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Global Warming Effects on Climactically-Imposed Ecological Gradients in the West

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I. PERSPECTIVE

Measuring and predicting the effects of global warming on the biota of western North America are among the most challenging tasks facing the science of ecology because of the enormous climatic variation within the region, in which the current plant and animal life functions. The latitudinal span from the U.S.-Mexican border to Point Barrow, Alaska is approximately 38 degrees. There are continuous temperature, day-length, and growing season gradients along this span. Additionally, precipitation changes from aridity in the south, to high levels in the middle, to low levels again in the far north. Moreover, temperatures and growing season lengths grade from high to low, and precipitation from low to high, along the elevational spans from valleys and foothills to the tops of the numerous mountain ranges and cordilleras in the region. Nevada alone has 120 mountain ranges.

Local climates vary at all points along these gradients, and different assemblages of plants and animals have formed at these points that are adapted to their local climates. Global climate change will alter these localized climates and, in varying ways, affect their biotas. The direct affects of localized climate changes will be on individual organisms of plant and animal species, but the collective responses of the individuals within the species will produce changes in their populations and the multi-species assemblages, communities, and ecosystems within which they function.

Each species has different physical-environmental requirements. Each will respond differently to a given environmental change. For example, each species functions within a tolerance range for temperature: a maximum and minimum temperature above and below which it cannot survive, and an optimum within which it functions best (Fig. 1). A species may survive in an area in which temperatures are barely within its upper limit of tolerance (see Species A in Fig. 1) but a temperature increase above that limit would eliminate it. That same increase might move temperatures into the optimum range for another species and benefit it (as with Species B in Fig. 1). And that increase might move temperatures within the tolerance range of another species that had not previously been able to exist in the area, and allow it to join the assemblage (as with Species C in Fig. 1).

Each species (as with Species A in Fig. 2) also functions within a matrix of other species. Some may be competitors, parasites, and predators which are

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detrimental and affect a species negatively. Others, like those which provide food and habitat, or are symbiotic, affect a species positively. These are typically complexes of species and each has its own physical and biotic environmental requirements. A given environmental change will affect them in varying ways, and in turn will affect their influences on other species. Thus the net effect of climate change on each species within a community or ecosystem is exceedingly complex, and the effects on entire communities or ecosystems are orders of magnitude more so.

The task confronting the ecologist attempting to generalize the ecological effects of climate change is first to measure and describe responses of individual organisms, species populations, and community and ecosystem structures to the climate changes that have occurred to date, largely during the twentieth century. Global mean annual temperatures rose approximately 0.6° C (1.1° F) during the century, but increases have been progressively higher with increasing latitude. Alaskan mean temperatures have risen 4–6° F. The second challenge is to predict ecological changes in the coming decades based on existing biological knowledge of species and ecosystems, and predicted climate changes in those decades. Global mean annual temperatures are predicted to rise between 2.5° and 10° F during the twenty-first century.

This paper summarizes a number of ecological changes that occurred during the twentieth century in western North America and a number of changes predicted for the twenty-first century.

II. CHANGES TO DATE

A. *Individual Species Responses*

1. *Distributional Shifts*

Many plant and animal species are limited at the northern and upper-elevational edges of their geographic ranges by low temperatures. The northward and upslope extension of a number of plant and animal species' ranges during the twentieth century has been reported by numerous observers. The most chronicled, based on decades of observations, is the range of Edith's checkerspot butterfly (*Euphydryas editha*) from northern Baja California to southern British Columbia.[1] Between the 1930s and 1990s, the species' distribution shifted 92 km northward and 105 meters upslope.

The pika (*Ochotona princeps*) is a small mammal occupying the intermediate and high elevations of the western mountain ranges that is intolerant of high temperatures. In 1946, mammologist E. Raymond Hall described and mapped the locations of twenty-five pika populations in Nevada mountain ranges.[2] In the 1990s and again in 2003 and 2005, National Park Service biologist Erik Beever observed that eight of Hall's 25 populations—those at lower elevations—had

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[1] Camille Parmesan, *Climate and Species' Range*, 382 NATURE 765, 765–66 (1996).

