

IV. IMPLICATIONS FOR FRESHWATER ECOSYSTEMS

Changing climate is already having an impact on the physical, chemical and biological characteristics of freshwater ecosystems, both directly through changes in air temperature and precipitation and indirectly through interaction with other stressors (Figure 17).⁶⁹³ Based on a search of the scientific and grey literature, the following implications of climate change for freshwater ecosystems in the NPLCC region have been identified:

1. Altered nutrient cycling and productivity
2. Changes to stratification and eutrophication
3. Changes to water input, level, and area
4. Changes to the length and date of seasonal ice cover
5. Habitat loss, degradation, and conversion

Trends toward warmer air temperatures, increased precipitation variability, decreased snowpack, and increased wildfire activity are already linked to warming streams and rivers, altered stream hydrologies, and increased channel disturbance from flooding and post-fire landslides and debris flows.⁶⁹⁴

Lakes differ widely in size, depth, transparency, and nutrient availability, characteristics that fundamentally determine how each lake will be affected by climate change.⁶⁹⁵ In general, however, warmer air temperatures are likely to lead to increasing water temperatures, which, in turn, can lower water level and oxygen content.⁶⁹⁶ Further, climate change will impact lake hydrology through effects on residence time and water level as well as through receptors and sources of streamflow.⁶⁹⁷

The vulnerability of wetlands to changes in climate depends on their position within hydrologic landscapes.⁶⁹⁸ Hydrologic landscapes are defined by the flow characteristics of ground water and surface water and by the interaction of atmospheric water, surface water, and ground water for any given locality or region.⁶⁹⁹ In general, the vulnerability of all wetlands to climate change fall between two extremes: those dependent primarily on precipitation for their water supply are highly vulnerable, and those dependent primarily on discharge from regional ground water flow systems are the least vulnerable, because of the buffering capacity of large ground water flow systems to climate change.⁷⁰⁰

⁶⁹³ *Nickus et al. "Direct impacts of climate change on freshwater ecosystems." In *Climate Change Impacts on Freshwater Ecosystems*. (2010, p. 60)

⁶⁹⁴ *Isaak et al. *Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network*. (2010, p. 1350). The authors cite Abatzoglou and Redmond (2007) and IPCC (2007) for information on warmer air temperatures; Hamlet et al. (2007) for information on increased precipitation variability; Hamlet et al. (2005) and Mote et al. (2005) for information on decreased snowpack; Westerling et al. (2006) and Morgan et al. (2008) for information on increased wildlife activity; Peterson and Kitchell (2001), Morrison et al. (2002), and Bartholow (2005) for information on warming streams and rivers; Stewart et al. (2005), Barnett et al. (2008), and Luce and Holden (2009) for information on altered stream hydrologies; and, Miller et al. (2003), Istanbuluoglu et al. (2004), and Hamlet and Lettenmaier (2007) for information on increased channel disturbance from flooding and post-fire landslides and debris flows.

⁶⁹⁵ *Kling et al. *Confronting Climate Change in the Great Lakes Region: Impacts on our Communities and Ecosystems*. (2003, p. 21)

⁶⁹⁶ *Kling et al. (2003, Fig. 17, p. 42)

⁶⁹⁷ *Verdonschot et al. (2010, p. 69)

⁶⁹⁸ *Winter. *The vulnerability of wetlands to climate change: a hydrologic perspective*. (2000, p. 305)

⁶⁹⁹ *Winter. (2000, p. 305)

⁷⁰⁰ *Winter. (2000, p. 305)

The following structure will be used to present information on the implications of climate change for the NPLCC region's freshwater ecosystems:

- **Observed Trends** – observed changes for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California. A few sections also include information on changes observed across the NPLCC region.
- **Future Projections** – projected direction and/or magnitude of change for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California. A few sections also include information on changes observed globally.
- **Information Gaps** – information and research needs identified by reviewers and literature searches.

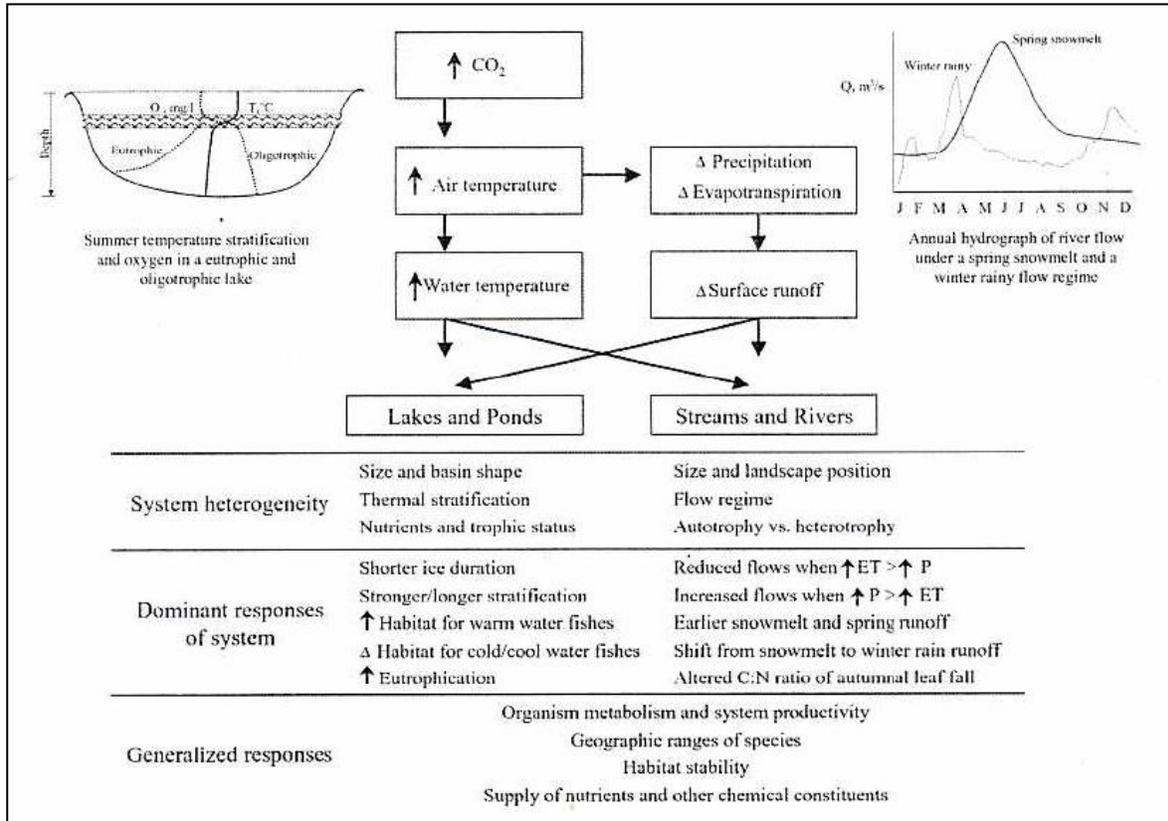


Figure 17. Linkages between atmospheric increases in CO₂ and environmental drivers of temperature and precipitation that regulate many physical and ecological processes in lakes and ponds (left) and rivers and streams (right). Studies of climate change impacts on lakes have emphasized responses to warming, which are affected by vertical temperature stratification. Studies of climate change impacts on rivers have emphasized responses to altered flow regime, including changes to magnitude, frequency, duration, and timing of discharge events. Some biological indicators shown at the bottom of the figure are general.

