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Projections of Fish Survival in US Streams after Global Warming

by

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PREFACE

In this report we have reproduced a manuscript entitled "Global Warming and Fish Survival in Streams: Low Temperature Constraint or High Temperature Constraint" and 57 maps of the lower US states on which potential stream fish habitat is identified. Potential stream fish habitat is derived from water temperatures measured at or projected for 764 USGS stream gaging sites. Water temperature measured at these stream gaging stations over variable length periods from 1961 to 1979 were used to identify past/current fish habitat that is labeled "$1\times CO_2$ climate condition" on the maps. Stream temperatures projected for a warmer climate scenario represented by a doubling of atmospheric CO_2 were used to give fish habitat identified by the label "$2\times CO_2$ climate condition" on the maps. The maps have not been reproduced anywhere else. Upper stream temperature constraint used for 57 fish species are given in Table 2 of the manuscript. Lower temperature constraint were 0 °C or 2 °C as shown on the maps.

The information for individual fish species is summarized for the cold-water, cool water and warm-water fish guilds in four separate summary maps. The loss in cold-water fish habitat is calculated state by state by counting the number of stream gaging stations that have cold-water fish habitat under the $1\times CO_2$ and $2\times CO_2$ climate conditions. The difference of the number of stations with cold-water fish habitat divided by the original number of stations is given as the percentage loss on the summary map.

Summary maps for cool-water and warm-water fishes were produced by the same method. For warm-water fishes there is no loss of habitat but only a gain. Therefore the station gains are counted and reported on the summary maps as percentages of the total number of original stations with cool-water or warm-water habitat.

For cool-water fishes, there are some gains and some losses. The net gains are reported by state on the map.

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ABSTRACT

To project fish habitat changes of 57 fish species under potential global warming, their suitable thermal habitat at 764 stream gaging stations in the contiguous US was studied. Water temperature records were available at these gaging stations. Global warming was specified by air temperature increases projected by the Canadian Center of Climate Modelling general circulation model for a doubling of atmospheric CO_2. The thermal regime at each gaging station was related to air temperature using a nonlinear stream temperature/air temperature relationship.

Suitable fish thermal habitat was assumed to be constrained by both maximum temperature and minimum temperature tolerances. Streams with weekly water temperatures between the maximum and minimum temperature tolerances of a fish species were considered to provide suitable thermal habitat for that fish species. Because information on minimum temperature tolerance of many fish species could not be found, both a 0 °C and a 2 °C lower temperature constraint were applied. There is a 38% difference in the number of stream gaging stations, with suitable thermal habitat for warmwater fishes, when 0 °C or 2° C is used as the lower temperature constraint.

The total number of stations with suitable thermal habitat for warmwater fishes is projected not to decrease under $2xCO_2$ climate conditions, regardless of whether a 0 °C or a 2 °C lower temperature constraint is applied but a northward spread of warmwater fishes under $2xCO_2$ climate conditions is projected. For cold-water and cool-water fishes, the number of stations with suitable thermal habitat under a $2xCO_2$ climate scenario is projected to decrease by 36% and 15%, respectively, with 0 °C as the lower temperature constraint. With a 2 °C lower temperature constraint, more suitable habitat for cool-water fishes and little change for cold-water fishes is projected. It is therefore concluded that the values of the lower temperature constraint, in addition to the upper temperature constraint, have a large influence on thermal habitat projections.

Key words: climate change, error analysis, fish, ecology, streams, water temperature.

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1. INTRODUCTION

Fish habitat in streams depends upon several interdependent factors which include water temperature, streamflow, channel structure and food web relationships [*Rundquist and Baldrige*, 1990]. If water temperature exceeds the maximum temperature tolerance of a fish species, the fish species is likely to be absent or disappear from that stream reach [*Eaton and Scheller*, 1996]. Under potential global warming, due to an increase of carbon dioxide and other greenhouse gases in the atmosphere, the thermal regimes of streams would change. It is quite likely that the higher water temperatures would exceed the maximum temperature tolerances of some fish species.

Studies of the potential effects of climate warming on fish thermal habitat in streams were previously conducted by *Coutant* [1990], *Magnuson et al.* [1990], *Stefan et al.* [1995], *Rahel et al.* [1996] and others. *Eaton and Scheller* [1996] were among the first to estimate fish habitat responses to climate change over the entire contiguous US. They projected maximum weekly stream temperatures at 1776 stream gaging stations by assuming a linear relationship between stream temperatures and air temperatures. The slope of the linear relationship was set equal to 0.90 for all records. They compared the maximum weekly temperature tolerance of 57 fish species (cold-water, cool-water and warmwater guilds) with the maximum weekly stream temperatures obtained under a baseline climate condition and a $2xCO_2$ climate condition. Finally, they projected the change in number of stream gaging stations with suitable thermal habitat for 57 fish species. The results of their study projected a 47% decrease in suitable thermal habitat for cold-water fish, a 50% decrease for cool-water fish and a 14% decrease for warmwater fish, under $2xCO_2$ climate conditions as projected by the general circulation model (GCM) developed at the Canadian Center of Climate Modelling (CCC).

Mohseni and Stefan [1999] recently studied the physics behind the stream temperature/air temperature relationships and concluded that stream temperatures increase linearly with air temperatures only at moderate air temperatures, i.e. air temperatures between approximately 5 °C and 25 °C. As air temperatures rise above about 25 °C, stream temperatures level off (Figure 1) due to extensive evaporative cooling. *Mohseni et al.* [1998a] showed that the stream temperature/air temperature relationship for 98% of the records studied is best explained by an S-shaped function. A linear extrapolation of the stream temperature/air temperature relationship beyond 25 °C is likely to overestimate stream temperatures, especially under a warmer climate with a 1.5 to 4.5 °C increase in mean global air temperature [*IPCC*, 1996].