[2] *See* E. RAYMOND HALL, MAMMALS OF NEVADA (Univ. of California Press 1946).

disappeared.[3] The lower edges of the 17 surviving populations had moved upslope an average of 130 meters.[4]

Another observer, Roger DiSilvestro, reports that spruce trees have moved 46–55 meters upslope in Banff National Park.[5] In Alaska, shrubby species have been observed to move northward onto tussock tundra.[6] Plant and animal distributional shifts have been reported for numerous species and areas around the globe.

2. Changing Phenology

Phenology is the study of the seasonal timing of biological events, including migration, reproduction, flowering, leaf emergence, etc. Phenological advances are being reported for numerous plant and animal species. For example, David Inouye has observed spring arrival dates of American robins (*Turdus migratorius*) at the Rocky Mountain Biological Laboratory (at 2,946 meters) since 1971.[7] The robins winter in the foothills of the mountains. In recent years robins, apparently responding to temperatures in their winter range, have migrated to their nesting range in the vicinity of the laboratory two weeks earlier than they did in Inouye's early years of observation. In addition, yellow-bellied marmots (*Marmota flaviventer*) in the same area have been emerging from hibernation one month earlier than in the earlier years of observation.

Also at the Rocky Mountain Laboratory, Francisca Saavedra has experimented with flowering dates of the wild flower *Delphinium nuttallianum* by removing snow in plots prior to the normal spring melt-off dates to simulate predicted warmer temperatures and decline of snowpacks.[8] Saavedra's studies have shown significant advance in the *Delphinium* flowering dates caused by the snow removal. Finally, Daniel Cayan observed a five to ten day advance in spring

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[3] Michelle Nijhaus, *In the Great Basin, Scientists Track Global Warming*, HIGH COUNTRY NEWS, Oct. 17, 2005, at 13.

[4] *Id.*

[5] Roger DiSilvestro, *The Proof Is in the Science*, NAT'L WILDLIFE, Apr./May 2005, at 22.

[6] Valerie Barber et al., *A Synthesis of Recent Climate Warming Effects on Terrestrial Ecosystems of Alaska*, *in* CLIMATE WARMING IN WESTERN NORTH AMERICA: EVIDENCE AND ENVIRONMENTAL EFFECTS (Frederic H. Wagner ed., Univ. Utah Press, forthcoming 2007).

[7] *See* Laura Tangley, *Out of Sync: Wildlife is at Risk as Global Warming Changes the Timing of Seasonal Behaviors Such as Breeding and Migration*, NAT'L WILDLIFE, Apr./May 2005, at 28.

[8] Francisca Saavedra, *Testing Climate Change Predictions with the Subalpine Species Delphinium Nuttalliandum*, *in* WILDLIFE RESPONSES TO CLIMATE CHANGE: NORTH AMERICAN CASE STUDIES 201 (Stephen H. Schneider & Terry L. Root eds., Island Press 2002).

flowering dates of lilac (*Syringa vulgaris*) and honeysuckle (*Lonicera tatarica* and *korolkowii*) in California.[9]

These changing phenologies are of biological interest in and of themselves; however, they take on increasing ecological significance by developing phenological asynchronies with the species among which they interact, both positively and negatively (Fig. 2). This occurs in part because the different species respond differently to any given temperature increase (Fig. 1). Thus Inouye observed that the earlier arrival of robins at the Rocky Mountain station precedes emergence of insect species on which they have traditionally fed, resulting in food shortages. Similarly, the earlier emergence of marmots occurs before snowmelt uncovers the plants on which they feed.

3. Population Responses

The positive and negative effects of temperature changes on individual species will affect their reproductive and mortality rates, either directly (Fig. 1), and/or by altering the numbers of the species with which they interact (Fig. 2). The ultimate effects will be population changes.