Source: Allan, Palmer, and Poff. (2005, Fig. 17.1, p. 277)

1. ALTERED NUTRIENT CYCLING AND PRODUCTIVITY

The productivity of inland freshwater ecosystems will be significantly altered by increases in water temperatures.⁷⁰¹ The metabolic rates of organisms and the overall productivity of ecosystems are directly regulated by temperature.⁷⁰² Warmer waters are naturally more productive, but the particular species that flourish may be undesirable or even harmful.⁷⁰³ Changes in precipitation and runoff modify the amount and quality of habitat for aquatic organisms, and thus, they indirectly influence ecosystem productivity and diversity.⁷⁰⁴ Further, higher temperatures may raise the rate of mineralization of organic matter in catchment soils, releasing carbon, phosphorus and nitrogen, and particulate phosphorus input may also be raised from increased erosion of catchment soils.⁷⁰⁵ Increased nutrient loading, coupled with water temperature increases, could thereby increase autochthonous productivity and greater autochthonous biogenic contributions to the sediment.⁷⁰⁶

In lake ecosystems, research indicates that the longer ice-free periods and higher surface water temperatures expected in the future will spur greater algal growth.⁷⁰⁷ Other aspects of climate change, however, may offset these productivity gains.⁷⁰⁸ Cloudy days can lower productivity by making less light available for algal photosynthesis.⁷⁰⁹ For example, cloud cover has increased in the Great Lakes region recently, but future trends in cloudiness are not clear.⁷¹⁰

Increased primary productivity could also be limited or even reversed by a decline in availability of nutrients, primarily nitrogen and phosphorus, necessary for plant growth.⁷¹¹ Predicted reductions in runoff and a general drying of watersheds during summer are likely to reduce the amounts of phosphorus and other dissolved materials that streams carry into lakes.⁷¹² Finally, prolonged or stronger stratification can also lead to lower primary production in lakes by preventing the mixing that brings nutrients from bottom waters and sediments up into surface waters.⁷¹³

Effects of nutrient enrichment in streams are highly variable, due to questions about which primary nutrient (nitrogen or phosphorus) is limiting, shading (light availability), water clarity, flow regime, and available substrate for periphyton (a broad organismal assemblage composed of attached algae, bacteria, their secretions, associated detritus, and various species of microinvertebrates) growth.⁷¹⁴ For example, forested streams are highly dependent upon inputs of terrestrial organic matter, especially leaf fall, for their energy supply, and so shifts in terrestrial vegetation and changes in leaf chemistry provide another, quite intricate set of pathways by which

⁷⁰¹ *Poff, Brinson and Day. *Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States*. (2002, p. iii)

⁷⁰² *Poff, Brinson and Day. (2002, p. iv)

⁷⁰³ *Poff, Brinson and Day. (2002, p. iii)

⁷⁰⁴ *Poff, Brinson and Day. (2002, p. iii)

⁷⁰⁵ *Verdonschot et al. (2010, p. 69-70)

⁷⁰⁶ *Verdonschot et al. (2010, p. 70)

⁷⁰⁷ *Kling et al. (2003, p. 25). The authors cite Fee et al. (1992) and Regier, Holmes and Pauly (1990) for this information.

⁷⁰⁸ *Kling et al. (2003, p. 25)

⁷⁰⁹ *Kling et al. (2003, p. 25). The authors cite Adams, Meinke and Kratz (1993) for this information.

⁷¹⁰ *Kling et al. (2003, p. 25)

⁷¹¹ *Kling et al. (2003, p. 25)

⁷¹² *Kling et al. (2003, p. 25). The authors cite Magnuson et al. (1997) and Schindler et al. (1996) for this information.

⁷¹³ *Kling et al. (2003, p. 25). The authors cite Boyce et al. (1993) and Peeters et al. (2002) for this information.

⁷¹⁴ *U. S. EPA. *Climate Change Effects on Stream and River Biological Indicators: A Preliminary Analysis (EPA/600/R-07/085)*. (2008a, p. 1-8). The authors cite Dodds and Welch (2000) as an example for this information.

stream biota and ecosystems can be affected.⁷¹⁵ Altered carbon-to-nitrogen ratios of the leaves likely will reduce palatability, temperature changes will affect leaf processing rates, and floods may export leaf matter before it can be processed.⁷¹⁶ These interactions are complex and potentially offsetting, making the overall impact of climate on this energy supply difficult to predict.⁷¹⁷

Hydrology is an important factor in determining levels of productivity, decomposition, and nutrient cycling in wetlands.⁷¹⁸ Whether precipitation increases or decreases, all of these functions will be affected.⁷¹⁹ Warmer temperatures in large bodies of water could boost productivity in the associated wetlands but would affect the mix of species that could thrive.⁷²⁰ Finally, warmer temperatures will increase the rates at which plants decompose, affecting the amount of organic material buried on the marsh floor.⁷²¹

Observed Trends

Regional

Pacific salmon (*Oncorhynchus* spp.) annually contribute large amounts of organic material to fresh waters of the North Pacific rim when they spawn and die.⁷²² This “fertilizer effect” can influence bottom-up ecosystem processes such as primary production, decomposition, and mineral cycling and top-down processes involving competition and predation.⁷²³ For example, salmon transport marine-derived nitrogen to the rivers in which they reproduce.⁷²⁴ Thus, the nutrients and energy provided by spawning salmon appear to increase freshwater and terrestrial ecosystem productivity, and may subsidize otherwise nutrient-poor Pacific Northwest ecosystems.⁷²⁵ As riparian forests affect the quality of instream habitat through shading, sediment and nutrient filtration, and production of large woody debris (LWD), this fertilization process (i.e., spawning salmon as a source of nutrients to the freshwater ecosystem) serves not only to enhance riparian production, but may also act as a positive feedback mechanism by which salmon-borne nutrients improve spawning and rearing habitat for subsequent salmon generations and maintain the long-term productivity of river corridors along the Pacific coast of North America.⁷²⁶

⁷¹⁵ *Allan, Palmer and Poff. (2005, p. 277)

⁷¹⁶ *Allan, Palmer and Poff. (2005, p. 285). The authors cite Rier and Tuchman (2002) and Tuchman et al. (2002, 2003) for this information.

⁷¹⁷ *Allan, Palmer and Poff. (2005, p. 285). The authors refer the reader to Fig. 17.5 in the cited report.

⁷¹⁸ *U.S.Congress, Office of Technology Assessment (OTA). *Preparing for an Uncertain Climate--Volume II, OTA-O-568: Chapter 4: Wetlands.* (1993, Box-4G, p. 175)

⁷¹⁹ *OTA. (1993, Box-4G, p. 175)

⁷²⁰ *OTA. (1993, Box-4G, p. 175)

⁷²¹ *OTA. (1993, Box-4G, p. 175)

⁷²² *Chaloner et al. *Marine carbon and nitrogen in southeastern Alaska food webs: evidence from artificial and natural streams.* (2002, p. 1258). The authors cite Levy (1997) for this information.

⁷²³ *Darimont et al. *Salmon for terrestrial protected areas.* (2010, p. 2). The authors cite Zhang et al. (2003), Mitchell and Lamberti (2005), Hocking and REimchen (2009) as examples for information on bottom-up ecosystem processes and Ben-David et al. (2004), Gende and Quinn (2004) and Darimont et al. (2008) as examples for information on top-down processes.

⁷²⁴ *Helfield and Naiman. *Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity.* (2001, p. 2403)

⁷²⁵ *Chaloner et al. (2002, p. 1258). The authors cite Willson et al. (1998), Wipfli et al. (1998), and Cederholm et al. (1999) for information on freshwater and terrestrial ecosystem productivity, and Polis et al. (1997), Cederholm et al. (1999), and Gresh et al. (2000) for information on subsidizing Pacific Northwest ecosystems.

⁷²⁶ *Helfield and Naiman. (2001, p. 2403)

Another principal concept describes salmon as ecosystem engineers.⁷²⁷ Salmon modify creek substrates while spawning and suspend nutrient-rich sediments and salmon eggs in the water column, resulting in substantive nutrient export to estuaries and downstream lakes.⁷²⁸ This process can alter the production of biofilm, rates of detrital processing, and the seasonal abundance of freshwater consumers.⁷²⁹ Collectively, these observations suggest that spawning activity can represent a key component of coupled marine–freshwater nutrient cycling.⁷³⁰

Southcentral and Southeast Alaska

Despite the extent of peatlands that occur within Pacific coastal temperate rainforest watersheds, there is little information describing how dissolved organic matter (DOM) storage and export patterns are related to soil saturation and temperature in the region.⁷³¹ In 2004 and 2005, D'Amore et al. (2010) measured soil water tables, soil temperatures and redox potential and compared these measurements to fluctuations in dissolved organic carbon (DOC) and nitrogen (DON) concentrations in a forested wetland and sloping bog in southeast Alaska (near the mouth of McGinnis Creek) to address this key information gap.⁷³² Key findings include:

- DOC concentrations ranged from 5 to 140 mg C l⁻¹ (milligrams carbon per liter) in wetland soils, 11 to 46 mg C l⁻¹ in streams, and varied greatly in response to changes in water table, redox potential and soil temperature.⁷³³
 - Mean stream DOC concentrations at the slope bog site ranged from 11.8 to 41.2 mg C l⁻¹.⁷³⁴
 - At the forested wetland site, there was a consistent outlet streamwater DOC concentration of approximately 30 mg C l⁻¹ maintained throughout the measurement period despite more variable and higher concentrations in the soil.⁷³⁵
- DON concentrations ranged from 0.03 to 2.4 mg N l⁻¹ (milligrams nitrogen per liter) in wetland soils, 0.2 to 0.6 mg N l⁻¹ in streams and concentrations also reflected seasonal changes in physical measures.⁷³⁶
 - Streamwater DON concentrations at the slope bog site were consistently about 0.5 mg N l⁻¹ throughout the measurement period.⁷³⁷ The concentrations of DON in the outlet stream at the slope bog site ranged from 0.2 to 0.6 mg N l⁻¹.⁷³⁸
 - At the forested wetland site, the outlet stream DON concentration was approximately 0.5 mg N l⁻¹ throughout the measurement period.⁷³⁹

⁷²⁷ *Darimont et al. (2010, p. 2)

⁷²⁸ *Darimont et al. (2010, p. 2). The authors cite Moore et al. (2007, 2008) for this information.

