Rivers, Streams, and Floodplains

Climate Change Vulnerability Assessment for the Santa Cruz Mountains Climate Adaptation Project

This document represents an initial evaluation of mid-century climate change vulnerability for ***rivers, streams, and floodplains*** *in the* ***Santa Cruz Mountains region*** *based on expert input during an October 2019 vulnerability assessment workshop as well as information in the scientific literature.*

Habitat Description

Rivers and streams in the Santa Cruz Mountains region are characterized by rain-dominated hydrological regimes, with variable flows and frequent disturbances[1]. Low-lying floodplains adjacent to river and stream channels experience periodic flooding[2], and often include riparian vegetation such as willow (*Salix* spp.), white alder (*Alnus rhombifolia*), Fremont's cottonwood (*Populus fremontii*), western sycamore (*Platanus racemosa*), valley oak (*Quercus lobata*), and coast live oak (*Q. agrifolia*)[1,3]. Important floodplains within the study area include those associated with Corte Madera Creek, Pajaro River, Pescadero Creek, and San Gregorio Creek[4].

Vulnerability Ranking

High Vulnerability

Low → High

High Confidence

Rivers, streams, and floodplains are sensitive to climate stressors (e.g., altered streamflow, changes in patterns of precipitation and runoff, increased drought, warmer water temperatures, reduced soil moisture) that impact hydrology, water quality, and the structure, composition, and distribution of riparian vegetation. Although rivers, streams, floodplains, and associated riparian areas are naturally dynamic systems, more frequent and/or severe disturbance events may impact habitat structure and ecosystem processes such as erosion and sediment transport. Non-climate stressors (e.g., development, agriculture, livestock grazing, roads/highways, dams, water diversions, pollutants, timber harvest) can exacerbate habitat sensitivity by altering habitat structure, water availability and quality, and riparian vegetation health and extent. Most rivers, streams, and floodplains within the region have been impact by one or more of these factors, reducing their ability to recover from climate-driven changes and increasing vulnerability to sudden ecological collapse. However, societal support for the protection and management of these habitats is high, and many restoration efforts are already occurring in the region. Management practices focused on reducing vulnerability to climate change are likely to focus on strategies that enhance structural and functional integrity. These include restoring variable flow regimes and increasing flow volumes in areas impacted by dams and water diversions, reducing nutrient inputs to minimize the risk of harmful algal blooms, restoring incised stream channels, and reconnecting floodplains with mainstem rivers.

Sensitivity and Exposure

High Impact

Low → High

Low Confidence

Sensitivity is a measure of whether and how a habitat is likely to be affected by a given change in climate and climate-driven factors, changes in disturbance regimes, and non-climate stressors. **Exposure** is a measure of how much change in these factors a resource is likely to experience.

Sensitivity and future exposure to climate and climate-driven factors

Rivers, streams, and floodplains are sensitive to climate stressors that impact hydrology and water quality, as well as those that alter the structure, composition, and distribution of riparian vegetation.

Climate Stressor	Trend Direction	Projected Future Changes
Streamflow	▲ ▼	• Generally, wet season flows are projected to increase and dry season flows are projected to decrease[5]
Precipitation & runoff	▲ ▼	• Uncertain trends in precipitation and runoff • Shorter winters and longer, drier summers likely, with higher interannual variability[6,7]
Drought	▲	• Increased frequency of drought years, including periods of prolonged and/or severe drought[6,8]
Water temperature	▲	• 1.1–2.0°C (2.0–3.6°F) increase in mean summer stream temperature by the 2090s[9]
Soil moisture	▼	• Reduced soil moisture likely due to increased evaporative demand[6,10]

