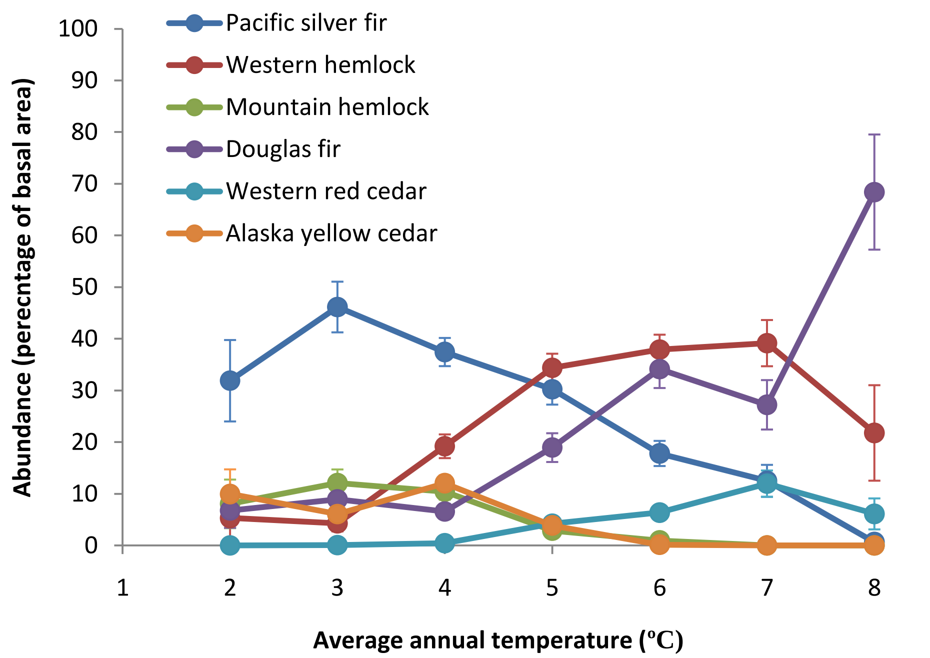

Figure 5. The relationship between tree species abundance and average annual temperature. Tree abundance is measured in terms of the percentage of total tree basal area for the given species (basal area is the area of a cross section of a tree's trunk measured at 137cm, or 4.5ft, above the ground). Error bars show standard error. The temperature data was produced by the PRISM climate model (Daly et al. 2008), while the data on tree abundance came from surveys of forest plots around the Park (Franklin et al. 1988).

However, major disturbances do occur in the Park. Historically, fire has been the most important disturbance and around 90% of the Park's forest has arisen after fire, with pre-European settlement fire return intervals of around 465 years (Franklin et al. 1988). Fire will probably become more frequent in the future due to higher summer temperatures and decreased summer precipitation creating drier conditions, making fire more likely. However, statistically based predictions of changes in fire regime cannot currently be made for forests in the western Cascade Mountains because of the long fire return intervals (Littell et al. 2009). But periods in the past with warmer temperatures were associated with a higher abundance of tree species that tend colonize recently burned areas, suggesting that fires at Mount Rainier were more prevalent during these periods (Dunwiddie 1986). Predicted changes in fire regime would likely alter forest structure, composition and productivity, accelerate tree species range shifts, and create threats to human lives and infrastructure (including buildings and roads that are part of the Mount Rainier National Historic Landmark District) (Littell et al. 2009).

Subalpine and alpine meadows

The subalpine and alpine meadows of Mount Rainier National Park form a diverse and ecologically important component of the Park's flora, and protecting these plant communities is important for maintaining biodiversity within the Park. For example, a majority of the Park's imperiled or rare plant species are found in subalpine or alpine environments. These meadows also provide important habitat for wildlife such as mountain goats, white-tailed ptarmigans, hoary marmots and the American pika (NPS 2001). In addition, the meadows are a popular destination in the Park, with about 65% of visitors travelling to the meadows to view wildflowers (NPS 2000).

Subalpine and alpine meadows are found at high elevations where temperatures are too cold or snow covers the ground for too long for trees to grow. They are found between about 1650m and 2000m on the west side of the Park, and 1900m and 2200m on the east side. At lower elevations, trees outcompete meadow species. At higher elevations, conditions are not suitable for any plants to cover a large fraction of the ground, and only a few plants are able to establish in sheltered "microhabitats." Meadows are probably found at lower elevations on the west compared to the east side of the Park because the west receives more snowfall, which shortens the snow-free period of the year. Topographic features can also be important in determining the distribution of these meadows. For example, in the subalpine zone of the Park, meadows are typically found in depressions in the landscape (where large amounts of snow accumulate and snow-free periods are short), while patches of trees occupy ridges where relatively little snow accumulates and snow-free periods are longer.