⁷²⁹ *Darimont et al. (2010, p. 2)

⁷³⁰ *Darimont et al. (2010, p. 2). The authors cite Mitchell and Lamberti (2005) and Lessard and Merritt (2006) for this information.

⁷³¹ *D'Amore et al. *Controls on dissolved organic matter concentrations in soils and streams from a forested wetland and sloping bog in southeast Alaska*. (2010, p. 249)

⁷³² *D'Amore et al. (2010, p. 249)

⁷³³ *D'Amore et al. (2010, p. 249)

⁷³⁴ *D'Amore et al. (2010, p. 256)

⁷³⁵ *D'Amore et al. (2010, p. 257)

⁷³⁶ *D'Amore et al. (2010, p. 249)

⁷³⁷ *D'Amore et al. (2010, p. 257)

⁷³⁸ *D'Amore et al. (2010, p. 256)

⁷³⁹ *D'Amore et al. (2010, p. 257)

- Depth to water table and soil temperature were significant factors related to the concentration of DOC in forested wetland soils and streams, while soil temperature was a significant factor that influenced stream DOC and DON concentrations.⁷⁴⁰
- Comparing soil solution and stream DOM concentrations indicated that nitrogen is retained in bogs, while both dilution and biotic/abiotic retention mechanisms control DOM export in forested wetlands.⁷⁴¹

The role of salmon in freshwater ecosystem nutrient cycling and productivity has also been assessed:

- Isotopic analyses conducted by Helfield and Naiman (2001) indicate that trees and shrubs near spawning streams derive 22–24% of their foliar nitrogen (N) from spawning salmon.⁷⁴² As a consequence of this nutrient subsidy, growth rates are significantly increased in Sitka spruce (*Picea sitchensis*) near spawning streams.⁷⁴³
- Wipfli et al. (1998) studied artificial and natural streams in southeast Alaska and found that total macroinvertebrate densities were up to eight and twenty-five times higher in carcass-enriched areas of artificial and natural streams, respectively; Chironomidae midges, *Baetis* and *Cinygmula* mayflies, and *Zapada* stoneflies were the most abundant taxa.⁷⁴⁴ The authors conclude increased biofilm in Margaret Creek (AK) and macroinvertebrate abundance in both systems suggest that salmon carcasses elevated freshwater productivity.⁷⁴⁵
- Chaloner et al. (2002) studied the contribution of salmon carcasses to the amount and distribution of marine carbon and nitrogen at the same site as Wipfli and colleagues (1998).⁷⁴⁶ The assimilation of marine-derived nitrogen by aquatic organisms and subsequent isotopic enrichment were similar in experimentally and naturally carcass-enriched streams.⁷⁴⁷ Their results suggest that pathways of marine-derived nitrogen incorporation into stream food webs include both consumption of salmon material by macroinvertebrates and fish and uptake of mineralized marine-derived nitrogen by biofilm.⁷⁴⁸

British Columbia

Information needed

Washington

Bilby et al. (1998) state the availability of organic matter and nutrients transported from the marine environment to streams by spawning salmon was increased in two small streams in southwestern Washington by adding salmon carcasses from a nearby hatchery.⁷⁴⁹ Stable isotope analysis indicated that the proportion of marine-derived nitrogen in the muscle tissue of juvenile salmonids increased as much as thirty-nine percent following

⁷⁴⁰ *D'Amore et al. (2010, p. 249)

⁷⁴¹ *D'Amore et al. (2010, p. 249)

⁷⁴² *Helfield and Naiman. (2001, p. 2403)

⁷⁴³ *Helfield and Naiman. (2001, p. 2403)

⁷⁴⁴ *Wipfli et al. *Influence of salmon carcasses on stream productivity: response of biofilm and benthic macroinvertebrates in southeastern Alaska, USA.* (1998, p. 1503)

⁷⁴⁵ *Wipfli et al. (1998, p. 1503)

⁷⁴⁶ *Chaloner et al. (2002).

⁷⁴⁷ *Chaloner et al. (2002, p. 1257). The authors cite Levy (1997) for this information.

⁷⁴⁸ *Chaloner et al. (2002, p. 1257). The authors cite Levy (1997) for this information.

⁷⁴⁹ *Bilby et al. *Response of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*) to the addition of salmon carcasses to two streams in southwestern Washington, U.S.A.* (1998, p. 1909)

carcass placement.⁷⁵⁰ Results suggest that eggs and carcasses of adult salmon provide a very important resource during a period when other food items are often scarce.⁷⁵¹

Oregon

Information needed.

Northwestern California

In Castle Lake, in years with incomplete vertical mixing, productivity is often less than in years with spring holomixis (i.e., complete mixing).⁷⁵² A 27-year record (specific date range not provided) of summer primary productivity had no long-term trend, but considerable interannual variability, with extreme years often occurring when ENSOs occurred.⁷⁵³ Further statistical analysis of interactions between the early summer productivity and climate revealed negative associations with the time of ice-out and total precipitation preceding the spring bloom.⁷⁵⁴ The time of ice-out sets the length of the growing season, and total precipitation affects flushing rates.⁷⁵⁵

Future Projections

Global

Experimental data suggest that rates of soil dissolved organic carbon (DOC) production are increased under higher temperatures and in response to a shift from anaerobic to aerobic conditions in saturated soils.⁷⁵⁶ A study by Tipping et al. (1999) also indicated that climatic warming will increase the production of potentially soluble organic matter.⁷⁵⁷ On the other hand, more severe drying during droughts may have the opposite effect on DOC leaching; field manipulation experiments on podsollic heathland soils in Wales (i.e., a type of soil common to Western Europe, created by long-term clearing of natural forest and woodland vegetation via grazing or burning, such that heathland, a dwarf-shrub habitat, develops) showed decreasing microbial activity and DOC concentrations in response to experimental drought, with increased DOC observed following soil re-wetting.⁷⁵⁸

Dissolved inorganic nitrogen (as nitrate, NO_3^-) levels may decrease if rates of denitrification are increased (e.g., by higher temperatures and lower oxygen), which could be important given increasing levels of nitrogen deposition.⁷⁵⁹ On the other hand, if discharge and sediment transport increase, then the downstream movement of nitrogen (as ammonium, NH_4^+) and phosphorus (as phosphate, PO_4^{3-}) may increase.⁷⁶⁰

In general in lakes, short residence times mean that pollutants such as excess nutrients from point sources are flushed out of the lake ecosystem, whereas with decreasing precipitation and longer residence times, they will accumulate, with likely changes in phytoplankton communities and in food-web composition and structure.⁷⁶¹ In

⁷⁵⁰ *Bilby et al. (1998, p. 1909)

⁷⁵¹ *Bilby et al. (1998, p. 1909)

⁷⁵² *Melack et al. (1997, p. 983). The authors cite Goldman and de Amezaga (1984) for this information.

⁷⁵³ *Melack et al. (1997, p. 983). The authors cite Jassby and Goldman (1992) for this information.

⁷⁵⁴ *Melack et al. (1997, p. 983). The authors cite Goldman et al. (1989) and Jassby et al. (1990) for this information.

⁷⁵⁵ *Melack et al. (1997, p. 983)

⁷⁵⁶ *Nickus et al. (2010, p. 60). The authors cite Clark et al. (2009) for this information.

⁷⁵⁷ *Nickus et al. (2010, p. 60)

⁷⁵⁸ *Nickus et al. (2010, p. 60). The authors cite Toberman et al. (2008) for this information.

⁷⁵⁹ *Palmer et al. *Wild and Scenic Rivers*. (2008, p. 31). The authors cite Baron et al. (2000) for this information.

⁷⁶⁰ *Palmer et al. (2008, p. 31).