- **Altered streamflow (i.e., changes in flow volume and timing)** due to **changes in patterns of precipitation and runoff** and **increased drought** are likely to influence channel geomorphology and physical processes, ultimately impacting aquatic organisms and ecosystem function[1,11–13]. For instance, reduction or elimination of scouring flows can alter channel structure by changing patterns of sediment deposition and erosion and allowing vegetation encroachment[14]. During periods of low precipitation and drought, significant flow declines can disconnect floodplains and stream reaches[15], creating isolated pools with high water temperatures and low dissolved oxygen[16]. Although most native species are adapted to periodic droughts[1,14,17], severe drought can reduce populations of salmonids and other aquatic organisms through increased competition, predation, and habitat loss[15,18]. Drought can also cause changes in the composition and structure of riparian vegetation through tree mortality and/or the displacement of riparian vegetation with drought-tolerant upland species[13,14].
- **Warmer water temperatures** directly influence the physical, chemical, and biological properties of rivers and streams, including dissolved oxygen levels, nutrient cycling, and ecosystem productivity. For aquatic organisms, increased water temperatures can impact physiological processes (e.g., food consumption, metabolic rates, cardiorespiratory performance)[19] as well as

migratory behavior, disease and parasite resistance, and inter- and intra-specific competition[20]. Warmer water temperatures in disconnected pools are also associated with harmful algal blooms, which impact water quality, alter the food web, and produce toxins[21–24]. As a result of these changes and other interacting stressors (e.g., loss of riparian vegetation, declining flows), salmonids and many other sensitive aquatic species are likely to experience reduced habitat availability and range contractions[15,25–27].

- **Reduced soil moisture** is likely to decrease plant growth and increase mortality, potentially altering riparian vegetation composition and structure[13]. For instance, increased moisture stress within riparian areas could contribute to shifts towards more drought-tolerant and/or non-native species, with riparian species such as cottonwoods and willows likely declining[13].

Sensitivity and future exposure to climate-driven changes in disturbance regimes

Although rivers, streams, and floodplains are naturally dynamic systems, more frequent and/or severe disturbance events may impact habitat structure and ecosystem processes (e.g., erosion and sediment transport).

Disturbance Regimes	Trend Direction	Projected Future Changes
Storms & flooding	▲	• Increased storm intensity and duration, resulting in more frequent extreme precipitation events and flooding[6,28,29]
Wildfire	▲	• Slight to moderate increase in wildfire risk, particularly in areas of higher rainfall[30,31]

- Flooding is a key disturbance regime that maintains riparian plant communities and riverine habitat features over the long term[12,14,17]. However, changes in the **intensity and/or frequency of storms and associated flooding** may slow or stop natural recovery in systems where hydrology and water quality has already been altered by climate and/or non-climate stressors. Severe flooding removes riparian vegetation and alters stream channel morphology by causing erosion and changing patterns of sediment transport[1,13]. Water quality also declines where large storms transport nutrients and suspended sediments into stream channels, especially when they occur at the start of the rainy season[32]. Aquatic organisms whose life cycles are adapted to seasonal high flows are likely to be significantly impacted by shifts in the timing of floods that cause mismatches between peak flows and important life history events, such as breeding and migration[17,33]. This is likely to result in reduced survival and recruitment for these species, impacting food webs and potentially causing extirpation in small and/or isolated populations[17,33].
- **Altered wildfire regimes** (e.g., increased extent and/or frequency of high-severity fire) are likely to degrade habitat quality, contributing to greater loss of riparian and aquatic species and preventing population recovery[34–36]. The loss of riparian vegetation following high-severity fires can significantly increase water temperatures[35–38] and increase the risk of large landslides and debris flows during post-fire rain events[39]. Landslides and debris flows also wash ash, sediment, nutrients, and contaminants into rivers and streams[32,40,41]. Sediment and debris can alter channel structure[42,43], while nutrients and toxins can impact the food web and/or directly affect invertebrates, fish, amphibians, and other species[40,44]. However, wildfire at low to moderate intensities can have positive influences on the ecology and geomorphology of rivers and

streams. For instance, fire can enhance stream productivity as nutrients enter the food web[34,44] and maintains instream habitat complexity over longer time scales[36,45]. Fire within riparian areas also enhances wildlife habitat by maintaining early-successional vegetation[46,47] and can reduce water use by high-density riparian vegetation, increasing runoff into streams[48].