Examples of population changes can be seen in several environments. W. G. Hewatt, operating out of the Hopkins Marine Station on Monterrey Bay, California in 1931, established a 100 meter transect perpendicular to the shore and placed 100 meter-square quadrants on the ocean bottom along the transect in the shallow waters of the intertidal zone. He counted 62 invertebrate species and recorded the number of individuals of each species. In 1993 and 1995, Raphael Sagarin repeated Hewatt's transect, again counting the numbers of each species.[10] He found that 24 of the species had increased in numbers while 22 had decreased.[11] Those that had increased were species with geographic distributions primarily south of Monterrey Bay along the Pacific coast, while those that had decreased were primarily distributed to the north.[12] The mean annual water temperature had increased 0.79° C between the two studies.

The Edith's checkerspot butterfly studied by Parmesan is distributed as metapopulations (small subpopulations in habitat islands scattered over the landscape).[13] During more than 60 years of observation, as the species' range has shifted northward and upslope, survival of the subpopulations has varied along the

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[9] Daniel R. Cayan et al., *Changes In the Onset of Spring In the Western United States*, 82 BULL. AMER. METEOR. SOC'Y 399, 401–08 (2001).

[10] Raphael Sagarin, *Historical Studies of Species' Responses to Climate Change: Promises and Pitfalls*, *in* WILDLIFE RESPONSES TO CLIMATE CHANGES: NORTH AMERICAN CASE STUDIES 127 (Stephen H. Schneider & Terry L. Root eds., Island Press 2002).

[11] *Id.* at 132.

[12] *Id.* at 134.

[13] Camille Parmesan, *Detection at Multiple Levels: Euphydryas editha and Climate Change*, *in* CLIMATE CHANGE AND BIODIVERSITY 56 (Thomas E. Lovejoy & Lee Hannah eds., Yale Univ. Press 2005).

latitudinal and altitudinal gradients.[14] Some 70% of subpopulations in the southern portions of the species' range disappeared during the study.[15] Between 35% and 50% of the subpopulations in central and low-elevation portions of the range were extinguished during the period.[16] Less than 20% of the subpopulations in the northern and high-elevation portions of the range disappeared.[17]

Some authors have projected the proportions of plant and animal species that may become extinct as temperatures rise. Elizabeth Kolbert cites one study predicting the extinction probability of 1100 species of butterflies by 2050.[18] Of mobile species that can extend their ranges northward as temperatures increase, 15% are projected to disappear. But the extinction rate of "stationary" or immobile species is predicted at 37%.

While much of the research emphasis has focused on species likely to be negatively affected, some species are expected to benefit. Conspicuous among these are montane species at high elevations forced to move to lower elevations in winter when snowpack covers food and habitat. These includes ungulates such as mule deer (*Odocoileus hemionus*) and North American elk (*Cervus elephas*) for which winter is considered a population "bottleneck" because of food scarcity in the limited winter range. With warming and shrinkage or disappearance of snowpack, most elevations or entire mountain ranges will become available for winter food, thus permitting population increases. This effect is likely to benefit many species that migrate altitudinally between the seasons.

B. Community and Ecosystem Responses

The changes in individual species described above occur in the context of entire natural communities and ecosystems (Fig. 2). As they occur, they alter the structure of communities and ecosystems. For example, when a species extends its range into an area in which it has not previously occurred, it both adds its presence to the community structure and it alters the structure by interacting, either positively or negatively, with the existing species. Moreover, when the dominant vegetation that largely determines the structure of a community (for example, forest trees) increases or decreases in response to climate change, the result can be major alteration of the community and ecosystem by affecting the majority of species associated with that vegetation.

1. Elevational Shifts

In 1915 Joseph Grinnell documented his faunal investigations of the Lyell Canyon region of Yosemite National Park. James Patton conducted a faunal survey

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[14] *Id.*

[15] *Id.* at 57–59.