⁷⁶¹ *Verdonschot et al. (2010, p. 69). The authors cite Schindler et al. (1990, 1996) and Hillbricht-Ilkowska (2002) for information on likely changes to phytoplankton communities.

lakes with long residence times internal processes may become more important (e.g., sorbing to particles, uptake by biota).⁷⁶² Further, higher flows can cause higher turbidity in lakes, which reduces the light penetration crucial to the health of some forms of aquatic life.⁷⁶³ On the other hand, where surface flows decline, erosion rates and sediment transport may drop, and lake clarity may improve but this may increase the concentration of pollutants.⁷⁶⁴

Southcentral and Southeast Alaska

There is some evidence for increased dissolved organic matter (DOM) export from peatlands to aquatic ecosystems due to climate warming in Great Britain.⁷⁶⁵ While there is also evidence that decreased sulfate deposition may also be a factor, the potential that stored soil organic matter may be exported as DOM through increased microbial activity and decomposition under warmer conditions is of concern in the coastal temperate rainforest.⁷⁶⁶ Increased DOM concentrations in the soils could be exported via shallow subsurface flowpaths, which could intensify with increased precipitation.⁷⁶⁷ However, increased precipitation may also inhibit decomposition and subsequent DOM production.⁷⁶⁸ Therefore, understanding how DOM concentrations vary in response to seasonal changes in soil temperature and saturation is important for elucidating DOM cycling in peatlands of the coastal temperate rainforest.⁷⁶⁹ The results can help calibrate regional watershed carbon flux models to predict the potential impacts of climate shifts and management activities on future wetland soil and stream DOM concentrations in coastal temperate rainforest watersheds.⁷⁷⁰

In arctic and subarctic North America, increased rates of decomposition and increased water residence time are predicted to increase primary and secondary productivity, yet it is not clear that these increases in production will be adequate to make up for the increased metabolic demand of higher temperatures for fishes.⁷⁷¹ Climatic warming could result in substantial changes in the mixing properties of many high latitude and mid-latitude lakes which, in turn, would produce large effects on deep-water dissolved oxygen concentrations and on primary productivity via effects on nutrient supplies and exposure of phytoplankton to light.⁷⁷² Although these effects are expected to be highly dependent on the morphometric (i.e., size and shape) characteristics of individual lakes and are difficult to predict, at high latitudes the effects are likely to result in higher primary productivity.⁷⁷³

⁷⁶² *Verdonschot et al. (2010, p. 69)

⁷⁶³ *Nelson et al. *In hot water: water management strategies to weather the effects of global warming*. (2007, p. 12). The authors cite Murdoch et al. (2000) for this information.

⁷⁶⁴ *Nelson et al. (2007, p. 12)

⁷⁶⁵ *D'Amore et al. (2010, p. 250). The authors cite Freeman et al. (2001) and Worrall et al. (2004) for this information.

⁷⁶⁶ *D'Amore et al. (2010, p. 250). The authors cite Evans et al. (2006) for information on sulfate deposition and Nadelhoffer et al. (1991) and Evans et al. (1999) for information on the export of soil organic matter as dissolved organic matter via increased microbial activity and decomposition under warmer conditions.

⁷⁶⁷ *D'Amore et al. (2010, p. 250). The authors cite Dalva and Moore (1991), Qualls (2000), and Emili and Price (2006) for this information.

⁷⁶⁸ *D'Amore et al. (2010, p. 250)

⁷⁶⁹ *D'Amore et al. (2010, p. 250)

⁷⁷⁰ *D'Amore et al. (2010, p. 249)

⁷⁷¹ *Meyer et al. *Impacts of climate change on aquatic ecosystem functioning and health*. (1999, p. 1375-1376). The authors cite Rouse et al. (1997) for this information.

⁷⁷² *Meyer et al. (1999, p. 1376). The authors cite Hostetler and Small (1999) for information on mixing properties in high- and mid-latitude lakes.

⁷⁷³ *Meyer et al. (1999, p. 1376)

British Columbia

With an increase in temperature and longer ice-free periods, streams that do not have current nutrient limitations may increase in productivity.⁷⁷⁴ Increased water temperatures could affect metabolic rates and increase biological activity and decomposition.⁷⁷⁵ In aquatic systems with sufficient nutrient and oxygen supplies, an increase in biological productivity can increase nutrient cycling and possibly accelerate eutrophication.⁷⁷⁶ However, it is likely that in aquatic systems currently stressed by high biological oxygen demand any subsequent increase in water temperatures could decrease biological productivity as a result of a decline in the oxygen-holding capacity of the water.⁷⁷⁷ Alternatively, in regions or specific water bodies where temperatures are below thermal optima for fish or temperature sensitivity is not a concern, increased water temperatures may promote fish growth and survival.⁷⁷⁸ One reviewer noted increased water temperatures may promote changes in diversity as well.⁷⁷⁹

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Evaluation of the potential effects of global warming on primary productivity in montane lakes is possible by linking GCM projections of climate change with a model of lacustrine (i.e., lake) productivity.⁷⁸⁰ Byron and Goldman (1990) attempted such an approach by using almost three decades of limnological data from Castle Lake to develop a regression model that related algal productivity to regional temperature and precipitation.⁷⁸¹ When used in combination with GCM calculations of temperature and precipitation under doubled CO₂ concentrations, their model predicted increased algal productivity.⁷⁸² These increases were driven by the GCM-projected higher temperatures, which were linked to earlier melt and a longer growing season.⁷⁸³ Because the GCMs calculated January-May precipitation as being similar to historical records, no effect of doubled CO₂ on runoff was observed; this result deserves additional study using newer, regional predictions of climate change.⁷⁸⁴

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends in British Columbia and Oregon and future projections in Washington and Oregon.

⁷⁷⁴ *Austin et al. *Taking Nature's Pulse: The Status of Biodiversity in British Columbia*. (2008, p. 189). The authors cite Tyedmers and Ward (2007) for this information.

⁷⁷⁵ *Pike et al. (2010, p. 729)

⁷⁷⁶ *Pike et al. (2010, p. 729). The authors cite Murdoch et al. (2000) for this information.

⁷⁷⁷ *Pike et al. (2010, p. 729)

⁷⁷⁸ *Pike et al. (2010, p. 729)

⁷⁷⁹ Comment from reviewer, April 2011.

⁷⁸⁰ *Melack et al. (1997, p. 983)

⁷⁸¹ *Melack et al. (1997, p. 983). The authors of the cited report are summarizing the work of Byron and Goldman (1990).

⁷⁸² *Melack et al. (1997, p. 983)

⁷⁸³ *Melack et al. (1997, p. 983)

⁷⁸⁴ *Melack et al. (1997, p. 983)

2. CHANGES TO STRATIFICATION AND EUTROPHICATION

Climate change expressed by increased water temperatures is expected to enhance the symptoms of eutrophication (i.e. the process of nutrient enrichment leading to dense algae growth.⁷⁸⁵) through increases in primary production and declines in oxygen storage capacity.⁷⁸⁶ Model studies predict that lake temperatures, especially in the epilimnion (i.e., the top-most layer in a thermally stratified lake), will increase with increasing air temperature, so that temperature profiles, thermal stability and mixing patterns are expected to change as a result of climate change.⁷⁸⁷

Fluctuations in lake surface water temperatures are transported downwards by vertical mixing, and can reach the deep waters when the thermal stratification is weak.⁷⁸⁸ In particular, the hypolimnetic temperatures of deep lakes, which are determined by winter meteorological conditions, and the amount of heat reaching deep-water layers before the onset of thermal stratification may act as a “climate memory.”⁷⁸⁹ Increasing air temperatures may thus lead to a progressive rise in deep-water temperatures, as found, for instance, by Ambrosetti & Barbanti (1999) for lakes in Northern Italy.⁷⁹⁰

Observed Trends

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

As described previously (Chapter III Section 4), spring water temperatures in Lake Washington have shown significant warming trends.⁷⁹¹ This trend affected the onset of spring thermal stratification in Lake Washington, which showed a significant advancement of spring warming trends from 1962 to 2002.⁷⁹² Stratification onset now occurs twenty-one days earlier than it did four decades ago.⁷⁹³

Oregon

Information needed.

Northwestern California

Information needed.

⁷⁸⁵ Brooks et al. (2003, p. 263)

⁷⁸⁶ *New Hampshire Dept. of Environmental Services (2003), *Environmental Fact Sheet: Lake or Pond – What is the Difference?*

⁷⁸⁷ *Nickus et al. (2010, p. 45). The authors cite Hondzon & Stefan (1993) and Stefan et al. (1998) as examples.