These meadows are dynamic ecosystems. Trees, mostly subalpine fir, have readily invaded the subalpine meadows of the Park over the course of the 20th century in association with warmer temperatures (Franklin et al. 1971, Henderson 1974, Rochefort and Peterson 1996) (Figure 6). These tree invasions have also been documented in a variety of other locations in the West (reviewed in Rochefort et al. 1994) and the rest of the world (reviewed in Harsch et al. 2009), though forest encroachment does not universally result when temperatures increase (Harsch et al. 2009). In addition, studies from Mount Rainier and other locations have shown that meadow plant species are able to colonize new habitat that was previously covered by ice or bare ground under favorable climatic conditions (Henderson 1974, Grabherr et al. 1994, Gottfried et al. 1999, Walther et al. 2005, Pauli et al. 2007, Cannone et al. 2008). Thus, increasing temperatures could cause the total geographic range of these meadows to shrink, expand or remain the same, depending on the relative rates at which meadow species colonize bare land and trees invade meadows.

However, a general upward movement of the meadows will likely reduce the area of land they occupy because there is less land at higher elevations due to the conical shape of mountains. And although meadows occupying the flanks of the volcano have high elevation land available to potentially colonize, meadows in the Park that occupy the peaks of lower elevation mountains will have no "escape route." Furthermore, forests might move into meadows faster than meadows expand onto bare ground because the lack of well developed soil on bare ground could slow the establishment of meadow plants, while trees would not face this constraint while establishing in meadows. This difference in rates of establishment by trees and meadow plants could also lead to meadows shrinking.

The length of the snow-free period is thought to be the primary determinant of whether trees are able to establish in subalpine meadows or not, with longer snow-free periods favoring establishment (Franklin et al. 1971). Higher temperatures are predicted to lead to reductions in snow pack (Elsner et al. 2009) which would, in turn, likely lead to lengthened snow-free periods and higher rates of tree establishment. Warmer temperatures during the growing season also generally favor tree establishment (Rochefort et al. 1994), indicating that the higher temperatures predicted for the Pacific Northwest (Mote and Salathé 2009) will also directly increase the rate of tree invasion. However, trees also require adequate summer soil moisture to establish in subalpine meadows (Rochefort et al. 1994). In the Pacific Northwest, precipitation is expected to decrease in the summer (Mote and Salathé 2009), which, along with elevated temperature, would increase drought stress experienced by tree seedlings. This elevated drought stress would tend to lower rates of establishment.

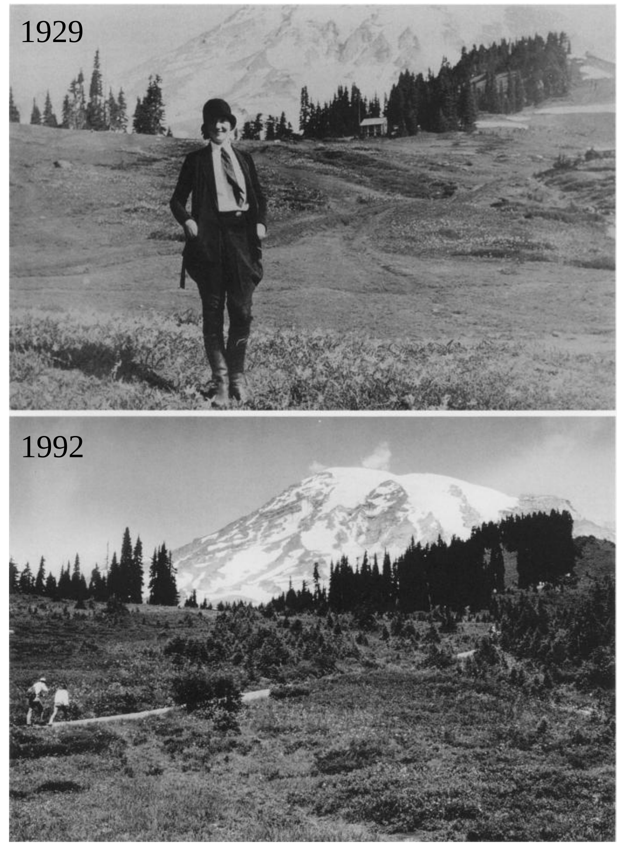

Figure 6. Photographs of the Paradise area of Mount Rainier taken in 1929 (upper) and 1992 (lower). Note the prominence of recent tree establishment (Rochefort and Peterson 1996).