[16] *Id.*

[17] *Id.*

[18] Elizabeth Kolbert, *Butterfly Lessons: Insects and Toads Respond to Global Warming*, THE NEW YORKER, Jan. 9, 2006, at 32–39.

of Grinnell's research site in 2003.[19] Patton's investigations observed five small mammal species at 3100 meters elevation observed by Grinnell at 610 meters lower elevation, but not at the higher levels.[20] Two other species observed by Grinnell at the high elevation had declined to rarity.[21] The latter species may have been affected by warming temperatures, or driven to lower densities by competition with the new arrivals. Thus the mammalian fauna had changed markedly in composition. Similarly, the 2003 studies recorded 17 avian species not observed by Grinnell, producing a fundamental change in the composition of the avifauna. The upslope movement of spruce forest in Banff National Park, reported above, has carried with it an invertebrate and vertebrate fauna associated with the spruce.[22]

2. Changing Hydrology of Western Streams

Approximately 85% of flow in western streams originates from the spring melt of montane snowpacks. This flow has a distinct seasonal pattern formed by the timing of spring melt and seasonality of precipitation. Philip Mote describes runoff in the Columbia River with a peak in May-June, decline through early summer, and low flows through late summer, fall, and winter.[23] Both the up-stream and the down-stream runs of the several anadromous fish species found in the river are adapted to different stages of the seasonal runoff patterns, both up-stream runs of spawners, and down-stream runs of fingerlings to the ocean.

Rising temperatures are markedly altering these stream hydrographs by reducing the size of snowpacks and altering seasonality of flows. Much of the precipitation in late fall and early winter that has historically fallen as snow and contributed to snowpacks is now falling as rain and immediately running off. Similarly, much of the precipitation in late winter and early spring that previously fell as snow now falls as rain and immediately runs off. The result is shrinking snowpacks[24] (Fig. 3) and smaller fractions of the total year's precipitation flowing in what has been the spring peak runoff period, as shown by a number of California streams.[25] Moreover, the reduced spring runoff peaks have been chronologically advanced by one to three weeks.[26]

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[19] Michelle Nijhaus, *The Ghosts of Yosemite*, HIGH COUNTRY NEWS, Oct. 17, 2005, at 8.

[20] *Id.*

[21] *Id.*

[22] DiSilvestro, *supra* note 5, at 23.

[23] PHILIP MOTE ET AL., IMPACTS OF CLIMATE VARIABILITY AND CHANGE IN THE PACIFIC NORTHWEST, 28–32 (JISAO/SMA Climate Impacts Group, Univ. Washington, 1999), *available at* http://cses.washington.edu/db/pdf/moteetalgreenbooks96.pdf.

[24] Philip Mote et al., *Variability and Trends in Mountain Snowpacks in Western North America*, *in* CLIMATE WARMING IN WESTERN NORTH AMERICA: EVIDENCE AND ENVIRONMENTAL EFFECTS (Frederic H. Wagner ed., Univ. of Utah Press, forthcoming 2007).

[25] *See* Daniel Cayan et al., *Variability and Trends in Spring Runoff in the Western United States*, *in* CLIMATE WARMING IN WESTERN NORTH AMERICA: EVIDENCE AND

II. POTENTIAL FUTURE CHANGES

A. Mountain Pine Beetle

The mountain pine beetle (*Dendroctonus ponderosae*) coexists with lodgepole pine (*Pinus contorta*).[27] The beetles insert eggs under the bark of mature pines and the larvae hatch from the eggs and burrow around the boles of the trees, consuming the inner bark tissue, girdling and killing the trees. The entire process is cyclic, extending through several decades. Young trees germinate in stands of dead trees then grow to the advanced ages at which beetle populations break out and kill them. Pines and beetles have coevolved so that they survive as species in this continuing natural oscillation.

The beetles are sensitive to cold and do not occur or undergo outbreaks above approximately 2750 meters elevation. But with rising temperatures, there is concern that the beetles will move up slope to the range of other pine species that have not previously been attacked and have not coevolved any protective mechanisms.[28] One example is whitebark pine (*P. albicaulis*) which produces cone nuts that are an important food source for grizzly bears (*Ursus horribilis*), red squirrels (*Tamiasciurus hudsonicus*), and numerous high-elevation avian species. Thus the potential demise of these pines would have widespread faunal effects in addition to change in the structure of the high-elevation vegetation.