Sensitivity and current exposure to non-climate stressors

Non-climate stressors can exacerbate habitat sensitivity to changes in climate factors and disturbance regimes by altering habitat structure, hydrology, water quality, and riparian vegetation.

- **Pollutants** such as pesticides, excess nutrients, and heavy metals (e.g., mercury associated with historical mining) reduce water quality, with potentially severe impacts on aquatic organisms due to direct toxicity or indirectly through effects on the food chain[23,24,32]. Excess nutrients have been identified as a major driver of harmful algae blooms, and are likely to be exacerbated by climate-driven increases in water temperature[23,24].
- **Roads, highways, and trails** increase runoff of stormwater and pollutants, deliver large amounts of sediment into waterways, and facilitate the spread of invasive species[49–51]. Roads and associated culverts also contribute to channel incision and floodplain disconnection by restricting the movement of sediment and debris as well as that of fish and other aquatic organisms[49–51].
- **Dams and water diversions** impact flow volume and timing in rivers and streams, which alters thermal regimes, erosion and sediment transport processes, and habitat continuity (e.g., by disconnecting floodplains or preventing upstream movement of anadromous fish)[52–54].
- **Residential and commercial development** within floodplains has resulted in significant habitat loss and fragmentation through draining of floodplains, vegetation removal, channel incision, and loss of floodplain connectivity[4,55].
- **Agriculture** and **livestock grazing** increase water demand for irrigation and livestock, contributing to water withdrawals that reduce flow volume[56]. Where livestock congregate along streambanks and in riparian areas, soil trampling and the loss of riparian vegetation can also increase bank erosion and channel incision[57].
- **Timber harvest** within riparian areas can increase water temperatures, affecting the growth, development, and survival of fish and invertebrates[58,59]. Increased erosion and debris slides are associated with logged slopes, and declines in water quality occur where sediment and debris enters streams[60,61].

Adaptive Capacity

Moderate Adaptive Capacity

Low → High

High Confidence

Adaptive capacity is the ability of a habitat to accommodate or cope with climate change impacts with minimal disruption.

Habitat extent, integrity, continuity, and barriers to dispersal

Within the Santa Cruz Mountains region, the San Gregorio and Pescadero Rivers are the only large rivers that remain relatively undeveloped by humans[4]. Most others have been degraded by land-use conversion to development and agriculture, dams, water diversions, and other anthropogenic changes that alter flow regimes and water quality. Additionally, many areas of floodplains and riparian habitat have been disconnected from mainstem rivers by culverts, water diversions, flood control structures (e.g., dikes and levees), stream channelization, and agricultural use[62–65].

Habitat diversity

Geomorphic features and structural elements comprised of sediment, woody debris, and other materials transported by stream flows create diverse physical habitats within rivers, streams, and floodplains[12]. Additionally, varied flow depth and velocity alter conditions within a single river on seasonal and annual time scales, contributing to diverse aquatic communities well-adapted to these conditions[12]. These include protected species such as steelhead (*Oncorhynchus mykiss*), coho salmon (*O. kisutch*), and California red-legged frogs (*Rana draytonii*).

Resistance and recovery

Rivers, streams, and floodplains with intact hydrological regimes are dynamic systems adapted to recovery from a variety of disturbance regimes over time[14,65]. However, degraded rivers and streams are less able to recover from both climate-driven changes and non-climate stressors[43]. Altered hydrological regimes, loss of riparian vegetation, and other changes that impact the structure and functioning of these systems may prevent post-disturbance recovery and/or lead to sudden ecological collapse[1,18,65].

Many aquatic organisms are well-adapted to the variable flow regimes typical of the region[1,14,17,33]. For instance, fish, frogs, and other longer-lived species generally exhibit behavioral, morphological, and physiological responses to flooding and low flows[14]. Areas of refugia may buffer aquatic species from some environmental stress and/or allow population recovery following episodic disturbances; these include microhabitats within the channel (e.g., gravel, pool-riffle, large woody debris), systems with higher groundwater inputs, and areas shaded by riparian vegetation[4,66–68]. Floodplains can also act as refugia from disturbances, providing access to additional habitat with low-velocity flows for foraging and spawning [69,70].