Non-climatic factors also have the potential to help set the geographic range of these meadows. For instance, animal grazing has the ability to either enhance or detract from tree establishment, depending on the animal's preference for tree or meadow forage, the impacts of trampling on the soil and the potential of the animals to disperse tree seeds into meadows (Cairns and Moen 2004). Fire also has the potential to expand the geographic distribution of subalpine meadows, at least on a small scale and for a period of decades. The ability of fire to create or maintain subalpine meadows has long been noted at Mount Rainier (Henderson 1974, Allen 1916, Griggs 1938, Stueve et al. 2009) as well as other locations (Kuramoto and Bliss 1970, Peet 1981, Shankman 1984). These studies have shown that high elevation trees are slow to reestablish after fires and that forests can often take several decades to regenerate. In the meantime, meadow vegetation predominates. Some of the past fires in the subalpine meadows of Mount Rainier were lightning ignited or accidently set by humans, but early reports state that other fires were intentionally lit by Yakama and Kickitat Native Americans to increase huckleberry production, make the landscape easier to traverse, create forage for their horses and improve deer hunting (Allen 1916, McIntyre 1952). Thus, some of the forest encroachment into subalpine meadows observed at Mount Rainier may be due to recovery of forest patches after fire disturbance, and not necessarily the response of an established ecological boundary to changes in climate.

The subalpine and alpine meadows of Mount Rainier are dynamic ecosystems and there are many factors that determine their geographic ranges. However, large increases in temperature and corresponding decreases in snowpack will, in all likelihood, lead to upward movement of the meadows and a reduction in the area of land they occupy. The reduction in area occupied by the meadows could lead to a loss of some of the meadow species from the Park.

Whitebark pine

The whitebark pine (scientific name: *Pinus albicaulis*) is an important tree species at Mount Rainier and in many mountainous regions of western North America because of its role in shaping habitat and providing food (in the form of its large seeds) for a variety of animals. The species is considered to be imperiled by climate change and other factors. Although far from being the only plant species at risk because of climate change, the whitebark pine has received a lot of focus because of its important role in many mountain ecosystems and provides a good example of how climate change and other human-caused factors will affect plant species.

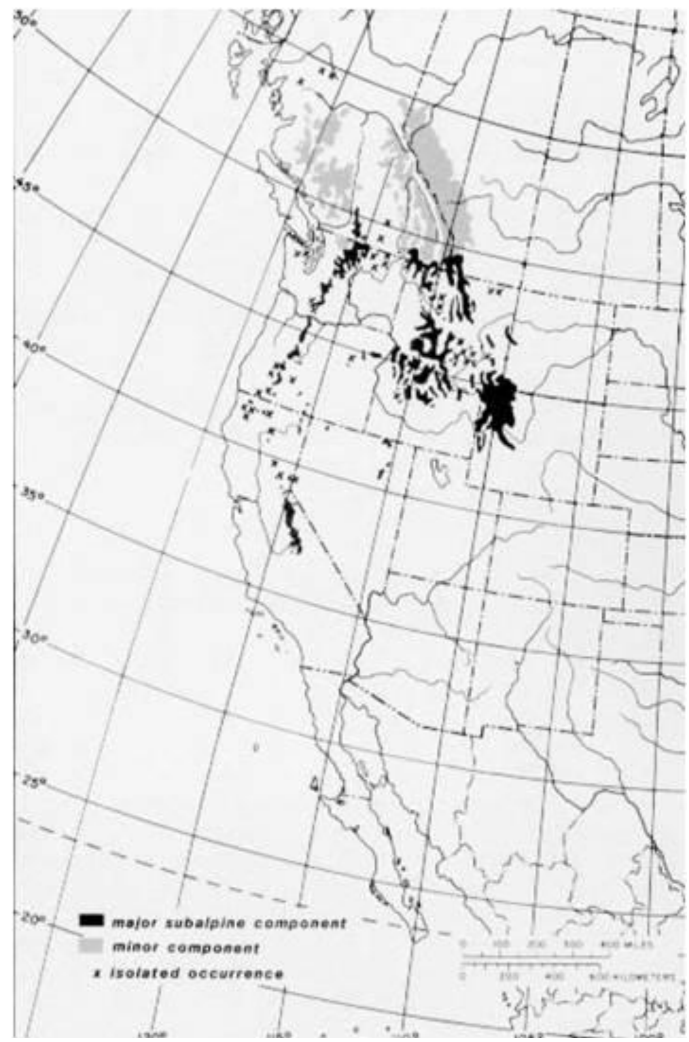

Figure 7. The geographical range of the whitebark pine (Burns and Honkala 1990).