⁷⁸⁸ *Nickus et al. (2010, p. 46)

⁷⁸⁹ *Nickus et al. (2010, p. 46)

⁷⁹⁰ *Nickus et al. (2010, p. 46)

⁷⁹¹ *Winder and Schindler. (2004a, p. 2102)

⁷⁹² *Winder and Schindler. (2004a, p. 2102)

⁷⁹³ *Winder and Schindler. (2004a, p. 2102)

Future Projectons

Global

Lakes may experience a longer stratification period in summer and a single circulation period in winter.⁷⁹⁴ This could enhance eutrophication and lead to oxygen depletion in deep zones during summer, eliminating refuges for coldwater-adapted fish species.⁷⁹⁵ In addition, warming may increase the potential for the production of nuisance algae and eliminate deep, cool refuge areas for large fish.⁷⁹⁶ Phytoplankton production may increase with higher temperatures due to increased nutrient availability, and eutrophication problems may thereby become more severe.⁷⁹⁷ Further, declines in surface water flows result in longer residence times for chemicals entering lakes.⁷⁹⁸ This is of greatest importance for biologically reactive chemicals (e.g., phosphorus) for which longer residence times can result in increased biological reaction and increased potential for eutrophication.⁷⁹⁹

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed for both observed trends and future projections in eutrophication and stratification.

⁷⁹⁴ *Euro-Limpacs. *Climate Change and Freshwater (website)*. (2011)

⁷⁹⁵ * Euro-Limpacs. (2011)

⁷⁹⁶ *New Hampshire Dept. of Environmental Services (2003), *Environmental Fact Sheet: Lake or Pond – What is the Difference?*

⁷⁹⁷ *Verdonschot et al. (2010, p. 69). The authors cite Mooij et al. (2005) for this information.

⁷⁹⁸ *Pike et al. (2010, p. 731). The authors cite Whitehead et al. (2009) for this information.

⁷⁹⁹ *Pike et al. (2010, p. 731). The authors cite Schindler (2001) for this information.

3. CHANGES TO WATER INPUT, LEVEL, AND AREA

Increased air temperatures may speed evaporation of surface water from wetlands (and from runoff and water bodies that supply wetlands) and could increase the rate at which wetland plants lose water through evaporation and transpiration if the warmer temperatures are not accompanied by increased rainfall.⁸⁰⁰ Drying is most likely to occur at the edges of wetlands and could reduce the size or extent of inland wetlands.⁸⁰¹ Earlier ice-out and snowmelt may shorten wet periods, especially in ephemeral wetlands.⁸⁰²

Flow exerts a strong control on stream temperature, and flow reductions will likely exacerbate stream temperature increases caused by increased incoming longwave (i.e. infrared) and sensible heat (i.e. heat energy transferred between the surface and air when there is a difference in temperature between them).⁸⁰³ If warmer temperatures produce a shift from snow to rain in higher or more northerly basins, this could reduce summer base flows in streams; in turn, habitat for invertebrates and fish would decrease and there would be less recharge into riparian groundwater tables that support tree communities.⁸⁰⁴ Changes in flood risk are likely to result in substantial changes in sediment transport and channel formation processes, and are also likely to affect ecological processes that are sensitive to changes in the probability distributions of high flow events.⁸⁰⁵

Snow-fed rivers and streams are likely to have less water in summer, which may diminish the quantity and quality of wildlife habitat.⁸⁰⁶ However, as one reviewer noted, this trend will vary by location and season.⁸⁰⁷

Winter (2000) lists the following examples of adverse effects to the water supply of riparian wetlands: (1) reduction of precipitation in headwaters areas, (2) reduction of groundwater contribution to the stream, and (3) increase in transpiration from valley bottom vegetation.⁸⁰⁸ Wetlands fed by regional groundwater sources may have relatively sustained water inputs, and therefore be somewhat buffered from changes in climate.⁸⁰⁹ However, small systems fed by local groundwater discharge may be more vulnerable because of their small watersheds.⁸¹⁰

Observed Trends

Southcentral and Southeast Alaska

Across the southern two-thirds of Alaska, the area of closed-basin lakes (lakes without stream inputs and outputs) has decreased over the past fifty years.⁸¹¹ This is likely due to the greater evaporation and thawing of permafrost that result from warming.⁸¹² As noted previously, the NPLCC region contains little permafrost.

⁸⁰⁰ *OTA. (1993, Box 4G, p. 175)

⁸⁰¹ *OTA. (1993, Box 4G, p. 175)

⁸⁰² Kling. (2003, Table 5, p. 28)

⁸⁰³ *Luce and Holden. (2009, p. 5)

⁸⁰⁴ Poff, Brinson and Day. (2002)

⁸⁰⁵ *Hamlet and Lettenmaier. (2007, p. 16)

⁸⁰⁶ *PRBO. (2011, p. 10)

⁸⁰⁷ Comment by reviewer, April 2011.

⁸⁰⁸ Winter. (2000)

⁸⁰⁹ Winter. (2000)

⁸¹⁰ Winter. (2000)

⁸¹¹ *US-GCRP. (2009, p. 141)

⁸¹² *US-GCRP. (2009, p. 141). The authors cite Klein et al. (2005) and Riordan et al. (2006) for this information.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Future Projections

Global

One of the most direct effects will be reduced lake levels, although areas that become wetter could have higher lake levels.⁸¹³ Increases in evapotranspiration brought about by higher temperatures, longer growing seasons, and extended ice-free periods, unless offset by equal or greater increases in precipitation, are likely to result in reduced lake levels and river inputs.⁸¹⁴ A decline in water level due to decreased precipitation may cause changes in the nutrient status and acidity of lakes with low buffering capacities.⁸¹⁵ In cases where precipitation and evapotranspiration both increase, lake levels might change little but water residence time in lakes would be expected to be shortened.⁸¹⁶

Permanent lowering of lake levels will expose more shoreline, possibly harming productive littoral (near-shore) zones and coastal wetlands of the Great Lakes.⁸¹⁷ Many of these lake-fringing wetlands may become isolated, reducing habitat for fish that require wetlands for spawning and nursery habitat.⁸¹⁸ The effects of water-level reductions in smaller lakes could be equally profound.⁸¹⁹

⁸¹³ *Poff, Brinson and Day. (2002, p. 15)

⁸¹⁴ *Allan, Palmer and Poff. (2005, p. 279)

⁸¹⁵ *Verdonschot et al. (2010, p. 69). The authors cite Carvalho and Moss (1999) for this information.

⁸¹⁶ *Allan, Palmer and Poff. (2005, p. 279)

⁸¹⁷ *Poff, Brinson and Day. (2002, p. 17). The authors cite Magnuson et al. (1997) for this information.

⁸¹⁸ *Poff, Brinson and Day. (2002, p. 17). The authors cite Brazner and Magnuson (1994) for this information.

⁸¹⁹ *Poff, Brinson and Day. (2002, p. 17)

Box 16. Multiple stressors in wetlands: climate change, and human and natural disturbance.

Any wetland already degraded as a result of human actions (e.g., pollution, water diversion, fragmentation) may be particularly vulnerable to climate change impacts. By 1997, the conterminous United States had lost more than half of the estimated 221 million acres (89.5 million hectares) of wetlands it contained at the time of European settlement (~115.5 million acres, or ~46.7 million hectares, lost). The potential for climate change to spur further losses and degradation could pose a significant threat to valued functions of wetlands.

The impacts of climate change will overlay current disturbances, further reducing the ability of riparian wetlands to perform functions such as stream bank maintenance, erosion reduction, flood buffering, and filtration of sediments and nutrients. Warmer temperatures may increase the susceptibility of seasonal wetlands to drought and fire, which would degrade vegetation and habitat. Areas that become drier due to changes in precipitation and soil moisture could experience greater disturbance than those that become wetter.

Disease and insect outbreaks are also projected to be affected by climate change. These ecological disturbance processes may then affect related riparian processes. Further, ecosystems may become more susceptible to invasion as temperatures warm, precipitation regimes fluctuate, and nutrient flows change, hampering the ability of the ecosystem to promote native species biodiversity. For information on disturbance due to invasive and non-native species, please see Chapter V Section 4. *Altered interaction with invasive and non-native species.*

Even if it does not become the primary driver of wetland loss, climate change is also likely to aggravate stresses such as agriculture, development, and pollution. Anthropogenic responses to climate change will also affect riparian wetlands; if conditions become drier, human demands for groundwater and surface water will increase, decreasing the amount of water available in aquifers to feed wetland systems.

Sources: Dahl. (2000); Pike et al. (2010); Poff, Brinson, and Day. (2002); U.S. Congress, Office of Technology Assessment. (1993); U.S. EPA. (2008b).

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Pacific Northwest

In Oregon (as well as transient rain-snow basins throughout the western U.S.), lower order streams in transient rain-snow basins will be the most vulnerable to rising summer air temperature and diminished low flow; a new dam or reservoir might be required to maintain environmental flow in summer.⁸²⁰

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends and future projections for specific lakes and wetlands, as well as regional assessments.