Management potential

Rivers, streams, and floodplains are critically-important ecosystems that provide water supplies and filtration, flood protection, and habitat for resident and migratory birds, fish, amphibians, and mammals[1,11,71,72]. These habitats are also valued by the public for the provision of fresh water as well as for recreational opportunities (e.g., swimming, boating, fishing)[1]. Generally, societal support (e.g., funding, regulatory mechanisms) for the protection and management of these habitats is high, and many constituency groups are involved in restoration efforts within the region[4].

Management practices that enhance the structural and functional integrity of rivers, streams, and floodplains may limit climate impacts to some extent, increasing the likelihood of habitat recovery following disturbances[4]. In particular, management efforts may focus on restoring variable flow regimes in areas impacted by dams and water diversions[53,73] and reducing water withdrawals to maintain or increase stream flows, particularly during the summer months and during periods of drought[74]. Reducing nutrient inputs to lakes and ponds would also minimize eutrophication and limit the risk of harmful algal blooms, particularly during periods of drought[24]. Restoring incised stream channels generally increases habitat complexity, enhances baseflow, and can reduce water temperatures[75,76]. Similarly, restoring connections between floodplains and mainstem rivers increases groundwater recharge and floodwater storage, and provides seasonal habitat for native fish[63,69,70].

Recommended Citation

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Further information on the Santa Cruz Mountains Climate Adaptation Project is available on the project page (http://ecoadapt.org/programs/awareness-to-action/santa-cruz-mountains).

Literature Cited

1. Power, M. E. *et al.* Rivers. in *Ecosystems of California* (eds. Mooney, H. & Zavaleta, E.) 713–752 (University of California Press, 2016).
2. Bendix, J. & Hupp, C. R. Hydrological and geomorphological impacts on riparian plant communities. *Hydrological Processes* **14**, 2977–2990 (2000).
3. CNPS. *A manual of California vegetation, online edition*. (California Native Plant Society Press, 2019).
4. Vuln. Assessment Workshop. Personal communication. (2019).
5. Grantham, T. E. W., Carlisle, D. M., McCabe, G. J. & Howard, J. K. Sensitivity of streamflow to climate change in California. *Climatic Change* **149**, 427–441 (2018).
6. Pierce, D. W., Kalansky, J. F. & Cayan, D. R. *Climate, drought, and sea level rise scenarios for the Fourth California Climate Assessment*. (2018).
7. Swain, D. L., Langenbrunner, B., Neelin, J. D. & Hall, A. Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change* **8**, 427 (2018).
8. Cook, B. I., Ault, T. R. & Smerdon, J. E. Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances* **1**, e1400082 (2015).
9. Hill, R. A., Hawkins, C. P. & Jin, J. Predicting thermal vulnerability of stream and river ecosystems to climate change. *Climatic Change* **125**, 399–412 (2014).
10. Thorne, J. H., Boynton, R. M., Flint, L. E. & Flint, A. L. The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. *Ecosphere* **6**, 1–30 (2015).
11. Poff, N. L., Brinson, M. M. & Day, J. W., Jr. *Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States*. (2002).
12. Poff, N. L. *et al.* The natural flow regime. *BioScience* **47**, 769–784 (1997).
13. Perry, L. G., Andersen, D. C., Reynolds, L. V., Nelson, S. M. & Shafroth, P. B. Vulnerability of riparian ecosystems to elevated CO_2 and climate change in arid and semiarid western North America. *Glob Change Biol* **18**, 821–842 (2012).
14. Gasith, A. & Resh, V. H. Streams in Mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events. *Annual Review of Ecology and Systematics* **30**, 51–81 (1999).
15. Obedzinski, M., Pierce, S. N., Horton, G. E. & Deitch, M. J. Effects of flow-related variables on oversummer survival of juvenile coho salmon in intermittent streams. *Transactions of the American Fisheries Society* **147**, 588–605 (2018).
16. Poole, G. C. & Berman, C. H. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management* **27**, 787–802 (2001).
17. Lytle, D. A. & Poff, N. L. Adaptation to natural flow regimes. *Trends in Ecology & Evolution* **19**, 94–100 (2004).
18. Bêche, L. A., Connors, P. G., Resh, V. H. & Merenlender, A. M. Resilience of fishes and invertebrates to prolonged drought in two California streams. *Ecography* **32**, 778–788 (2009).
19. Whitney, J. E. *et al.* Physiological basis of climate change impacts on North American inland fishes. *Fisheries* **41**, 332–345 (2016).
20. Lynch, A. J. *et al.* Climate change effects on North American inland fish populations and assemblages. *Fisheries* **41**, 346–361 (2016).