Background and non-climate change threats to the whitebark pine

The whitebark pine is prevalent at Mount Rainier and in many mountainous areas in western North America (Figure 7). It is most abundant at dry, high elevation sites and is typically found on the north and east sides of the Park at elevations above about 1500m (or about 5000ft) (Biek 2000). There are approximately 22,000 adult whitebark pines found throughout the Park (Cottone and Ettl 2001).

Whitebark pine is considered a "foundation species" in certain subalpine ecosystems because the large, nutrient rich seeds it produces are an important food resource for a number of animal species (Ellison et al. 2005). Unlike most pines, which have seeds that are carried away from the parent tree by the wind, whitebark pine seeds lack wings and primarily rely on a mutualistic relationship with a bird called the Clark's nutcracker for dispersal (Tomback et al. 2001). The cones of the whitebark pine generally remain closed until pried open by the beak of a Clark's nutcracker which eats the seeds or stores them in a pouch under its tongue for transport (Figure 8). Clark's nutcrackers can hold over 150 whitebark pine seeds in this pouch at a time. The bird then caches these seeds for later consumption, but typically caches far more seeds than it can eat. The forgone seeds can then germinate and grow into an adult tree. Clark's nutcrackers often cache these seeds at the sites of recent burns, allowing the whitebark pine to be one of the first trees to colonize these disturbed sites. The caches are also an important food source for a variety of animals, including bears and a number of small mammals (Tomback et al. 2001).

Figure 8. A Clark's nutcracker prying seeds out of a whitebark pine cone (photo credit: D.F. Tomback, whitebarkfound.org)

The whitebark pine currently faces a number of serious threats. One is a non-native fungal disease introduced to North America in 1910 called the white pine blister rust (Tomback et al. 2001). The blister rust soon spread throughout most of the range of the whitebark pine. The pathogen was first discovered in Mount Rainier in 1928 on western white pines and was observed on whitebark pines in 1937 (Rochefort 2008). In a survey conducted in the Park from 1994-1999, Rochefort (2008) observed that 13.5% of whitebark pine trees were infected with the blister rust and 33.4% were dead (presumably, but not necessarily, from the blister rust), while 24.3% of whitebark pine saplings were infected and 8.6% were dead. Given these high mortality rates and the tree's slow growth, the long-term persistence of the whitebark pine at Mount Rainier is in question. Ettl and Cottone (2004) developed a model of whitebark pine populations at Mount Rainier that predicts there will be less than 100 whitebark pine trees in the Park in 148 years given current demographic trends (Figure 9).

In addition, fire suppression may also be contributing to the decline of whitebark pine at Mount Rainier. Whitebark pine tends to thrive in post-fire environments, but is often outcompeted by other species, such as subalpine fir, in the absence of disturbance (Tomback et al. 2001). However, a study of historical fire regimes at whitebark pine stands in the Park shows a high degree of variability across the Park in terms of fire frequency (Siderius and Murray 2005). For instance, there was little to no evidence of fire at whitebark pine stands near the volcano itself, suggesting that fire has not been responsible for maintaining these stands in the past. But there was evidence of frequent fires (~50 year return intervals) at the stands around Crystal and Deadwood Lakes along the eastern border of the Park, with a wide range of severities. Fire may have played a significant role in sustaining whitebark pine populations at these locations.

Climate change threats to the whitebark pine

Climate change creates yet more potential threats to the whitebark pines at Mount Rainier. One of these threats is a potential increase in the likelihood and severity of mountain pine beetle (MPB) outbreaks (Figure 10). The MPB is an insect native to North America that bores into pine trees to lay eggs under the tree's bark. When the eggs hatch, the emerging larvae consume the tree's vascular tissue, and if the infestation rate is high enough the beetles can girdle and kill the trees (Gibson et al. 2008). Currently an unprecedented outbreak of the MPB is occurring in British Columbia that has destroyed over 130,000 square kilometers of lodgepole pine forest, an area four times the size of Vancouver Island (Ministry of Forests, Lands and Natural Resource Operations 2008).

Figure 9. Patch of live and dead whitebark pines near Sunrise. Photo credit: K.R. Ford.