In this paper, we have attempted to project again changes in fish habitat for the 57 fish species studied by *Eaton and Scheller* [1996]. The two main differences between this and the *Eaton and Scheller* [1996] study are: (1) utilizing the S-shaped function introduced by *Mohseni et al.* [1998a] instead of a linear relationship, and (2) applying a separate S-shape function to each stream gaging station. After a brief review of the stream temperature model and the data used, the projected effects of a warmer climate on the thermal habitat of 57 fish species will be shown. A second aspect of this paper is to

demonstrate that the lower temperature constraint or tolerance is also very significant for the assessment of fish habitat. Most previous studies have acknowledged the existence of this limit, but have not paid much attention to its quantitative effect. Lower temperature constraints of 0 °C and 2 °C will be used in the habitat assessment for all 57 fish species and differences in the results will be shown.

2. NONLINEAR STREAM TEMPERATURE MODEL

Mohseni et al. [1998a] observed that a nonlinear relationship between weekly stream temperatures and air temperatures exists. The stream temperature/air temperature relationship was explained by the following S-shaped function:

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \tag{1}$$

In equation 1, T_s is the estimated stream temperature, T_a is the air temperature measured at or near the stream gaging site, the coefficient α is the upper bound stream temperature, μ is the minimum estimated stream temperature, γ is a measure of the steepest slope of the function and β is the air temperature at the inflection point. *Erickson et al.* [1998] developed a method to estimate α as an extreme value (probable maximum stream temperature at a gaging station) using a universal standard deviate. The values of β, γ and μ were determined by a least squares regression method. *Mohseni et al.* [1998a] fitted equation 1 to 584 US stream temperature/air temperature of three-year length. The goodness of fit of equation 1 to weekly data was not significantly affected by the distance between stream gaging and weather stations when air temperatures were taken from weather stations that were 2 to 244 km away from the stream gaging stations. The fit between the model and the available stream temperature data for individual streams was measured by the Nash-Sutcliffe Coefficient, ***NSC*** [*Nash and Sutcliffe*, 1970]

$$NSC = 1 - \frac{\sum_{i=1}^{n} \left(T_{sim_i} - T_{obs_i}\right)^2}{\sum_{i=1}^{n} \left(\overline{T}_{obs} - T_{obs_i}\right)^2} \tag{2}$$

where T_{sim}, T_{obs} and $\overline{T}_{obs}$ are weekly simulated, weekly observed and mean weekly observed stream temperatures, respectively. *Mohseni et al.* [1998a] also noticed that some streams exhibited hysteresis, which was attributed to heat storage effects [*Webb and Nobilis*, 1997]. To take hysteresis into account, separate functions were fitted to the data representing the rising limb and the falling limb. The limbs were distinguished from each other using the associated week numbers.

3. DATA

3.1. Stream Temperature Data

Stream temperature records at 993 stream gaging stations were obtained from the US Environmental Protection Agency, Mid-Continent Division, Duluth, MN, and the USGS home page on the Internet. The records were from 1961 to 1990. Forty-six records with less than 100 weekly stream temperature data points were eliminated from the database (insufficient information on the stream temperature regime). The remaining records were utilized to obtain the four parameters of equation 1.

No regression equation was found for four stream gaging stations. A very weak relationship between water temperatures and air temperatures (***NSC***s less than 0.60) was evident at 19 gaging stations which were mostly downstream of deep reservoirs. It was also found that some streams had a significant number of outliers [*Mohseni et al.,* 1998b]. It was decided to study only those stream gaging stations which are most responsive to air temperatures, i.e. those with high ***NSC***s. This approach eliminates stream gaging stations affected by deep water releases from reservoirs, or those located in streams with small average daily flows and affected by effluent releases from wastewater treatment plants or industrial units. The threshold ***NSC*** must be high enough to exclude all those stream gaging stations which are adversely affected by anthropogenic effects. After investigating different thresholds for ***NSC***, a value of 0.85 was chosen, leaving 803 stream gaging stations in the database.

3.2. Air Temperature Data

Air temperature data were obtained from 197 weather stations in the Solar and Meteorological Surface Observation Network (SAMSON) provided by the National Oceanic and Atmospheric Administration (NOAA) and the National Renewable Energy Laboratory (NREL). For each stream gaging station, the closest weather station was selected. Therefore, some weather stations were used several times and others were not used at all. The total number of weather stations used in this study was 166.

3.3. Climate Change Scenario

The output from a general circulation model (GCM) developed at the Canadian Center of Climate Modelling (CCC) [*McFarlane et al.*, 1992] was used to specify the $2xCO_2$ climate scenario, i.e. a climate after doubling of carbon dioxide in the atmosphere. The second generation CCC GCM is a spectral coupled atmosphere-ocean model with a grid size of 3.75° x 3.75°. Climate variables are calculated at grid points. To project air temperatures under the $2xCO_2$ climate scenario, air temperatures recorded from 1961-1979 at the 166 weather stations were incremented by the difference between $2xCO_2$ and $1xCO_2$ values. Since on a weekly time scale, air temperature does not vary significantly within a grid cell of the CCC-GCM, except in alpine areas, no downscaling method was

employed for air temperature projections. Thus the differences between $2xCO_2$ and $1xCO_2$ values, simulated by the CCC-GCM, were taken from the grid point nearest to a weather station. Projected weekly air temperatures were used to estimate weekly stream temperatures for the $2xCO_2$ climate condition.

4. ERRORS IN PROJECTED STREAM TEMPERATURES

There are errors associated with the projection of air temperatures by the GCMs and errors in the stream temperature model simulations. Errors associated with the GCMs are not well known, even for past climate conditions, due to uncertainties in observed data [*Lau et al.*, 1996]. An error analysis was conducted for the stream temperature model simulations. It was assumed that errors associated with the stream temperature model simulations would not change under new climate conditions.