21. Power, M. E., Bouma-Gregson, K., Higgins, P. & Carlson, S. M. The thirsty Eel: summer and winter flow thresholds that tilt the Eel River of northwestern California from salmon-supporting to cyanobacterially degraded states. *Copeia* **103**, 200–211 (2015).
22. Visser, P. M. *et al.* How rising CO_2 and global warming may stimulate harmful cyanobacterial blooms. *Harmful Algae* **54**, 145–159 (2016).
23. Coffey, R., Paul, M. J., Stamp, J., Hamilton, A. & Johnson, T. A review of water quality responses to air temperature and precipitation changes 2: nutrients, algal blooms, sediment, pathogens. *JAWRA Journal of the American Water Resources Association* **55**, 844–868 (2019).
24. Paerl, H. W. *et al.* Mitigating a global expansion of toxic cyanobacterial blooms: confounding effects and challenges posed by climate change. *Mar. Freshwater Res.* (2019) doi:10.1071/MF18392.
25. Eaton, J. G. & Scheller, R. M. Effects of climate warming on fish thermal habitat in streams of the United States. *Limnology and Oceanography* **41**, 1109–1115 (1996).
26. Mohseni, O., Stefan, H. G. & Eaton, J. G. Global warming and potential changes in fish habitat in US streams. *Climatic Change* **59**, 389–409 (2003).
27. O'Neal, K. *Effects of global warming on trout and salmon in US streams*. (2002).
28. Dettinger, M. Climate change, atmospheric rivers, and floods in California – a multimodel analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association* **47**, 514–523 (2011).
29. Shields, C. A. & Kiehl, J. T. Simulating the Pineapple Express in the half degree Community Climate System Model, CCSM4. *Geophysical Research Letters* **43**, 7767–7773 (2016).
30. Flint, L. E. & Flint, A. L. *California Basin Characterization Model: a dataset of historical and future hydrologic response to climate change (Ver. 1.1, May 2017)*. https://doi.org/10.5066/F76T0JPB (2014).
31. Flint, L. E., Flint, A. L., Thorne, J. H. & Boynton, R. Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance. *Ecological Processes* **2**, 25 (2013).
32. Aguilera, R. & Melack, J. M. Relationships among nutrient and sediment fluxes, hydrological variability, fire, and land cover in coastal California catchments. *Journal of Geophysical Research: Biogeosciences* **123**, 2568–2589 (2018).
33. Power, M. E., Parker, M. S. & Dietrich, W. E. Seasonal reassembly of a river food web: floods, droughts, and impacts of fish. *Ecological Monographs* **78**, 263–282 (2008).
34. Minshall, G. W. Responses of stream benthic macroinvertebrates to fire. *Forest Ecology and Management* **178**, 155–161 (2003).
35. Dwire, K. A. & Kauffman, J. B. Fire and riparian ecosystems in landscapes of the western USA. *Forest Ecology and Management* **178**, 61–74 (2003).
36. Pettit, N. E. & Naiman, R. J. Fire in the riparian zone: characteristics and ecological consequences. *Ecosystems* **10**, 673–687 (2007).
37. Dunham, J. B., Rosenberger, A. E., Luce, C. H. & Rieman, B. E. Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. *Ecosystems* **10**, 335–346 (2007).
38. Hitt, N. P. Immediate effects of wildfire on stream temperature. *Journal of Freshwater Ecology* **18**, 171–173 (2003).
39. Cannon, S. H. & DeGraff, J. The increasing wildfire and post-fire debris-flow threat in western USA, and implications for consequences of climate change. in *Landslides - Disaster Risk Reduction* (eds. Sassa, K. & Canuti, P.) 177–190 (Springer-Verlag Berlin Heidelberg, 2009).
40. Burton, C. A. *et al.* Trace elements in stormflow, ash, and burned soil following the 2009 Station Fire in southern California. *PLOS ONE* **11**, e0153372 (2016).
41. Klose, K., Cooper, S. D., Leydecker, A. D. & Kreitler, J. Relationships among catchment land use and concentrations of nutrients, algae, and dissolved oxygen in a southern California river. *Freshwater Science* **31**, 908–927 (2012).
42. Long, J. W. & Davis, J. Erosion and restoration of two headwater wetlands following a severe wildfire. *Ecological Rest.* **34**, 317–332 (2016).
43. Hunsaker, C. T., Long, J. W. & Herbst, D. B. Watershed and stream ecosystems. in *Science synthesis to support socioecological resilience in the Sierra Nevada and southern Cascade Range. Gen. Tech. Rep. PSW-GTR-247* (eds. Long, J. W., Quinn-Davidson, L. & Skinner, C. N.) 265–322 (U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 2014).
44. Klose, K., Cooper, S. D. & Bennett, D. M. Effects of wildfire on stream algal community structure and nutrient limitation. *Freshwater Science* **34**, 1494–1509 (2015).