The mountain pine beetles have also not historically occurred north of southern British Columbia, although lodgepole pine extends northward to southern Alaska. In recent years the beetles have extended their range northward into more northerly British Columbia pine forests not previously infested and have caused heavy tree mortality. The Canadian timber industry has become increasingly concerned and large sums have been appropriated for research efforts seeking means of control.

The continental lodgepole pine range overlaps at its northeastern limits with the northwestern range limit of jack pine (*P. banksiana*) in central Alberta and the Northwest Territories. Jack pine extends southeastward in a wide swath across central Canada to the Great Lake states and New England where it overlaps with

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ENVIRONMENTAL EFFECTS (Frederic H. Wagner ed., Univ. of Utah Press, forthcoming 2007). *See also* Michael Dettinger, *Changes in Streamflow Timing in the Western United States in Recent Decades*, U.S. Geol. Survey Fact Sheet 2005-3018, *available at* http://pubs.usgs.gov/fs/2005/3018 (last visited Nov. 1, 2006).

[26] *See* Michael Dettinger & Daniel R. Cayan, *Large-Scale Atmospheric Forcing of Recent Trends Toward Early Snowmelt Runoff in California*, 8 J. OF CLIMATE 606, at 609–13 (1995). *See also* Iris T. Stewart et al., *Changes in Snowmelt Runoff Timing in Western North America Under a 'Business As Usual' Climate Change Scenario*, 62 CLIMATIC CHANGE 217, at 218–20 (2004).

[27] J.A. Logan & J.A. Powell, *Ecological Consequences and Climate-Change-Altered Forest Insect Disturbance Regimes*, *in* CLIMATE WARMING IN WESTERN NORTH AMERICA: EVIDENCE AND ENVIRONMENTAL EFFECTS (Frederic H. Wagner ed., forthcoming 2007).

[28] *Id.*

the distribution of white pine (*P. strobus*) and Norway pine (*P. resinosus*). The range of these primarily northeastern pines extends down the Appalachian chain to the southeastern United States where it intersects the range of the loblolly pine (*P. taeda*), a species that occurs westward through the Gulf states to east Texas. None of these species has coevolved with mountain pine beetle, nor evolved protective mechanisms to coexist with them. Moreover, in the southeastern quadrant of the United States, with its warm temperatures, it is likely that the beetles' populations would function more robustly than in the cooler climes of western North America. Ecologists Logan and Powell, while not unequivocally predicting that the beetles will spread through the continental crescent of pines, suggest nevertheless that it is a possibility that could have serious consequences.[29]

B. Alaskan Spruce Forest

Tree ring studies of radial growth in northeastern Alaska white spruce (*Picea glauca*) between the 1860s and the present by University of Alaska ecologists have shown an inverse correlation between May-August temperatures and radial growth.[30] Temperatures increased over this century and a half between approximate 13° C and 14.5° C. Physiological study of the spruces indicates that the growth will be so reduced by temperatures in the range of 16.5°-17.0° C that the species will be eliminated. One computer model projects that this temperature range will be reached by approximately 2070.

As noted above, Alaskan forests have already experienced widespread tree mortality as a result of temperature-induced water stress and increased susceptibility to insect attack. This mortality increases fuel for fire. Fire probability is additionally increased with prolonged snow-free seasons caused by rising temperatures. In the northeast quadrant of Alaska, 2004 was a record fire year with 2.7 million hectares burned. The second most severe fire season was 2005 with 1.7 million hectares burned. If extensive forest mortality occurs in the future, fires are likely to rage over more extensive areas of Alaska.

C. Shifting Elevational Zones

Vegetation in mountainous regions is arrayed in elevational zones produced by the positive correlation between altitude and precipitation and negative correlation of temperature. The detailed taxonomic composition of these zones varies geographically, but in general they occur in four structural types: varying combinations of shrubby vegetation and grasslands in the arid to semi-arid valley bottoms and lower foothills; "pygmy" conifers typically in the upper foothills; conifer forests with varying combinations of pines, firs, spruces and other genera in the intermediate to high elevations; and alpine tundra at extremely high elevations and mountain tops, where conditions are too severe for tree growth.