The error analysis was a two-tail paired ***t***-test at 10% significance level between the mean of the errors

$$\bar{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}\left| T_{sim_i} - T_{obs_i} \right| \tag{3}$$

and the mean of the changes under the $2xCO_2$ climate scenario

$$\overline{\Delta T} = \frac{1}{n}\sum_{i=1}^{n}\left| T_{sim_i} - T_{2xCO2_i} \right| \tag{4}$$

at each gaging station for the available records between 1961-1979. In the above equations T_{2xCO2} is the projected stream temperature under $2xCO_2$ climate conditions and the parameter ***n*** is the number of all weekly data at a gaging station. Values of ***n*** ranged from 100 to 1038. For 39 stream gaging stations, the results projected a significant stream temperature change below the 90% confidence level under the $2xCO_2$ climate scenario (Table 1). Stream temperature simulations at those 39 gaging stations were therefore not considered good enough for any effect study under the CCC-GCM $2xCO_2$ climate scenario. Figure 4 shows the locations of the remaining 764 stream gaging stations.

Table 1. Comparison between the stations showed a significant change and those which showed no significant change at 90% confidence level under the $2xCO_2$ climate scenario. The values in the table are the mean of the parameters. **RMSE** = root mean squared errors

	Error Analysis Results			Simulation Characteristics	
	No. of stations	**Mean absolute error (°C)**	**Mean change (°C)**	***NSC***	**RMSE (°C)**
Mean Annual Stream Temperatures					
Stations with significant change	764	1.68	3.14	0.93	1.84
Stations with no significant change	39	2.23	2.27	0.89	1.89
Maximum Weekly Stream Temperatures					
Stations with significant change	399	1.88	2.24	0.93	1.85
Stations with no significant change	404	1.98	2.06	0.92	1.84
Minimum Weekly Stream Temperatures					
Stations with significant change	455	1.14	2.25	0.93	1.77
Stations with no significant change	349	1.61	1.85	0.93	1.93

A separate error analysis was conducted for the projected maximum and minimum weekly stream temperatures which are of particular importance to the maximum and minimum temperature tolerances of fishes. For this error analysis, only maximum or minimum weekly stream temperatures were employed in equations 3 and 4, and the parameter ***n*** now designated the number of years of records ranged from 3 to 19. Only 399 stream gaging stations showed a significant change in maximum weekly stream temperatures and only 455 in minimum weekly stream temperatures, under the $2xCO_2$ climate scenario (Table 1).

The notable difference between the results of the error analysis of the mean weekly stream temperatures and the maximum/minimum stream temperatures is attributed to the S-shaped stream temperature function. Maximum and minimum weekly stream temperatures are often located on the tails of the S-shaped function. If the observed maximum/minimum weekly stream temperatures are in the proximity of the tails of equation 1, where the slope is close to zero, even a large change in air temperature under a climate change scenario may not cause a change in maximum or minimum weekly stream temperatures larger than the error in the simulations. The values given in Table 1 illustrate this point.

On average the mean weekly stream temperatures in the contiguous US under the $2xCO_2$ climate scenario would be 2 to 4 °C warmer than present, but there would be only a 1 to 3 °C increase in the maximum and minimum weekly stream temperatures under the $2xCO_2$ climate scenario [*Mohseni et al.*, 1999].

5. FISH TEMPERATURE TOLERANCES

To study the fish presence or absence in a river reach, represented here by a stream gaging station, the authors focused first on the maximum weekly temperature tolerances of 57 fish species which were previously given by *Eaton and Scheller* [1996]. Information on minimum temperature tolerances of fish species is much more sparse, although values for a few particular fish species could be found in the literature. *Shaheen et al.* [1990] , for example, found that young green sunfish died as water temperature was reduced from 5 to 4 °C. *Packer and Hoff* [1998] observed that 2 °C to 4 °C caused mortality for Mid-Atlantic Summer Flounder. *Scheller et al.* [1998] took 2 °C as the lower temperature constraint for 15 warmwater fish species in their multivariate statistical model of the influence of stream thermal regimes on fishes.

Because of this lack of information on minimum temperature tolerance of fresh water fishes, only two values were considered: 0 °C and 2 °C were assigned as the minimum temperature tolerance for all 57 fish species. The rationale behind this choice was to investigate the significance of a 2 °C difference in minimum temperature tolerance on the fish habitat under a warmer climate.

6. RESULTS AND DISCUSSION

The number of stream gaging stations with suitable thermal habitat for the $1xCO_2$ and $2xCO_2$ climate conditions using the 0 °C lower temperature constraint is listed in Table 2. Fish species are listed in increasing order of maximum temperature tolerance. The results show that there would be a 33% to 49% decrease in the number of streams thermally suitable for cold-water fishes, an 11% to 22% decrease for cool-water fishes and almost no change for warmwater fishes. For most warmwater fishes, more than 760 stream reaches (gaging stations) of the 764 investigated have thermally suitable habitat (Figure 3). The results in Table 2 are significantly different from those obtained by *Eaton and Scheller* [1996]. The difference comes from the projected maximum weekly stream temperatures. The logistic function (equation 1) does not indicate a significant increase in stream temperatures under the $2xCO_2$ climate scenario. Therefore, warmwater fishes and most cool-water fishes would not lose much habitat by the small predicted increase in water temperatures. The fish guild that would be harmed the most are the cold-water fishes. Figure 4 shows that under the $2xCO_2$ climate condition, rainbow trout, for example, would disappear from the gaging stations located in the Midwest, the Ohio River basin and the East Coast. More precisely, rainbow trout would not vanish from stream reaches at higher altitudes (e.g. the Rocky Mountains and the Appalachian Mountains) because those stations are not projected to experience very warm water temperatures under the $2xCO_2$ climate scenario. This is similar to the shift of cold-water fish thermal habitat projected by Rahel et al. [1996] for the Platte River watershed. White Sucker, a cool-water fish, would find it more difficult to live in the lower Mississippi plain and the southern part of the East Coast (Figure 5); i.e. thermal range boundaries would be extended northward and to higher altitudes.

If the minimum temperature tolerance is set at 2 °C, a very different picture of fish thermal habitat is obtained (Table 3). Because of the 2 °C lower temperature constraint, the number of stream gaging stations suitable for fish is smaller under the $1xCO_2$ (present) climate conditions. Consequently, under a warmer $2xCO_2$ climate, there would be a significant increase in the thermal habitat of fishes because the projected minimum weekly stream temperatures would become higher and could more easily exceed the lower temperature constraint for fishes. Figure 6 therefore shows that there would be an increase in the thermal habitat of many fish species. Especially warmwater fishes would find many more inhabitable stream reaches after climate change. For cold-water species the increase would be less or negative (loss).