45. Arkle, R. S. & Pilliod, D. S. Prescribed fires as ecological surrogates for wildfires: a stream and riparian perspective. *Forest Ecology and Management* **259**, 893–903 (2010).
46. Hankins, D. L. The effects of indigenous prescribed fire on riparian vegetation in central California. *Ecol. Process* **2**, 24 (2013).
47. Hankins, D. The effects of indigenous prescribed fire on herpetofauna and small mammals in two Central Valley California riparian ecosystems. *The California Geographer* **49**, 31–50 (2009).
48. Tague, C., Seaby, L. & Hope, A. Modeling the eco-hydrologic response of a Mediterranean type ecosystem to the combined impacts of projected climate change and altered fire frequencies. *Climatic Change* **93**, 137–155 (2009).
49. Trombulak, S. C. & Frissell, C. A. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* **14**, 18–30 (2000).
50. Coffin, A. W. From roadkill to road ecology: a review of the ecological effects of roads. *Journal of Transport Geography* **15**, 396–406 (2007).
51. Forman, R. T. T. & Alexander, L. E. Roads and their major ecological effects. *Annual Review of Ecology and Systematics* **29**, 207–231 (1998).
52. Power, M. E., Dietrich, W. E. & Finlay, J. C. Dams and downstream aquatic biodiversity: potential food web consequences of hydrologic and geomorphic change. *Environmental Management* **20**, 887–895 (1996).
53. Poff, N. L. & Hart, D. D. How dams vary and why it matters for the emerging science of dam removal. *BioScience* **52**, 659–668 (2002).
54. Yarnell, S. M. *et al.* Functional flows in modified riverscapes: hydrographs, habitats and opportunities. *BioScience* **65**, 963–972 (2015).
55. Duffy, W. G. *et al.* Wetlands. in *Ecosystems of California* (eds. Mooney, H. A. & Zavaleta, E. S.) 669–692 (University of California Press, 2016).
56. Bauer, S. *et al.* Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. *PLOS ONE* **10**, e0120016 (2015).
57. Belsky, A. J., Matzke, A. & Uselman, S. Survey of livestock influences on stream and riparian ecosystems in the western United States. *Journal of Soil and Water Conservation* **54**, 419–431 (1999).
58. Johnson, S. L. & Jones, J. A. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. *Canadian Journal of Fisheries and Aquatic Sciences* **57**, 30–39 (2000).
59. Welsh, H. H., Hodgson Garth R. & Karraker Nancy E. Influences of the vegetation mosaic on riparian and stream environments in a mixed forest-grassland landscape in "Mediterranean" northwestern California. *Ecography* **28**, 537–551 (2005).
60. Amaranthus, M. P., Rice, R. M., Barr, N. R. & Ziemer, R. R. Logging and forest roads related to increased debris slides in southwestern Oregon. *Journal of Forestry* **83**, 229–233 (1985).
61. Bottorff, R. L. & Knight, A. *The effects of clearcut logging on the stream biology of the North Fork of Caspar Creek, Jackson Demonstration State Forest, Fort Bragg, California*. (1996).
62. Gucinski, H., Furniss, M. J., Ziemer, R. R. & Brookes, M. H. *Forest roads: a synthesis of scientific information*. http://www.fs.fed.us/pnw/pubs/gtr509.pdf (2001).
63. Opperman, J. J. *et al.* Sustainable floodplains through large-scale reconnection to rivers. *Science* **326**, 1487–1488 (2009).
64. Opperman, J. J., Luster, R., McKenney, B. A., Roberts, M. & Meadows, A. W. Ecologically functional floodplains: connectivity, flow regime, and scale. *Journal of the American Water Resources Association* **46**, 211–226 (2010).
65. Tockner, K. & Stanford, J. A. Riverine floodplains: present state and future trends. *Environmental Conservation* **29**, 308–330 (2002).
66. Sedell, J. R., Reeves, G. H., Hauer, F. R., Stanford, J. A. & Hawkins, C. P. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. *Environmental Management* **14**, 711–724 (1990).
67. Ebersole, J. L., Liss, W. J. & Frissell, C. A. Relationship between stream temperature, thermal refugia and rainbow trout *Oncorhynchus mykiss* abundance in arid-land streams in the northwestern United States. *Ecology of Freshwater Fish* **10**, 1–10 (2001).
68. Fullerton, A. H. *et al.* Longitudinal thermal heterogeneity in rivers and refugia for coldwater species: effects of scale and climate change. *Aquat Sci* **80**, 3 (2018).
69. Moyle, P. B., Crain, P. K. & Whitener, K. Patterns in the use of a restored California floodplain by native and alien fishes. *San Francisco Estuary and Watershed Science* **5**, (2007).