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[29] *Id.*

[30] Barber, *supra* note 6.

From south to north in western North America, these zones occur at progressively lower elevations as mean temperatures decline and moisture conditions moderate. By the latitude and moisture conditions of much of the Pacific Northwest, the coniferous forest zone descends to sea level. And in northern Alaska, Arctic tundra at sea level can be considered analogous to the alpine tundra descending to that elevation. Thus the maximum expression of the elevational zones occurs from the inland mountains of the Pacific Northwest, and generally from southern Washington southward throughout the western region.

Forest ecologists predict that these zones will shift altitudinally depending on the nature of both temperature and precipitation changes.[31] If only temperatures rise with no change in precipitation, all zones are projected to move upslope. Conditions on the alpine tundra will moderate to the point of allowing tree growth, and the coniferous forest will move out on the tundra to obliterate it. The entire tundra vegetation and associated animal life will be eliminated. This upward movement of conifer forest onto the alpine tundra has not yet been observed in the American Rocky Mountains,[32] but as noted above there has been a 46–55 meter rise in the spruce forest in Banff National Park.[33]

The arid to semi-arid conditions of the lower zones will be exacerbated by the higher temperatures which will increase evapotranspiration. Consequently, the lower edges of the coniferous forest zones are predicted to disappear and will be replaced by the upper edges of the pygmy conifer zones. The lower edges of the pygmy conifer zones are projected to disappear and be replaced by a rising shrub-grassland zone.

If rising temperatures are accompanied by increasing precipitation—and such an increase is predicted for much of the West[34] where increases were measured during the twentieth century[35]—the upper forest zones are still predicted to move upslope. But the lower edges of the forest zone and pygmy conifers are predicted to move downslope, possibly even out into the valleys and lower elevations in response to the moderating moisture conditions.[36]

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[31] *See* William A. Reiners, *Natural Ecosystems: The Rocky Mountains*, PREPARING FOR A CHANGING CLIMATE: THE POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE 145 (Utah State Univ. Press, 1993).

[32] *Id.*

[33] *See* DiSilvestro, *supra* note 5.

[34] *See* Linda O. Mearns, *GCM Scenarios for the RMGB Region*, *in* PREPARING FOR A CHANGING CLIMATE: THE POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE 72, 72–73 (Utah State Univ. Press, 1993).

[35] Mote, *supra* note 24. *See also* Connely K. Baldwin, *Historical Climate Analysis*, PREPARING FOR A CHANGING CLIMATE: THE POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE 58, 58–59 (Utah State Univ. Press, 1993).

[36] Ronald P. Neilson, *Potential Effects of Global Warming on Natural Vegetation at Global, National, and Regional Levels*, *in* PROCEEDINGS OF THE ROCKY MOUNTAIN/GREAT BASIN REGIONAL CLIMATE-CHANGE WORKSHOP 55, 59 (Fredric H. Wagner & Jill Barron eds., 1998), at http://www.usgcrp.gov/usgcrp/nacc/rockiesworkshop.pdf.

While the emphasis here has been on the movements of the dominant vegetations, the changes will certainly include the lesser plant species and entire associated fauna, hydrologic processes, and nutrient cycling regimens. In short, the total effect will be elevational shifts of entire ecosystems.

D. Elevational Shifts in Stream Biota

Water temperatures in western mountain streams occur in gradients from warmer levels at lower elevations to colder levels at high elevations. The different aquatic plant, invertebrate and vertebrate species have different temperature tolerances (Fig. 1) and array themselves along the stream temperature gradients according to their temperature preferenda. For example, the introduced brown trout (*Salmo trutta*) in Utah streams is tolerant of slightly warmer waters and typically occupies the lower reaches of streams. The native cutthroat trout (*Oncorhynchus clarki*) is less temperature tolerant and occurs in the higher-elevation reaches. The entire biota sorts out along the temperature gradient according to these species-specific constraints.