⁸²⁰ *Chang and Jones. (2010, p. 132)

4. CHANGES TO THE LENGTH AND DATE OF SEASONAL ICE COVER

High-latitude rivers and lakes develop an ice cover in winter.⁸²¹ Although the area and volume are small compared to other components of the cryosphere (which consists of snow, river and lake ice, sea ice, glaciers and ice caps, ice shelves and ice sheets, and frozen ground⁸²²), this ice plays an important role in freshwater ecosystems, winter transportation, bridge and pipeline crossings, etc.⁸²³ Changes in the thickness and duration of these ice covers can therefore have consequences for both the natural environment and human activities.⁸²⁴ According to IPCC (2007), freeze-up is defined conceptually as the time at which a continuous and immobile ice-cover forms, while break-up is generally the time when open water becomes extensive in a lake or when the ice-cover starts to move downstream in a river.⁸²⁵

Major variables affecting duration and thickness of lake and river ice are air temperature, wind, snow depth, heat content of the water body and rate and temperature of potential inflows.⁸²⁶ Dates of freeze-up and ice break-up have proved to be good indicators of climate variability at local to regional scales, and as a response to large-scale atmospheric forcing.⁸²⁷ As climate changes, and air temperatures, particularly in the winter, tend to increase, these shifts should be reflected in ice-cover.⁸²⁸

Observed Trends

Regional

Several authors have used the correlation of ice-cover dates and air temperature to translate shifts in freeze-up and break-up into estimated changes in air temperature.⁸²⁹ A typical value for lakes at mid-latitude is a four- to five-day shift in mean freeze-up or break-up dates for each degree Celsius change in mean autumn or spring temperatures.⁸³⁰ Relationships tend to be stronger for freezing dates and in colder climates.⁸³¹

Southcentral and Southeast Alaska

Information needed.

British Columbia

Increasing temperatures have affected the length and date of seasonal lake ice cover.⁸³² A Canada-wide study showed significantly earlier lake “ice-free” dates for the 1951–2000 period.⁸³³ In several British Columbia lakes,

⁸²¹ *Lemke et al. (2007, p. 342)

⁸²² *Lemke et al. (2007, p. 339)

⁸²³ *Lemke et al. (2007, p. 342)

⁸²⁴ *Lemke et al. (2007, p. 342)

⁸²⁵ *Nickus et al. (2010, p. 51)

⁸²⁶ *Nickus et al. (2010, p. 51)

⁸²⁷ *Nickus et al. (2010, p. 51). The authors cite Walsh (1995), Livingstone (1999, 2000), Yoo & D’Odorico (2002), and Blenckner et al. (2004) as examples for this information.

⁸²⁸ *Nickus et al. (2010, p. 51)

⁸²⁹ *Nickus et al. (2010, p. 51). The authors cite Palecki and Barry (1986), Roberston et al. (1992), Assel and Robertson (1995), and Magnuson et al. (2000) as examples for this information.

⁸³⁰ *Nickus et al. (2010, p. 51)

⁸³¹ *Nickus et al. (2010, p. 51). The authors cite Walsh (1995) for this information.

⁸³² *Pike et al. (2010, p. 703)

⁸³³ *Pike et al. (2010, p. 703). The authors cite Duguay et al. (2006) for this information.

the first melt date and ice-free date was two to eight days earlier per decade from 1945 to 1993, whereas the duration of ice cover decreased by up to forty-eight days over the 1976–2005 period.⁸³⁴

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Ecological processes in montane lakes such as Castle Lake may be strongly influenced by climatic conditions, and, therefore, be sensitive to changes in climate caused by global warming.⁸³⁵ For example, during the extraordinary El Niño of 1983, Castle Lake remained frozen until early July and summer primary productivity was only twenty-five percent of the long-term average.⁸³⁶

Future Projections

Global

Climate change will reduce the spatial and seasonal extent of ice cover on lakes, which may influence community and invasion processes by increasing light levels for aquatic plants, reducing the occurrence of low oxygen conditions in winter, and exposing aquatic organisms to longer periods of predation from terrestrial predators.⁸³⁷ For example, longer ice-free periods potentially lengthen the growing season for algae and aquatic macrophytes.⁸³⁸ On the other hand, shorter ice cover periods can be a mixed blessing for fish.⁸³⁹ Reduced ice will lessen the severity of winter oxygen depletion in many small inland lakes, thus significantly reducing winter kill in many fish populations.⁸⁴⁰ However, small species uniquely adapted to live in winterkill lakes go extinct locally when predatory fishes are able to invade and persist in lakes that previously experienced winterkill.⁸⁴¹

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

⁸³⁴ *Pike et al. (2010, p. 703). The authors cite B.C. Ministry of Environment (2002) and Rodenhuis et al. (2007) for this information.

⁸³⁵ *Melack et al. (1997, p. 983)

⁸³⁶ *Melack et al. (1997, p. 983). The authors cite Strub et al. (1985) for this information.

⁸³⁷ *Rahel and Olden. *Assessing the effects of climate change on aquatic invasive species.* (2008, p. 525). The authors cite Magnuson et al. (2000) for information on climate change and reduced extent of ice cover on lakes in the northern hemisphere.

⁸³⁸ *Verdonschot et al. "Climate change and the hydrology and morphology of freshwater ecosystems." In *Climate Change Impacts on Freshwater Ecosystems.* (2010, p. 69)

⁸³⁹ *Kling et al. (2003, p. 23)

⁸⁴⁰ *Kling et al. (2003, p. 23). The authors cite Stefan, Fang and Eaton (2001) for information on the severity of winter oxygen depletion in small inland lakes.

⁸⁴¹ *Kling et al. (2003, p. 23-24). The authors cite Jackson and Mandrak (2002) for this information.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends in specific lakes and rivers, as well as future projections throughout the region.

5. HABITAT LOSS, DEGRADATION, AND CONVERSION

Climate change could affect the distribution and condition of U.S. wetlands by reducing the area they cover and potentially altering the assemblages of plant and animal species they support.⁸⁴² In many areas, the direct effects of climate change may not overtake existing sources of degradation and loss as the dominant threat to wetlands in the near term, but will likely exacerbate current trends of loss and degradation.⁸⁴³

In areas that become drier, the edges of wetlands will start to recede.⁸⁴⁴ Some small or seasonal streams and their associated wetlands could disappear altogether.⁸⁴⁵ In a drier climate, peat-based wetlands would be especially hard-hit as the highly organic soils undergo oxidation and subsidence, thus altering drainage patterns, topography, and exposure to fire.⁸⁴⁶ In a more humid climate, precipitation-dominated wetlands could expand, assuming no barriers from competing land uses.⁸⁴⁷ Further, riparian wetlands have some capacity to adapt to a changing climate by migrating along river edges up- and downstream as well as up- and down-slope to follow the water.⁸⁴⁸ However, in those areas subject to hotter and drier conditions, rivers are likely to shrink, so migration will likely involve retreat rather than expansion.⁸⁴⁹ Overall, in areas where increases in precipitation are greater than evapotranspiration losses due to higher temperatures, wetlands may expand, while increases in precipitation less than evapotranspiration increases, stable precipitation, or declining precipitation would cause may cause rivers to shrink and wetlands to retreat in a warmer climate.⁸⁵⁰

The patterns of water depth, and the duration, frequency, and seasonality of flooding together constitute a wetland's hydroperiod, which determines its vegetation composition, habitat for aquatic organisms, and other ecosystem characteristics.⁸⁵¹ Vegetation on wetlands can be forests, shrubs, mosses, grasses, and sedges.⁸⁵² Regional wetland types range from wet meadows and forested wetlands to fens, bogs, slope wetlands, seeps, and riparian wetlands, among others.⁸⁵³ Longer growing seasons with warmer temperatures likely will result in faster growth.⁸⁵⁴ Those conditions also will favor more rapid decomposition and a transition of bog and forested wetlands to forests with larger stature trees.⁸⁵⁵ Although glaciers and snow fields currently provide habitat for only a few species, the loss of snowpack with warming may allow (alpine) vegetation establishment in these areas, leading to improved habitat conditions for other high elevation wildlife species.⁸⁵⁶ In the short term, vegetation establishment will be limited to areas with substrate that is favorable to rapid soil development, such as

⁸⁴² *OTA. (1993, p. 172)

⁸⁴³ *OTA. (1993, p. 179)

⁸⁴⁴ *OTA. (1993, p. 172)

⁸⁴⁵ *OTA. (1993, p. 184)

⁸⁴⁶ *Poff, Brinson and Day. (2002, p. 20)

⁸⁴⁷ *Poff, Brinson and Day. (2002, p. 20)

⁸⁴⁸ *OTA. (1993, p. 184-185)

⁸⁴⁹ *OTA. (1993, p. 185)

⁸⁵⁰ OTA. (1993)

⁸⁵¹ *Poff, Brinson and Day. (2002, p. 18-19). The authors refer the reader to Box 2 in the cited report.