70. Sommer, T. R., Nobriga, M. L., Harrell, W. C., Batham, W. & Kimmerer, W. J. Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. *Can. J. Fish. Aquat. Sci.* **58**, 325–333 (2001).
71. Duffy, W. G. & Kahara, S. N. Wetland ecosystem services in California's Central Valley and implications for the Wetland Reserve Program. *Ecological Applications* **21**, S18–S30 (2011).
72. Colloff, M. J. *et al.* Adaptation services of floodplains and wetlands under transformational climate change. *Ecol Appl* **26**, 1003–1017 (2016).
73. Poff, N. L. & Zimmerman, J. K. H. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology* **55**, 194–205 (2010).
74. Klein, R. D., McKee, T. & Nystrom, K. Shrinking streamflows in the Redwood Region. in *Coast Redwood Science Symposium—2016: past successes and future direction. Gen. Tech. Rep. PSW-GTR-258* (eds. Standiford, R. B. & Valachovic, Y. S.) 187–197 (U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 2017).
75. Justice, C., White, S. M., McCullough, D. A., Graves, D. S. & Blanchard, M. R. Can stream and riparian restoration offset climate change impacts to salmon populations? *Journal of Environmental Management* **188**, 212–227 (2017).
76. Pollock, M. M. *et al.* Using beaver dams to restore incised stream ecosystems. *BioScience* **64**, 279–290 (2014).