The high elevation habitats of whitebark pines have historically been too cold to allow MPB populations to reach epidemic proportions in most years (Logan and Powell 2001). However, outbreaks have occurred in whitebark pine stands in the past in conjunction with above average temperatures (Gibson et al. 2008). Higher temperatures are believed to enable MPB epidemics because they increase the beetle's survival rate and allow the insect to complete its life cycle in one year (as opposed to the typical two at high elevations) (Logan and Powell 2001), leading to large populations that can synchronously attack trees and override their defensive mechanisms (Amman et al. 1997). Climate change is expected to increase the likelihood of high elevation whitebark pine stands experiencing the warm temperatures amenable to MPB outbreaks (Logan and Powell 2001). Consistent with this expectation is the observation in recent years that the MPB has expanded its range to higher elevations in association with increasing temperatures (Gibson et al. 2008).

However, at Mount Rainier the MPB has only rarely been observed in whitebark pine stands and is not believed to be a major cause of mortality (Rochefort 2008). The lack of infestation could be due in part to the absence of large stands of lodgepole pines in Mount Rainier (Rochefort 2008). In areas with abundant lodgepole pine populations, outbreaks in stands of these lower elevation trees can often "spill over" into higher elevation whitebark pine stands, causing widespread whitebark pine mortality (Tomback et al. 2001). However, whitebark pine stands can sustain MPB outbreaks even in the absence of neighboring lodgepole pine stands, if the climate is suitable (Logan and Powell 2001). Thus, the MPB could become a serious threat to whitebark pine stands at Mount Rainier as temperatures continue to rise (Rochefort 2008).

Climate change may also affect the severity of white pine blister rust infestations in whitebark pine stands. Mortality from the blister rust declines with increasing elevation in the Park, potentially because the shorter growing season at higher elevations reduces the rate at which the pathogen can spread in the tree (Rochefort 2008). If climate change prolongs the growing season, whitebark pines could experience increased mortality from the blister rust (Rochefort 2008).

a) The mountain pine beetle

b) Whitebark pines killed by mountain pine beetles in Yellowstone National Park in 2004.

Figure 10. (a) wikimedia.org; (b) (Gibson et al. 2008).

It is also important to note that these multiple stressors will not act alone, but instead will likely interact synergistically to threaten whitebark pine populations. For example, whitebark pines weakened by white pine blister rust and suffering from competition with trees that have established in the absence of fire will be more likely to succumb to MPB infestations (Ellison et al. 2005, Tomback et al. 2001). Due to this litany of threats, the International Union for Conservation of Nature has listed the whitebark pine as “vulnerable” on its Red List of Threatened Species (Reuling 2008) while the Natural Resource Defense Council has petitioned for the species to be listed as endangered under the Endangered Species Act (NRDC 2008). The US Fish and Wildlife Service is currently reviewing the status of the whitebark pine to determine whether listing the species is warranted (US Fish and Wildlife Service 2010a).

It is also possible that whitebark pines could be favored, to some extent, by the potential increase in fire frequency due to climate change because fires create good opportunities for whitebark pine establishment. However, the benefits of increased establishment could be outweighed by the costs of tree mortality if the disturbances tend to be high intensity stand-replacing crown fires as opposed to low intensity surface fires.

Even in the absence of climate change, the whitebark pine would face several threats to its existence. Future climate change will likely exacerbate these other threats and create new ones, making the long-term persistence of this already imperiled species even less certain.

The American pika

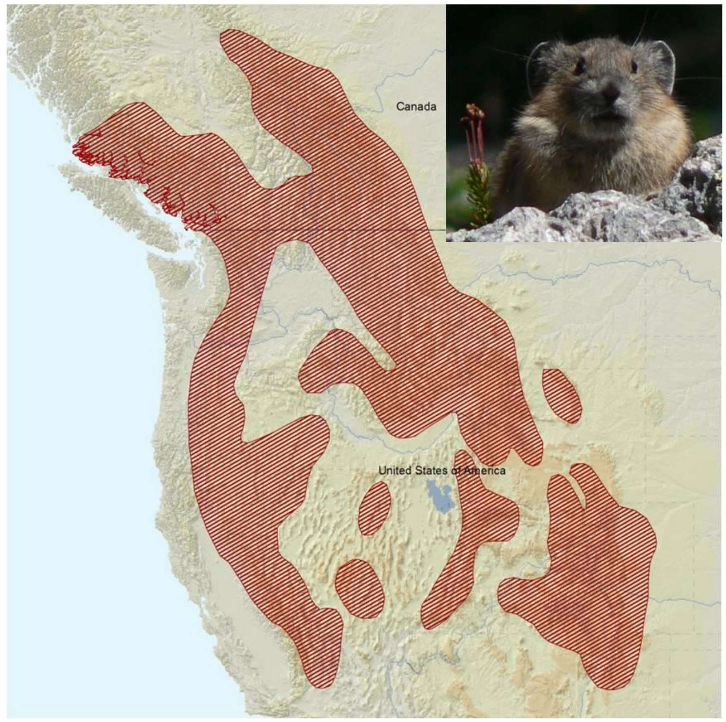

Figure 11. Native range of the American pika. Map: (Beever and Smith 2008); photo: wikimedia.org.