⁸⁵² *Brooks et al. (2003, p. 120)

⁸⁵³ U.S. Army Corps of Engineers (2008) *Interim Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Western Mountains, Valleys, and Coast Region*. US ACoE: Washington D.C. ERDC/EL TR-08-13. 154 pp. Available online at: < http://www.usace.army.mil/CECW/Documents/cecwo/reg/west_mt_intersupp.pdf>

⁸⁵⁴ *Kelly et al. (2007, p. 51)

⁸⁵⁵ *Kelly et al. (2007, p. 51)

⁸⁵⁶ Halofsky et al. (in press)

shallow-gradient slopes with deep layers of fine-grained glacial till.⁸⁵⁷ The flora of alpine wetlands, restricted to the highest peaks in the continental United States, are particularly vulnerable because an increase in temperature will eliminate species that require cold thermal regimes.⁸⁵⁸

Although CO₂ could potentially enhance photosynthesis and productivity for some wetland plants, the effects of increased atmospheric CO₂ concentrations on wetland plant communities in general are difficult to predict.⁸⁵⁹ Some groups of plants are more responsive to higher CO₂ concentrations than others because of fundamental physiological differences.⁸⁶⁰ However, it is difficult to generalize about the effects of CO₂ on wetlands because of uncertainty about changes in other important factors such as water use efficiency, insect and fungal damage, and soil bacterial activity.⁸⁶¹

Further, as vegetation composition in the watershed responds to climate change, so too will the amounts of water intercepted, evaporated, and transpired, thus altering snow accumulation and melt processes, water balance, groundwater recharge, and ultimately streamflow and mass wasting processes.⁸⁶² For example, increases in the length of the snow-free season and changes in atmospheric evaporative demand are likely to increase plant transpiration, assuming soil water is available.⁸⁶³

Observed Trends

Southcentral and Southeast Alaska

As precipitation in southeastern Alaska shifts toward increased rain and less snow, more water will run off the landscape rather than being stored.⁸⁶⁴ Meadows and bogs may dry as a result.⁸⁶⁵ At the same time, wetlands may become more forested and productive.⁸⁶⁶ As in bogs, alpine tundra is likely to shrink as lower-altitude and lower-latitude edges dry.⁸⁶⁷

In a modeling and connectivity study by Murphy et al. (2010), Alaska's current biome types were predicted using SNAP climate data (Figure 18). Simulated, rather than actual, climate data were used to represent existing conditions in part because actual data for the 2000–2009 decade were not yet available during the modeling for this project in 2008 and 2009.⁸⁶⁸

⁸⁵⁷ Halofsky et al (in press)

⁸⁵⁸ *Poff, Brinson and Day. (2002, p. 23)

⁸⁵⁹ OTA. (1993)

⁸⁶⁰ *Poff, Brinson and Day. (2002, p. 19)

⁸⁶¹ *Poff, Brinson and Day. (2002, p. 19). The authors cite Thompson and Drake (1994) for this information.

⁸⁶² *Pike et al. (2010, p. 713)

⁸⁶³ *Pike et al. (2010, p. 713)

⁸⁶⁴ *Kelly et al. (2007, p. 53)

⁸⁶⁵ *Kelly et al. (2007, p. 53)

⁸⁶⁶ *Kelly et al. (2007, p. 53)

⁸⁶⁷ *OTA. (1993, p. 185)

⁸⁶⁸ *Murphy et al. *Connecting Alaska landscapes into the future: Results from an interagency climate modeling, land management and conservation project. Final Report.* (August 2010, p. 15)

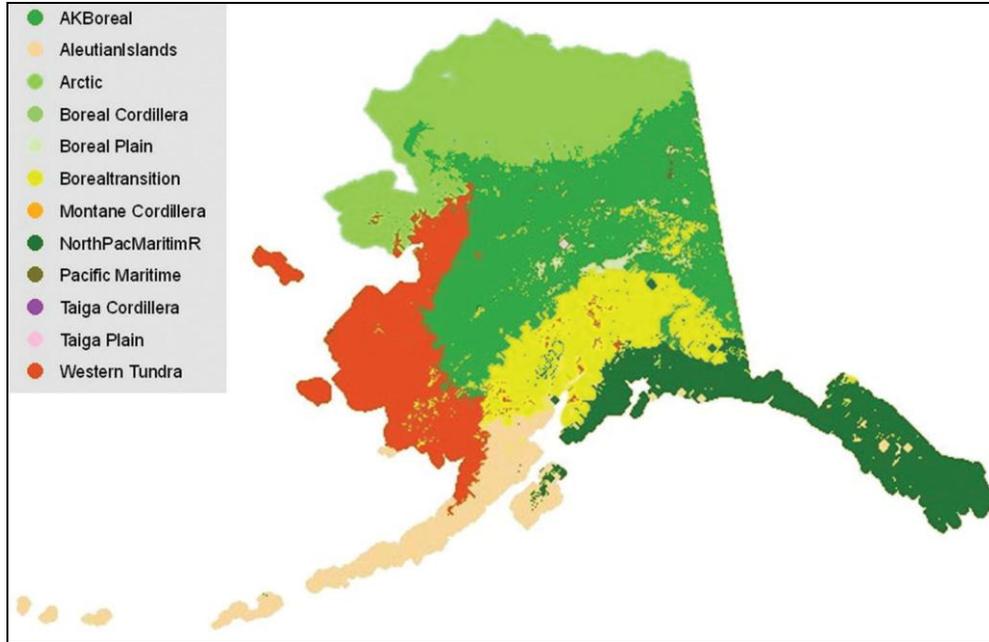


Figure 18. Current biome types as predicted by SNAP climate data. This map shows the best fit for each 2 km pixel in Alaska for 2000–2009 climate projection data, based on climate envelopes for pre-defined biomes and ecoregions in Alaska and Canada. *Source: Reproduced from Murphy et al. (August 2010, Fig. 4, p. 16) by authors of this report.*

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Future Projections

Southcentral and Southeast Alaska, and British Columbia

The abundant peatlands in arctic and subarctic North America are vulnerable to changes in water table depth influenced by permafrost melting and altered water balances.⁸⁶⁹ A changing climate can shift them from a net sink to a net source for CO₂.⁸⁷⁰ In arctic and subarctic North America, reduction in ice-jams on rivers are predicted to result in loss of river delta lakes.⁸⁷¹

⁸⁶⁹ *Meyer et al. (1999, p. 1376)

⁸⁷⁰ *Meyer et al. (1999, p. 1376)

⁸⁷¹ *Meyer et al. (1999, p. 1376)

Murphy et al. (2010) projected spatial shift in potential biomes for three future periods: 2030-2039, 2060-2069, and 2090-2099.⁸⁷² Climate data inputs were all based on the midrange (A1B) emissions scenario for the Scenarios Network for Alaska Planning (SNAP's) Composite GCM, and included mean monthly temperatures and precipitation for the months of June and December for the decades 2000-2009, 2030-2039, 2060-2069, and 2090-2099.⁸⁷³ Figure 19 shows results from 2090-2099.

By 2069, projections indicate marked northward shifts, almost complete change in western coastal regions, and some Canadian biomes moving in from the east.⁸⁷⁴ It is important to note that these shifts represent **potential** rather than actual biome shift, since in many cases it is unconfirmed that seed dispersal, soil formation, and other functional changes could occur at the same rate as climate change (emphasis in original).⁸⁷⁵ In addition, much of southeast Alaska may be in the process of shifting from North Pacific Maritime to Canadian Pacific Maritime—again, as constrained by functional barriers (Box 17).⁸⁷⁶

The model suggests that two-thirds of Alaska will experience a potential biome shift in climate this century, although shifts are occurring at temporally and spatially different rates across the landscape.⁸⁷⁷ Not surprisingly, the three most southern biomes (Boreal Transition, Aleutian Islands, and North Pacific Maritime) were the only biomes with climate envelopes that occur in greater distribution through the next century.⁸⁷⁸ Using Marxan, Murphy and colleagues find that, in general, the Boreal Transition, Aleutian, and Northern Pacific Maritime regions in the southeast portions of the state are more likely to be resilient to change (Figure 20).⁸⁷⁹

Box 17. Vegetation in the North Pacific Maritime and Canadian Pacific Maritime regions.