Among the 10 cold-water fishes, seven fish species are projected to encounter a reduction in suitable thermal habitat of approximately 2 to 6%, which may not be statistically significant. In cold water streams, maximum water temperatures are often in the mid-range temperatures, i.e. between 20 to 25 °C, where the stream temperature/air temperature relationship is linear with a slope close to unity [*Mohseni and Stefan*, 1999]. Therefore, a 3 °C increase in air temperatures would cause a 3 °C increase in water temperatures which may exceed the maximum temperature tolerance of a cold-water fish.

Table 2. Number of US stream gaging stations (out of 764 investigated) with thermal regimes within the maximum and minimum temperature tolerances under $1xCO_2$ and $2xCO_2$ climate conditions. The minimum temperature tolerance is set equal to 0 °C for all fish species.

Fish species	Maximum temperature tolerance	Number of stations		% change in number of stations
		1xCO2	2xCO2	
Warmwater				
Bluntnose minnow	30.1	762	707	**-7.2**
Sauger	30.1	762	707	**-7.2**
Black crappie	30.5	762	721	**-5.4**
Golden shiner	30.9	762	737	**-3.3**
Spotted bass	30.9	762	737	**-3.3**
White perch	30.9	762	737	**-3.3**
White crappie	31.0	763	743	**-2.6**
White bass	31.4	763	753	**-1.3**
Longnose gar	31.6	763	758	**-0.7**
Emerald shiner	31.8	763	760	**-0.4**
Sand shiner	32.1	763	761	**-0.3**
River carpsucker	32.1	763	761	**-0.3**
Suckermouth minnow	32.5	763	761	**-0.3**
Orange spotted sunfish	32.6	763	761	**-0.3**
Freshwater drum	34.0	763	763	**0.0**
Bullhead minnow	34.0	763	763	**0.0**
Black bullhead	34.0	763	763	**0.0**
Flathead catfish	34.0	763	763	**0.0**
Flathead minnow	34.0	763	763	**0.0**
Ghost shiner	34.0	763	763	**0.0**
Gizzrd shad	34.0	763	763	**0.0**
Green sunfish	34.0	763	763	**0.0**
Longear sunfish	34.0	763	763	**0.0**
Mosquitofish	34.0	763	763	**0.0**
Red shiner	34.0	763	763	**0.0**
Smallmouth buffalo	34.0	763	763	**0.0**
Warmouth	34.0	763	763	**0.0**
Common carp	35.0	763	763	**0.0**
Channel catfish	35.0	763	763	**0.0**
Largemouth bass	35.5	763	763	**0.0**
Bluegill	36.0	763	763	**0.0**
			average	***-1.2***

Table 2. (continued)

Fish species	Maximum temperature tolerance	Number of stations		% change in number of stations
		1xCO2	2xCO2	
Cold-water				
Chum salmon	19.8	172	114	**-33.7**
Pink salmon	21.0	246	148	**-39.8**
Brook trout	22.4	338	219	**-35.2**
Mountain white fish	23.1	401	260	**-35.2**
Cutthroat trout	23.3	423	267	**-36.9**
Coho salmon	23.4	431	271	**-37.1**
Chinook salmon	24.0	484	306	**-36.8**
Rainbow trout	24.0	484	306	**-36.8**
Brown trout	24.1	493	312	**-36.7**
Mottled sculpin	24.3	515	330	**-35.9**
			average	***-36.4***
Cool-water				
Johnny darter	26.5	634	493	**-22.2**
Longnose dance	26.5	634	493	**-22.2**
Creek chub	27.1	662	545	**-17.7**
Blacknose dance	27.2	665	549	**-17.4**
White sucker	27.4	678	555	**-18.1**
Northern pike	28.0	714	598	**-16.2**
Walleye	29.0	753	652	**-13.4**
Pumpkinseed	29.1	757	656	**-13.3**
Yellow perch	29.1	757	656	**-13.3**
Common shiner	29.2	757	662	**-12.5**
Rock bass	29.3	759	665	**-12.4**
Brown bullhead	29.4	760	666	**-12.4**
Smallmouth bass	29.5	762	672	**-11.8**
Golden redhorse	29.6	762	677	**-11.2**
Northern hog sucker	29.6	762	677	**-11.2**
Silver red horse	29.6	762	677	**-11.2**
			average	***-14.8***

Table 3. Number of US stream gaging stations (out of 764 investigated) with thermal regimes within the maximum and minimum temperature tolerances under $1xCO_2$ and $2xCO_2$ climate conditions. The minimum temperature tolerance is set equal to 2 °C for all fish species.

Fish species	Maximum temperature tolerance	Number of stations		% change in number of stations
		1xCO2	2xCO2	
Cold-water				
Chum salmon	19.8	82	87	**6.1**
Pink salmon	21.0	122	117	**-4.1**
Brook trout	22.4	175	178	**1.7**
Mountain white fish	23.1	211	211	**0**
Cutthroat trout	23.3	224	214	**-4.5**
Coho salmon	23.4	229	216	**-5.7**
Chinook salmon	24.0	256	244	**-4.7**
Rainbow trout	24.0	256	244	**-4.7**
Brown trout	24.1	260	249	**-4.2**
Mottled sculpin	24.3	273	260	**-4.8**
			average	**-2.5**
Cool-water				
Johnny darter	26.5	350	380	**8.6**
Longnose dance	26.5	350	380	**8.6**
Creek chub	27.1	377	422	**11.9**
Blacknose dance	27.2	380	424	**11.6**
White sucker	27.4	392	430	**9.7**
Northern pike	28.0	425	468	**10.1**
Walleye	29.0	463	520	**12.3**
Pumpkinseed	29.1	467	524	**12.2**
Yellow perch	29.1	467	524	**12.2**
Common shiner	29.2	467	530	**13.5**
Rock bass	29.3	469	533	**13.6**
Brown bullhead	29.4	470	534	**13.6**
Smallmouth bass	29.5	472	540	**14.4**
Golden redhorse	29.6	472	544	**15.3**
Northern hog sucker	29.6	472	544	**15.3**
Silver red horse	29.6	472	544	**15.3**
			average	***12.4***