The American pika (scientific name: *Ochotona princeps*) is a small mammal that lives at high elevations at Mount Rainier National Park and in cold environments at many locations in western North America and could face serious threats from a changing climate (Figure 11). Though far from the only wildlife species to be threatened by climate change, the vulnerability of the pika to warming has been the focus of several recent studies and legal actions. Thus, the pika provides a useful case study for how animal species in mountainous habitats such as at Mount Rainier may respond to climate change.

Pikas are solitary and territorial animals that maintain dens in piles of boulders and rocks, and forage in the surrounding vegetation (typically alpine and subalpine meadows). During the summer, pikas directly consume plants in the meadows, but also bring some of this vegetation back to their dens to create stockpiles of food called haypiles (Smith and Weston 1990). The pika has been considered a “keystone species” in high elevation meadows because its grazing appears to have a large effect on the species composition of these plant communities, particularly in its ability to enhance the persistence of cushion plants (Huntly 1987). These animals remain in the same high elevation territories year round (Smith and Weston 1990). They do not hibernate in the winter and must feed on surrounding vegetation (which they can access via snow tunnels) or on haypiles in their dens (that they build up during the summer) to survive (Smith and Weston 1990). In fact, pikas have been known to cache plants with high levels of toxins, wait until late in the winter when these toxins have degraded and then consume the now palatable plants. In the meantime, the toxins have slowed plant decomposition and helped provide a long-lasting food supply for the pika. In this way, the pikas have apparently co-opted the plant toxins (presumably an anti-herbivore defense) for food preservation (Dearing 1997).

Climate change could pose serious threats to the pika. These mammals have very low heat tolerance and exposure to temperatures between 26ºC and 29ºC (79ºF and 84ºF) for several hours can be lethal (Smith 1974a, MacArthur and Wang 1973). Given this low tolerance, higher summer temperatures could result in portions of the pika’s current range becoming uninhabitable as lethal temperatures become more common (Beever et al. 2003). High temperatures have also been correlated with altered activity levels that force pikas to forego their typical midday foraging (Smith 1974a). Elevated summer temperatures brought about by climate change could reduce the amount time pikas can forage during the day, potentially preventing them from gaining sufficient biomass or collecting sufficient hay to survive the winter (Beever et al. 2003). The reduced foraging opportunities could be especially harmful to pikas given their high metabolic rate (pikas must fill their stomachs nine times a day to meet their energy demands) (Smith and Weston 1990).

It seems likely that higher temperatures would force pikas upward in elevation and northward in latitude. The results of a study in Yosemite National Park supported this expectation by documenting a 153 meter increase in the lower elevational limit of the pika since the early 20th century, in association with rising temperatures (Moritz et al. 2008). Similarly, Grayson (2005) estimated that the average elevation of pikas in the Great Basin region of the Southwestern US has increased by 152 meters in recent times. This trend will likely decrease the amount of habitat available to pikas, since there is less land at higher elevations or no land at all if pika populations already occupy a summit. In addition, pikas would likely have difficulty moving northward from one mountain peak to another due to their limited dispersal ability – maximum dispersal distances are typically 3 kilometers (Smith 1974b) and dispersal across warm, low elevation lands are particularly unlikely (Smith 1974a). Perhaps a testament to their limited dispersal abilities, pikas are not found in the Olympic Mountains despite being common in the nearby Cascade Mountains, presumably because they have not been able to cross the warm, unsuitable lowlands of the Puget Trough which separates these two mountain ranges.

Results from a series of studies of pika populations in the Great Basin are consistent with the expectation that pikas will be vulnerable to climate change. Beever et al. (2011) have re-surveyed 25 sites in the Great Basin where pika populations had been observed at some point during the 20th century and found that ten have apparently been extirpated (died out), including four since 1999 (Figure 12). Extirpated sites tended to be at low elevations (relative to latitude) and to have high summer temperatures compared to surviving populations (Beever et al. 2003, Beever et al. 2010, Wilkening et al. 2011, Beever et al. 2011), suggesting that pikas are sensitive to high temperatures and that documented warming trends might have played a role in these extirpations.