As air temperatures warm, water temperatures are expected to increase at all points along a stream, but retain an elevational gradient. Aquatic species are predicted to move upslope in the streams to continue occupying reaches with temperatures in their preferenda.[37] But cold water species occupying the upper reaches will not be able to move any higher than the stream headwaters. The net result will be shorter reaches with tolerable temperatures, and thus less satisfactory habitat. Aquatic ecologists predict that a 3° C mean July temperature increase would reduce stream lengths habitable for salmonid species in the Rockies by 21%.[38] A 5° C July temperature increase would reduce inhabitable stream length by 43%.[39]

IV. DISCUSSION

I have presented herein a sampling of the many reported ecological changes that occurred during the twentieth century and that have been inferred to be responses to the temperature increases of the century. Many authors caution that correlations cannot automatically be inferred to represent cause and effect, and an entire volume discusses the problem.[40] Climate change investigators have proposed a set of observational and research protocols to allow meaningful analysis of the probability of causation. Eight of these protocols are described below.

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[37] *Id.* at 55–63.

[38] Christopher J. Keleher & Frank J. Rahel, *Thermal Limits to Salmonoid Distributions in the Rocky Mountain Region and the Potential Habitat Loss Due to Global Warming: A Geographic Information System (GIS) Approach*, 125 TRANSACTIONS OF THE AM. FISHERIES SOC'Y 1, at 4 (1996).

[39] *Id.*

[40] *See* WILDLIFE REPONSES TO CLIMATE CHANGE: NORTH AMERICAN CASE STUDIES (Stephen H. Schneider & Terry L. Root eds., Island Press 2002).

1) Observations of both northward and upslope range extensions, as with Parmesan's research of the checkerspot butterfly.[41]
2) Phenological advances concurrent with the northward/upslope range extensions.[42]
3) Concurrent range extensions by large numbers of species. In Europe, 22 of 35 "generalist" butterfly species moved northward during the twentieth century. Only one moved southward.[43] A majority of North American Great Plains bird species have moved northward or upslope since the 1960s.[44]
4) Concurrent phenological advances of large numbers of species. In the Boston area flowering shrubs are blossoming 8 days earlier than in previous years. In the New York region four of six frog species began calling in spring 10 days earlier than historically recorded.[45] In the District of Columbia, 89 of 100 flowering plant species are blossoming an average 4.5 days earlier than in the 1970s.[46] In Europe, 20 bird species began laying eggs nine days earlier in 1995 than in 1971.[47]
5) A knowledge based on prior research of the effects of temperature variations on species' physiology.
6) Laboratory experiments on the effects of temperature variability on species' physiology.[48]
7) Observations of range extensions, and phenological and population changes at ecotones where two communities adjoin, and where species compete.[49]
8) Modeling studies based on species' physiological processes.[50]

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[41] Parmesan, *supra* note 1.

[42] *Id.*; Parmesan, *supra* note 13; Reiners, *supra* note 31.

[43] *See* Logan, *supra* note 27.

[44] Stephen H. Schneider & Terry L. Root, *Climate Change*, *in* STATUS AND TRENDS OF THE NATION'S BIOLOGICAL RESOURCES 89, 101 (United States Geological Survey 1998).

[45] *See* Logan, *supra* note 27.

[46] Reiners, *supra* note 32.

[47] *Id.*

[48] Sagarin, *supra* note 9; *See also* Lisa Crozier, *Climate Change and Its Effects on Species Range Boundaries: A Case Study of the Northern Skipper Butterfly, Atalopedes campestris*, *in* WILDLIFE REPONSES TO CLIMATE CHANGE: NORTH AMERICAN CASE STUDIES 57 (Steven H. Schneider & Terry L. Root eds., Island Press 2002); Stuart F. Chapin et al., *Response of Arctic Tundra to Experimental and Observed Changes in Climate*, 76 ECOLOGY 694 (1995).

[49] *See* Parmesan, *supra* note 13.