Table 3. (continued)

Fish species	Maximum temperature tolerance	Number of stations		% change in number of stations
		1xCO2	2xCO2	
Warmwater				
Bluntnose minnow	30.1	472	574	**21.6**
Sauger	30.1	472	574	**21.6**
Black crappie	30.5	472	588	**24.6**
Golden shiner	30.9	472	604	**28.0**
Spotted bass	30.9	472	604	**28.0**
White perch	30.9	472	604	**28.0**
White crappie	31.0	473	610	**29.0**
White bass	31.4	473	620	**31.1**
Longnose gar	31.6	473	625	**32.1**
Emerald shiner	31.8	473	627	**32.6**
Sand shiner	32.1	473	628	**32.8**
River carpsucker	32.1	473	628	**32.8**
Suckermouth minnow	32.5	473	628	**32.8**
Orange spotted sunfish	32.6	473	628	**32.8**
Freshwater drum	34.0	473	630	**33.2**
Bullhead minnow	34.0	473	630	**33.2**
Black bullhead	34.0	473	630	**33.2**
Flathead catfish	34.0	473	630	**33.2**
Flathead minnow	34.0	473	630	**33.2**
Ghost shiner	34.0	473	630	**33.2**
Gizzrd shad	34.0	473	630	**33.2**
Green sunfish	34.0	473	630	**33.2**
Longear sunfish	34.0	473	630	**33.2**
Mosquitofish	34.0	473	630	**33.2**
Red shiner	34.0	473	630	**33.2**
Smallmouth buffalo	34.0	473	630	**33.2**
Warmouth	34.0	473	630	**33.2**
Common carp	35.0	473	630	**33.2**
Channel catfish	35.0	473	630	**33.2**
Largemouth bass	35.5	473	630	**33.2**
Bluegill	36.0	473	630	**33.2**
			average	***31.4***

Warmwater fish species encounter more thermally suitable habitats under $2xCO_2$ (present) climate conditions and a 33% increase is projected for most of them. Warm water streams would not experience a high water temperature rise under a $2xCO_2$ climate condition due to evaporative cooling. Hence, most stream gaging stations retain suitable thermal habitat for warmwater fishes. In cool streams, minimum stream temperatures rise due to climate warming from say 0 °C to 3 °C, therefore, the presence of warmwater fishes would be much facilitated. For example, there would be a 33% increase in the number of stations thermally suitable for Largemouth Bass (Figure 7). More rivers in the Rocky Mountains and at northern latitudes would become inhabited by Largemouth Bass. Figure 7 shows that there would likely be a northward spread of Largemouth Bass under the $2xCO_2$ climate scenario. The projection for Largemouth Bass is in agreement with that obtained by *Eaton and Scheller* [1996].

The 2 °C lower temperature constraint for some cold-water and cool-water fish species may be too high. Similarly, a 0 °C lower temperature constraint may be too low for some warmwater fishes. For that reason Figure 3 may be more representative for cold-water fishes and Figure 6 for warmwater fishes. To facilitate the comparison, the difference between the changes under the $2xCO_2$ climate scenario for both low temperature constraints are illustrated in Figure 8. It can be seen that the projected effect of climate change (from $1xCO_2$ to $2xCO_2$) on stream thermal fish habitat is accentuated if the lower temperature constraint is set at 0 °C for cold-water fishes and 2 °C for warmwater fishes, rather than constant for all species. The most likely response to climate change (from a $1xCO_2$ to a $2xCO_2$ climate scenario) would therefore be a 36% decrease in thermal habitat for cold-water fishes (as predicted with a 0 °C lower temperature tolerance) and a 31% increase for warmwater fishes (as predicted with a 2 °C lower temperature tolerance).

Altogether, the results in Figure 3 and 6 indicate that for projecting fish habitat under a warming climate scenario, reliable lower temperature tolerances for different fish species are as important as upper temperature tolerance of fishes. Because of evaporative cooling, already high stream temperatures will not significantly increase, thus, the upper temperature constraint will not be a crucial factor. Cold-water streams will be warmed more than warmwater streams if the climate becomes warmer. Cold-water fishes will be affected by this warming and lose their habitat (Figure 4). The warming would be even more dramatic for shaded cold-water streams if the riparian trees are lost. This effect is not included in the S-shaped stream temperature/air temperature relationship derived from data and used in this study.

7. SUMMARY

The four-parameter nonlinear stream temperature model developed by *Mohseni et al.* [1998a] was utilized to simulate weekly stream temperatures at 764 US stream gaging stations. For the $2xCO_2$ climate condition, weekly stream temperatures were obtained from incremented weekly air temperatures using the output of the CCC-GCM. Finally, the suitable thermal habitats for 57 fish species were projected utilizing their maximum and minimum weekly temperature tolerances. Because of a lack of information on minimum temperature tolerance of fishes either a 0 °C or a 2 °C lower temperature constraint was imposed. The results showed that different lower temperature constraints gave very different habitat results. With 0 °C as the lower temperature constraint, a 36% decrease in thermal habitats suitable for cold-water fish was projected, and almost no change in warmwater fish thermal habitats. With 2 °C as the lower temperature constraint, a 3% decrease was projected in cold-water fish thermal habitats and a 32% increase in warmwater fish thermal habitats.

The results of this study also show that the maximum temperature tolerance will not have a crucial effect on warmwater fish habitats because of the evaporative cooling of streams. The maximum temperature tolerance is, however, a limiting factor, which will cause a northward range extension of cold-water fishes. Conversely, the lower temperature constraint plays an important role for habitats of all fishes. The percentage decrease in suitable thermal habitat of cold-water fishes, and northward spread of warmwater fishes depend upon their minimum temperature tolerances, which need to be determined accurately.