However, summer temperature is probably not the only factor governing pika extirpations in the Great Basin. Extirpated sites tended to experience more days during the winter with extremely low temperatures (less than -10°C or 14°F) within the rock piles where pikas make their dens (Beever et al. 2010, Beever et al. 2011). Sites likely experienced these extremely low temperatures because of a lack of snow cover that can insulate the rock piles and maintain temperatures around the freezing point, a relatively high temperature during winter in these high elevation environments. These extremely low temperatures are likely stressful for pikas and could increase mortality. Livestock grazing and being outside of designated wilderness areas were also correlated with pika extirpations, indicating that climate is not the only factor important in determining the persistence of pika populations. In fact, a new population of pikas was recently discovered in the Great Basin at a low elevation, high temperature site, showing that there is not a strict relationship between pikas and climate (Beever et al. 2008).

But in spite of these complicating factors, one of the main messages to come out of this research is that pikas are sensitive to warming and appear to be declining in the Great Basin. Furthermore, these trends might be representative of the threats the species faces throughout its range. This view is bolstered by a study in which Galbreath et al. (2009) created computer models of the climate pikas tend to occur in (the pika's *climate envelope*) and found that the area of land in western North America that experiences this climate will likely shrink dramatically given projections of warming for the 21st century. Presumably, this reduction in the pika's climate envelope will lead to a reduction in pika population size. These concerns for pika populations led the Center for Biological Diversity (CBD) to petition to have the species listed as "threatened" under the US Endangered Species Act (CBD 2007).

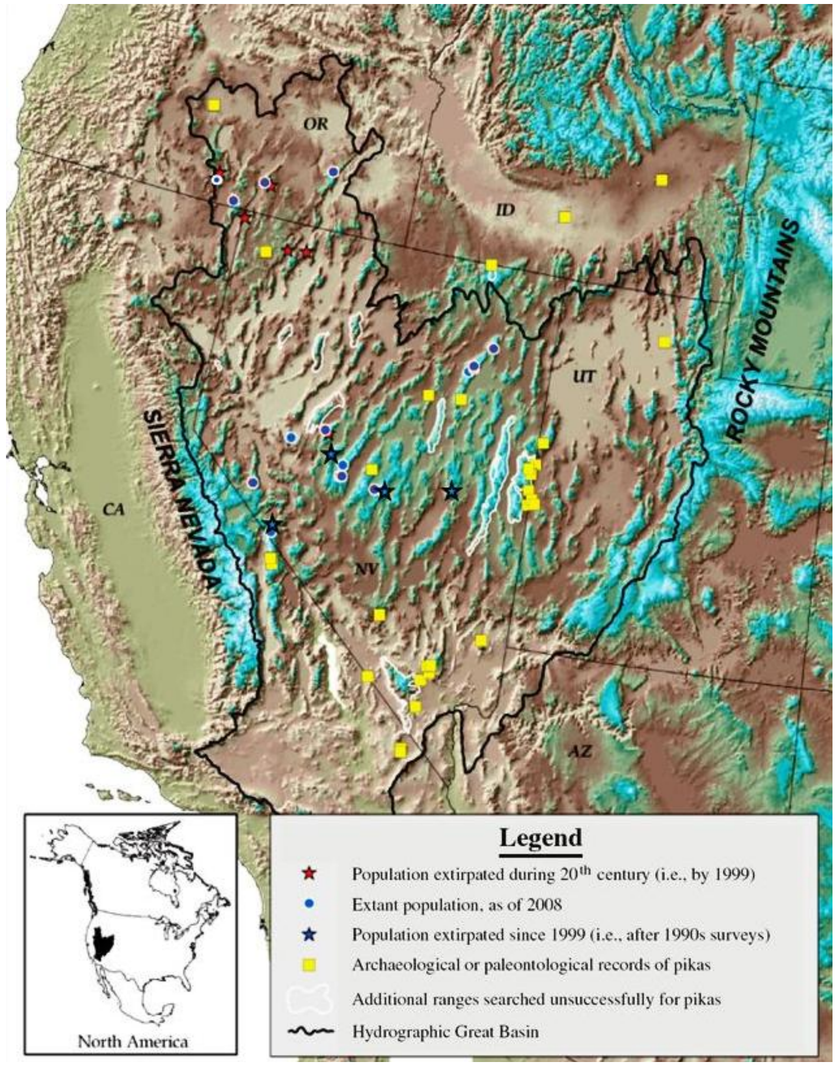

Figure 12. Patterns of pika population extirpations in the Great Basin (Beever et al. 2003).