Alaska's North Pacific Maritime biome extends along the north and east shores of the Gulf of Alaska. Old-growth forests of Sitka spruce, hemlock, and cedar are found in the Alexander Archipelago. Hemlock extends to the end of the Kenai Peninsula, while cedar extends to Prince William Sound. Wetlands are found throughout the region. As elevation increases, upper forests are replaced by a narrow subalpine zone of alder and herbaceous meadow. Alpine tundra and bedrock or ice are found at the highest elevations.

Canada's Pacific Maritime Ecozone includes the mainland Pacific coast and offshore islands of British Columbia. Mixtures of western red cedar, yellow cedar, western hemlock, Douglas-fir, amabilis fir, mountain hemlock, Sitka spruce, and alder comprise the region's temperate coastal forests. Amabilis fir is more common in the north, and Douglas-fir is found largely in the extreme southern portion of the ecozone. Ecosystems range from low-elevation coastal rainforest (mild, humid) to higher-elevation, cool boreal and alpine conditions. Mountain hemlock tends to populate higher elevations.

Source: Murphy et al. (August 2010, p. 65-66, 68-69).

⁸⁷² *Murphy et al. (August 2010, p. 14)

⁸⁷³ *Murphy et al. (August 2010, p. 14)

⁸⁷⁴ *Murphy et al. (August 2010, p. 21)

⁸⁷⁵ *Murphy et al. (August 2010, p. 21)

⁸⁷⁶ *Murphy et al. (August 2010, p. 21)

⁸⁷⁷ *Murphy et al. (August 2010, p. 21)

⁸⁷⁸ *Murphy et al. (August 2010, p. 21)

⁸⁷⁹ *Murphy et al. (August 2010, p. 29)

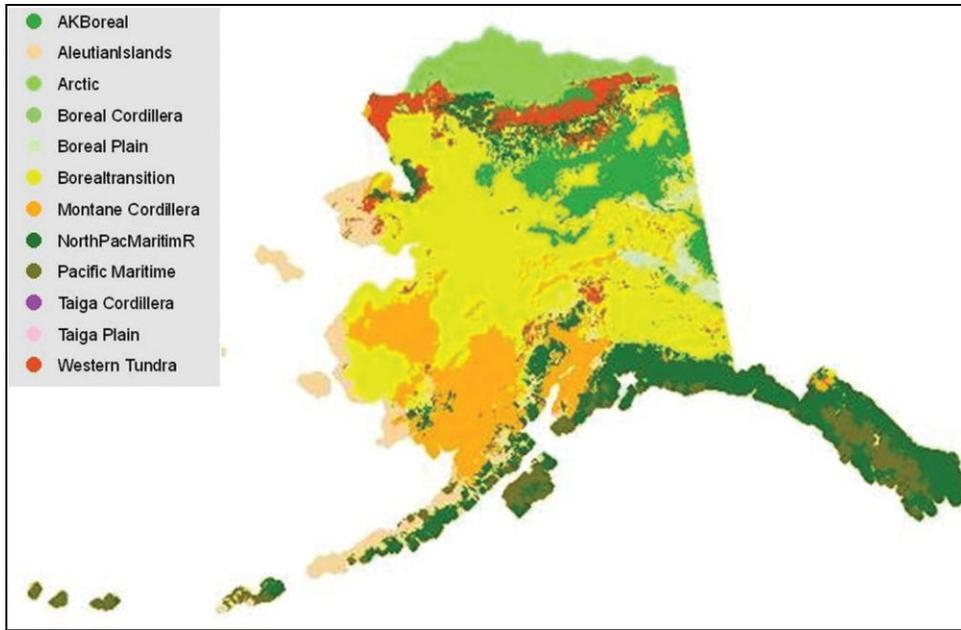


Figure 19. Projected potential biomes for 2090-2099. The Arctic, Alaska Boreal, and Western Tundra biomes are all greatly diminished, in favor of the Montane Cordillera and Boreal Transition. In addition, nearly half of southeast Alaska has shifted from North Pacific Maritime to the Canadian Pacific Maritime.

Source: Reproduced from Murphy et al. (August 2010, Fig. 7, p. 19) by authors of this report.

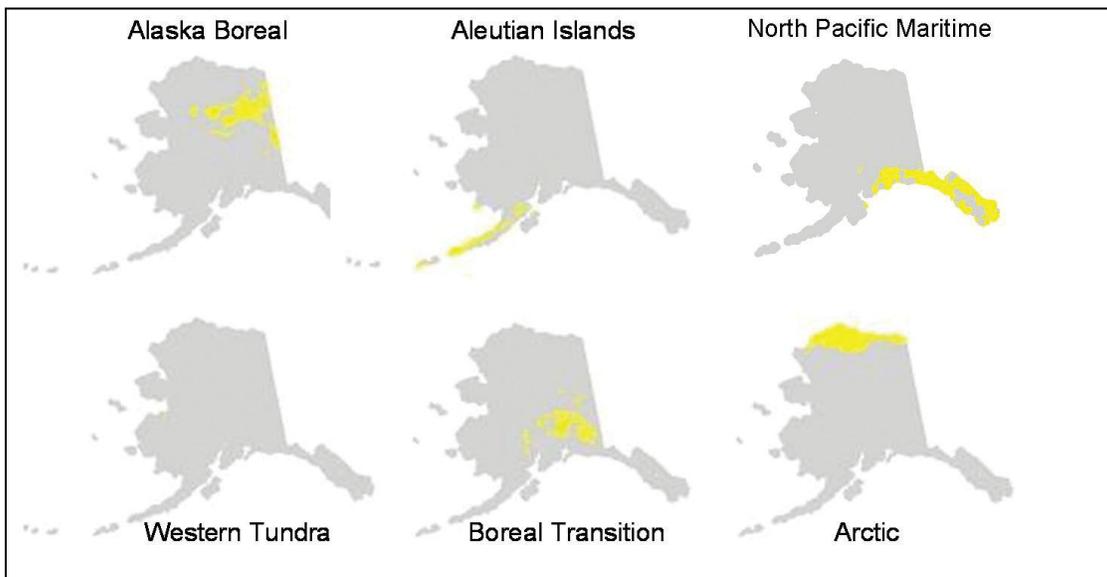


Figure 20. Biome refugia. Areas shaded in yellow are projected to see no change in potential biome by the end of the twenty-first century. Thus, these regions may be more ecologically resilient to climate change and may serve as refugia for species assemblages from each biome.

Source: Reproduced from Murphy et al. (August 2010, Fig. 11, p. 25) by authors of this report.

Washington

In the Queets River, and other coastal rivers, variability in sediment delivery, discharge and benthic shear stress determine the structure, composition and spatial distribution of riparian vegetation.⁸⁸⁰ Climatically induced changes in the hydrological regime are expected to have substantial consequences for riparian forests, in terms of their structure, biogeochemical processes and resiliency.⁸⁸¹ Much of the possible variability is apparent in the species, and their life history strategies in the temperate coastal rainforest.⁸⁸² Rivers with high discharge favor willow, sexually reproducing black cottonwood and many exotic species.⁸⁸³ In contrast, rivers with little variability favor more upland species such as western hemlock, sitka spruce and Douglas fir, asexually reproducing cottonwood and less exotic species.⁸⁸⁴

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here.

Box 18. Sediment Accumulation Rate (SAR): Observed trends and future projections.

The Sediment Accumulation Rate (SAR) indicates the rate of sediment accumulation over space and time. Verdonshot et al. (2010) note the SAR affects lake morphology and the characteristics of lake habitats, as well as physical and chemical stratification. All of these factors affect the distribution of aquatic flora and fauna, particularly in lake shoreline areas. Over the last 100 years (specific study period not provided), an increase in SAR has been observed in many lakes. Increased biogenic sedimentation from eutrophication and accelerated catchment soil erosion, caused by changes in land use and management, contributed to the observed increase in SAR. Climate change, through increases in winter run-off, may increase the suspended sediment load to lakes, which could lead to increases in the SAR. Similarly, increases in catchment soil erosion induced by more rainfall or increased frequency of extreme events (e.g., summer droughts, winter storms), may increase allochthonous input to lakes and as a result, may increase the SAR.

Source: Verdonshot et al. (2010, p. 70)

⁸⁸⁰ *Melack et al. (1997, p. 985). The authors cite Fetherston et al. (1995) for this information.

⁸⁸¹ *Melack et al. (1997, p. 985). The authors cite Naiman et al. (1993) for this information.

⁸⁸² *Melack et al. (1997, p. 985). The authors cite Naiman and Anderson (1997) for this information.

⁸⁸³ *Melack et al. (1997, p. 985). The authors cite DeFerrari and Naiman (1994) for this information.

⁸⁸⁴ *Melack et al. (1997, p. 985)