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LIST OF FIGURES

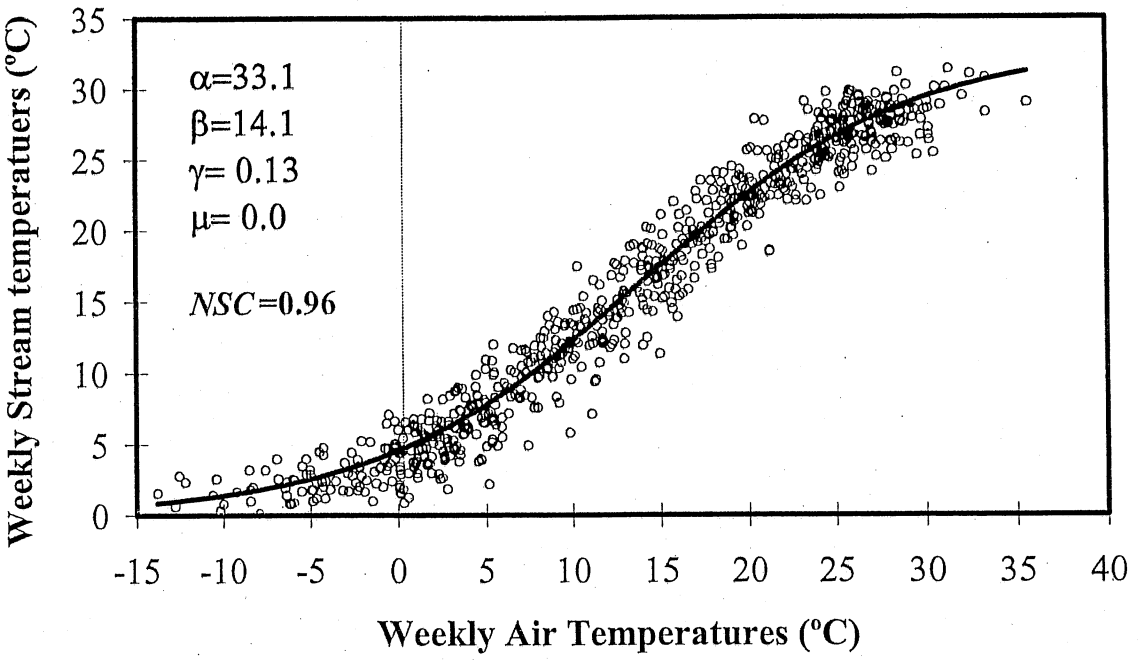


Figure 1. Weekly measured stream temperatures at the Salt Fork of the Arkansas River near Jet, OK, versus weekly air temperatures recorded at Wichita, KS. The line represents the nonlinear least squares regression between stream temperatures and air temperatures.

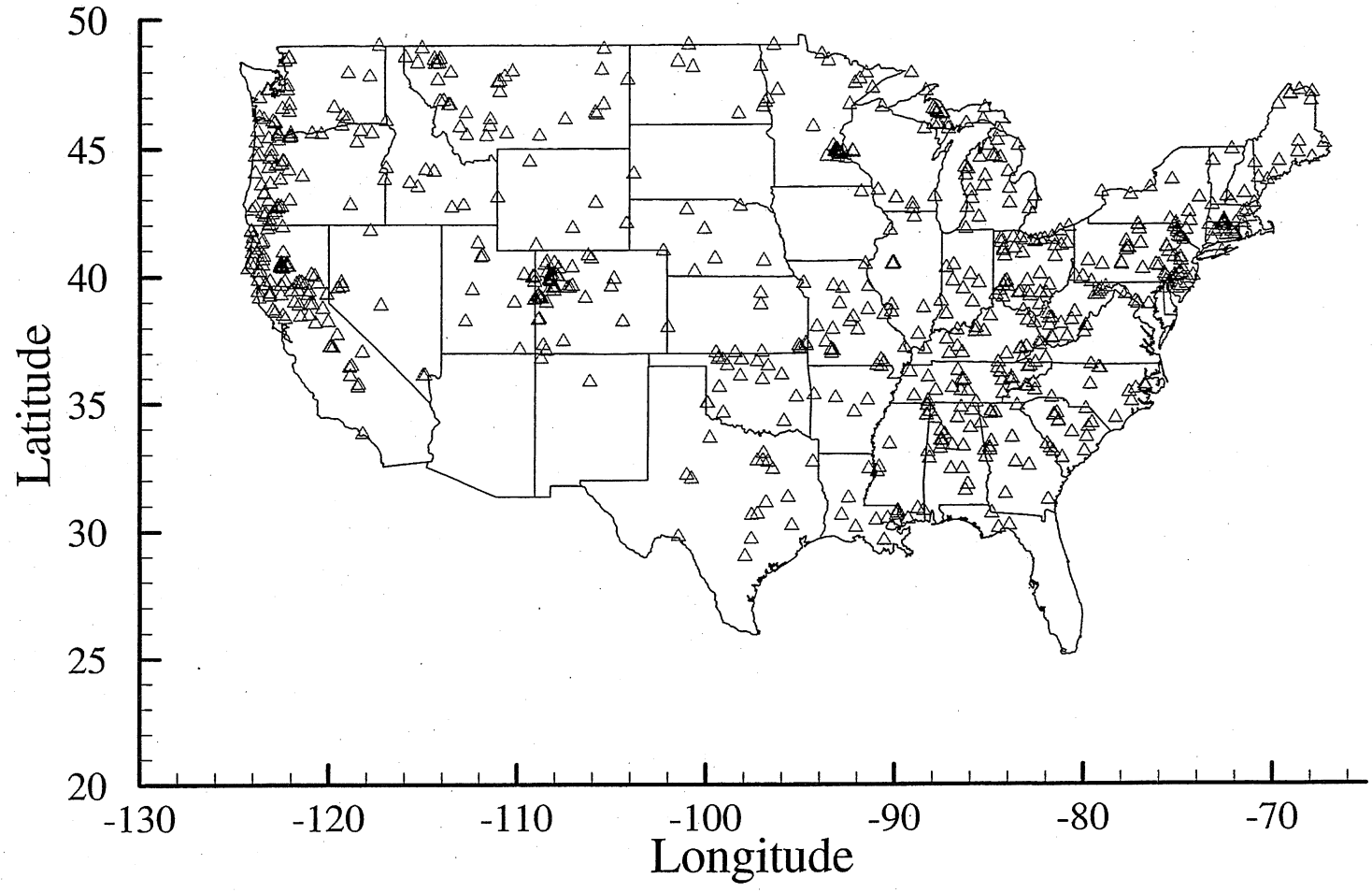


Figure 2. Locations of 764 stream gaging stations used to study fish thermal habitat in streams of the contiguous US.