However, there are several lines of evidence that suggest the species as a whole may be well suited to cope with climate change. For example, Millar and Westfall (2010) recently surveyed a large number of sites in the Sierra Nevada Mountains, as well as parts of the Great Basin and Oregon Cascade Mountains, and found a large number of pika populations, suggesting that the species is currently abundant in this region. In addition, they found that pikas currently occur in a wide range of elevations and experience a wide range of temperatures. However, the authors did find that sites with suitable pika habitat (i.e. large rock piles) but without pikas were substantially warmer than sites currently occupied by pikas. Together, these data suggest that although climate change could make some current pika habitat too warm for pikas to persist, it is unlikely that it could make all currently occupied sites too warm for the species. Pikas have also been known to adjust their behavior to cope with high temperatures by resting inside shady rock piles during hot weather (MacArthur and Wang 1974) and shifting their foraging to cooler times of day, and have even been observed foraging at night when daytime temperatures are high (Smith 1974a). This behavioral flexibility could aid the pika in surviving a warmer world.

Due to the lack of evidence that the species as a whole, or any of its five subspecies, will be likely driven to extinction by climate change (at least in the "foreseeable future") the US Fish and Wildlife service found that protection of the pika under the Endangered Species Act is not currently warranted (US Fish and Wildlife Service 2010b). However, this does not mean the pika is free from danger. Certain populations may still be extirpated by climate change, and the status of the species beyond the foreseeable future (which the US Fish and Wildlife Service defined as being the middle of the 21st century) is uncertain. Thus, unmitigated climate change could still very well pose a threat to the pika.

Given the challenges faced by the pika in this period of rapid climate change, Mount Rainier will likely become an increasingly important refuge for the species. The non-climate stressors experienced by pikas (livestock grazing and recreational hunting) are not present in the Park (Beever et al. 2003, Beever et al. 2011). In addition, Mount Rainier has an abundance of rock piles and boulder fields at high elevations, which serve as important, cool shelters for pikas that will likely be critical for surviving a warmer climate (Millar and Westfall 2010, Beever et al. 2011). Thus, if pikas populations do rapidly decline because of climate change in the region, Mount Rainier would likely be one of the best remaining habitats for the species and could become increasingly important for the species' survival. In fact, Mount Rainier's abundance of high elevation lands and protected wilderness will likely make the Park an important refuge for many of the region's mountain-dwelling species in a warming world.

Other species potentially at risk

There are several other species present at Mount Rainier National Park that are thought to be at risk due to climate change that I would like to briefly discuss. One is the bull trout, a "threatened" species under the Endangered Species Act that depends on cold water for spawning and early rearing. Climate is thought to strongly limit the geographic distribution of this fish, and climate change is expected to result in a large loss of habitable area (Rieman et al. 2007). The "threatened" Puget Sound population of Chinook salmon, which are thought to occur in the Park in small numbers (NPS 2001), could also be harmed by changes in stream temperature and increased flooding that are predicted to accompany climate change (Mantua et al. 2009). In addition, it has been speculated that other alpine animals, besides the American pika (discussed above), will be sensitive to climate change because of the possible reduction and fragmentation of alpine habitat. These species include the mountain goat, white-tailed ptarmigan and hoary marmot (Martin 2001). And there are still other species in the Park which have been identified as potentially vulnerable to climate change, but have not been discussed here. Furthermore, species not known to be seriously at risk could in fact be threatened by climate change for currently unidentified reasons. Climate plays an important role in the life history of virtually every species, so an exhaustive list of species that will be positively or negatively affected by climate change is probably impossible to create.

Conclusions

Climate change will likely create or exacerbate a variety of problems for conserving the resources and values of Mount Rainier National Park. A number of these problems will probably be unprecedented in the history of the Park. Many of the geological, biological, cultural and historical features that the Park was created to protect will be at risk of degradation or elimination. Preservation of these resources will require a combination of global scale actions to reduce greenhouse gas emissions and local efforts in the Park to adapt to the changes likely to take place this century. However, climate change will pose these threats to natural resources everywhere. In general, these resources will probably be best preserved within protected areas such as Mount Rainier where there are fewer direct threats from human activity (i.e. habitat destruction). The high elevation habitats of the Park will also sustain relatively cool climates that will become progressively more rare in the lower elevation landscapes surrounding the volcano, making Mount Rainier an increasingly important refuge for cold-adapted species. In an age of rapid warming, Mount Rainier is more important than ever for preserving the region's natural resources and biodiversity.

Further reading

Below is a list of additional sources of information about climate change and its impacts.

The Mount Rainier Climate Friendly Parks Action Plan:
www.nps.gov/climatefriendlyParks/Parks/Mount Rainier.html

The Washington Climate Change Impacts Assessment:
cses.washington.edu/cig/res/ia/waccia.shtml

The Intergovernmental Panel on Climate Change:
www.ipcc.ch

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