[50] Elena Shevliakova, *Modeling Potential Impacts of Climate Change on the Spatial Distribution of Vegetation in the United States With a Probabilistic Biogeography Approach*, *in* WILDLIFE REPONSES TO CLIMATE CHANGE: NORTH AMERICAN CASE STUDIES 57 (Steven H. Schneider and Terry L. Root eds., Island Press 2002).

Predictions of future changes depend on knowledge of, or experiments on, species' biological processes and modeled predictions of temperature changes.

Plant and animal species worldwide living in natural environments have adapted to temperatures in their geographic regions, and to coexist with other species which too have accommodated to the local, physical environments. Changing temperatures will inevitably affect them and their coexisting species in countless ways with the result of universally altered natural communities and ecosystems. Ultimately, it is likely that the entire global biota will change in ways too diverse, and in many cases too profound, to predict at this time. Widespread extinctions are predicted to follow.

Figure 1

Hypothetical Examples of Changes in the Species Composition of Natural Communities with Temperature Change

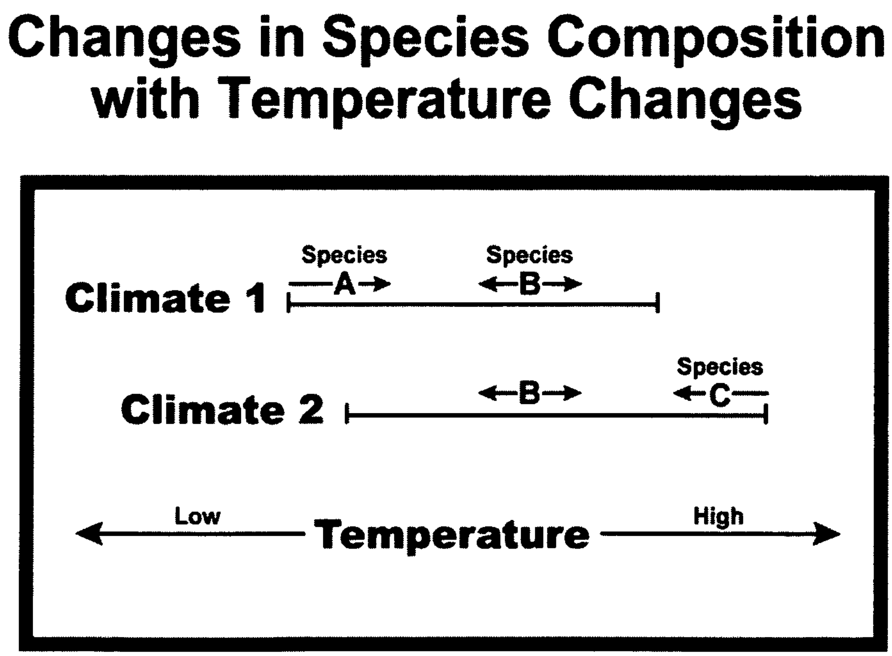

Figure 2

Hypothetical Example of the Matrix of Biological Interactions in which a Species Functions in a Natural Community

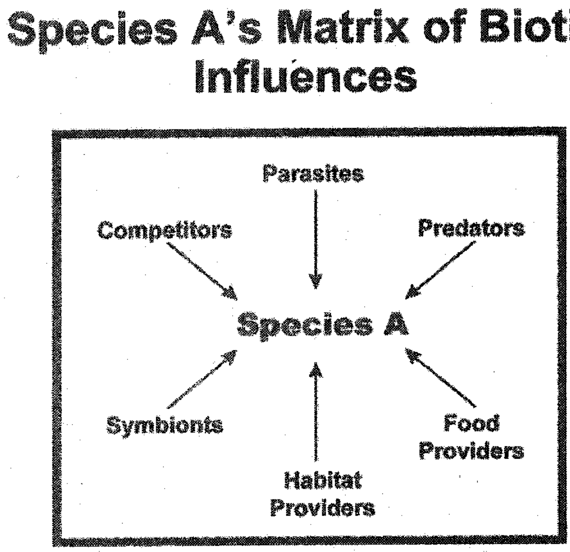

Figure 3

Projected Shrinkage in Montane Snowpacks with Rising Temperatures