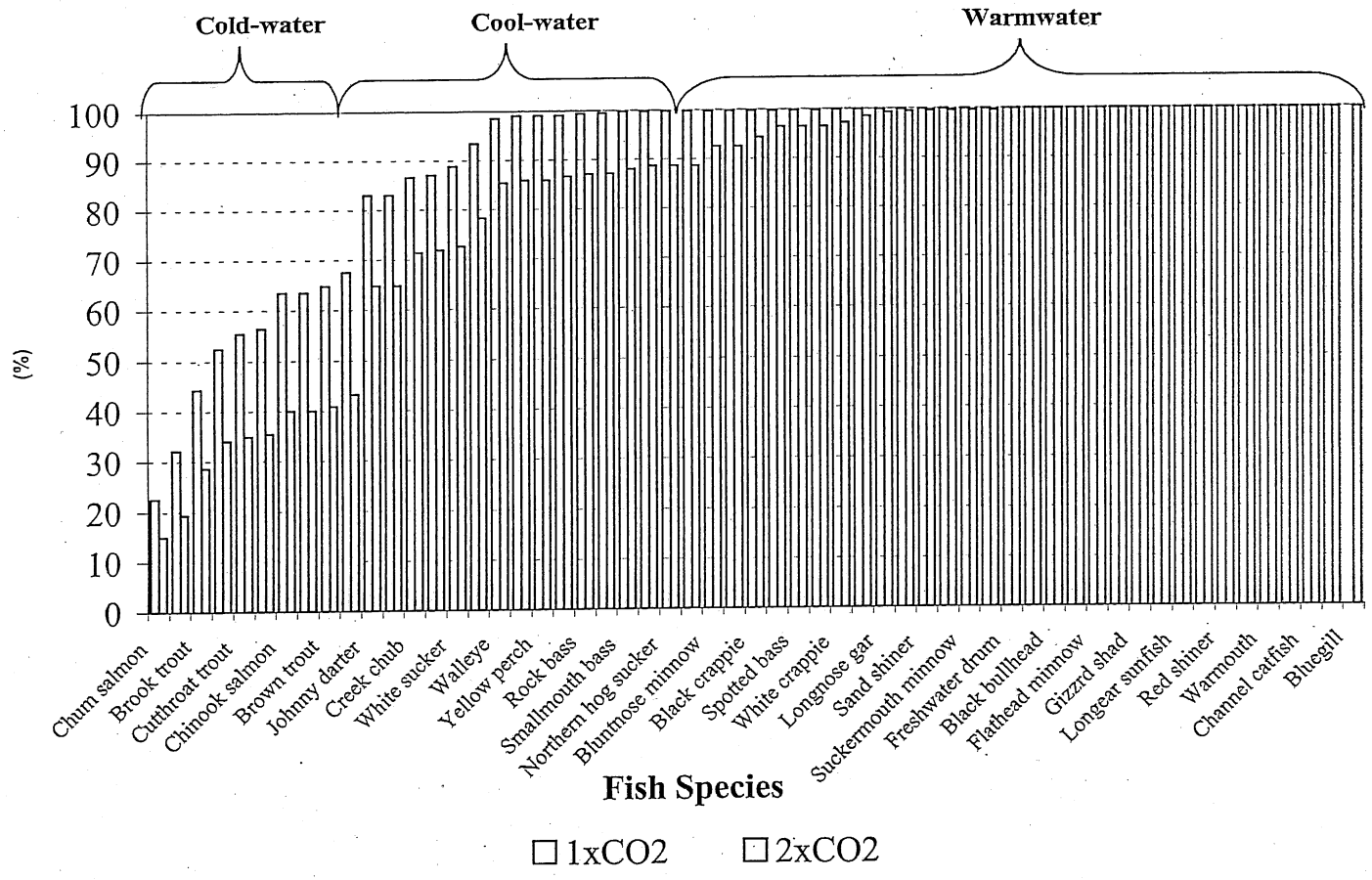


Figure 3. Suitable thermal habitats of 57 fish species as a percentage of all records (764) under $1xCO_2$ and $2xCO_2$ climate conditions. The minimum weekly temperature tolerance for all fishes is set equal to 0 °C.

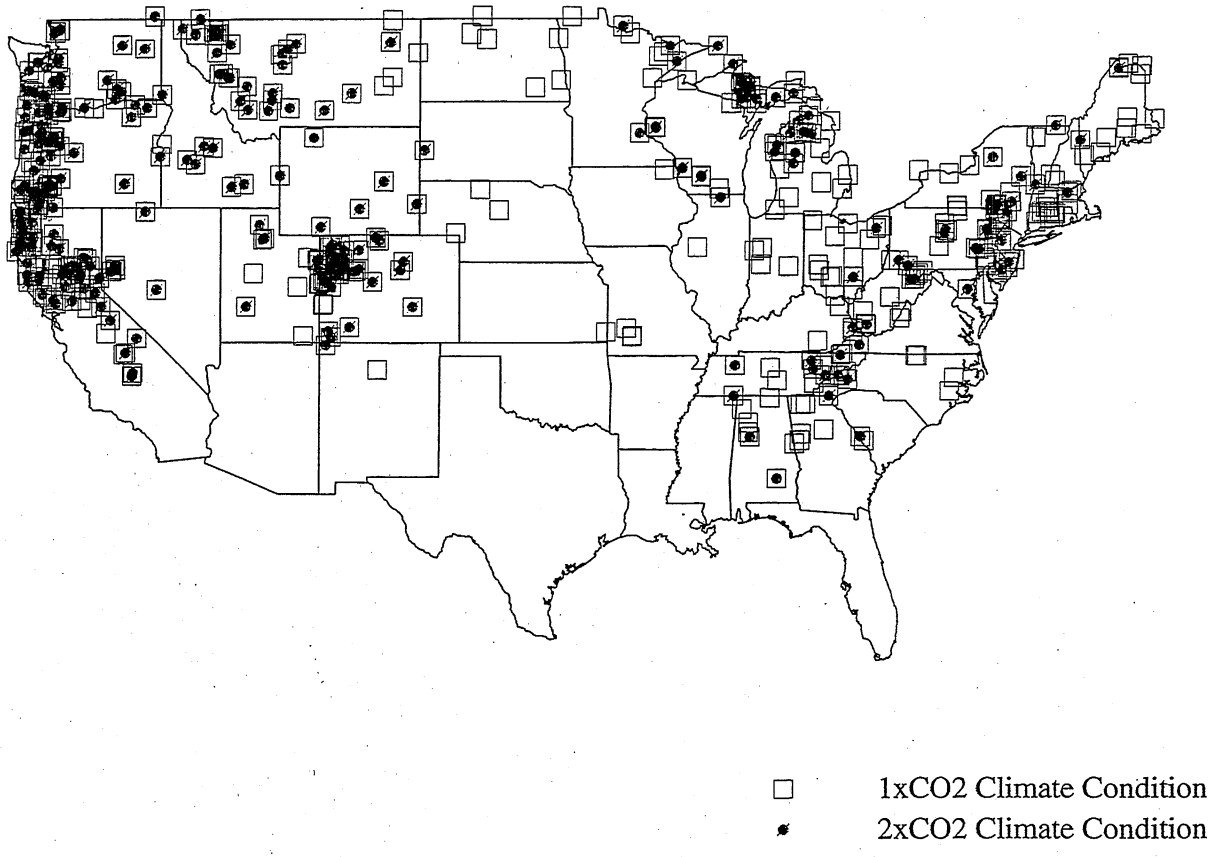


Figure 4. Stream gaging stations with suitable thermal regime for Rainbow Trout under past and $2xCO_2$ climate conditions. The minimum weekly temperature tolerance is set equal to 0 °C.

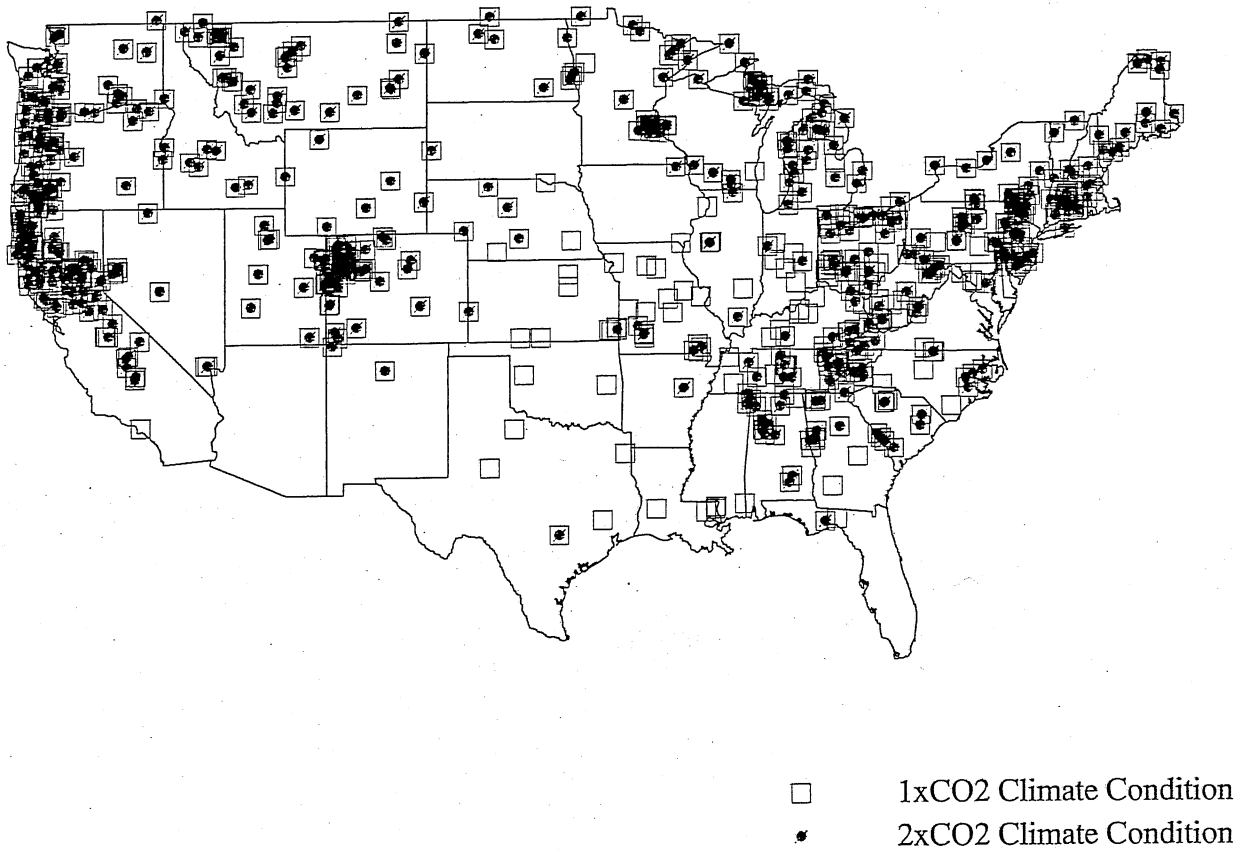


Figure 5. Stream gaging stations with suitable thermal regime for White Sucker under past and $2xCO_2$ climate conditions. The minimum weekly temperature tolerance is set equal to 0 °C.

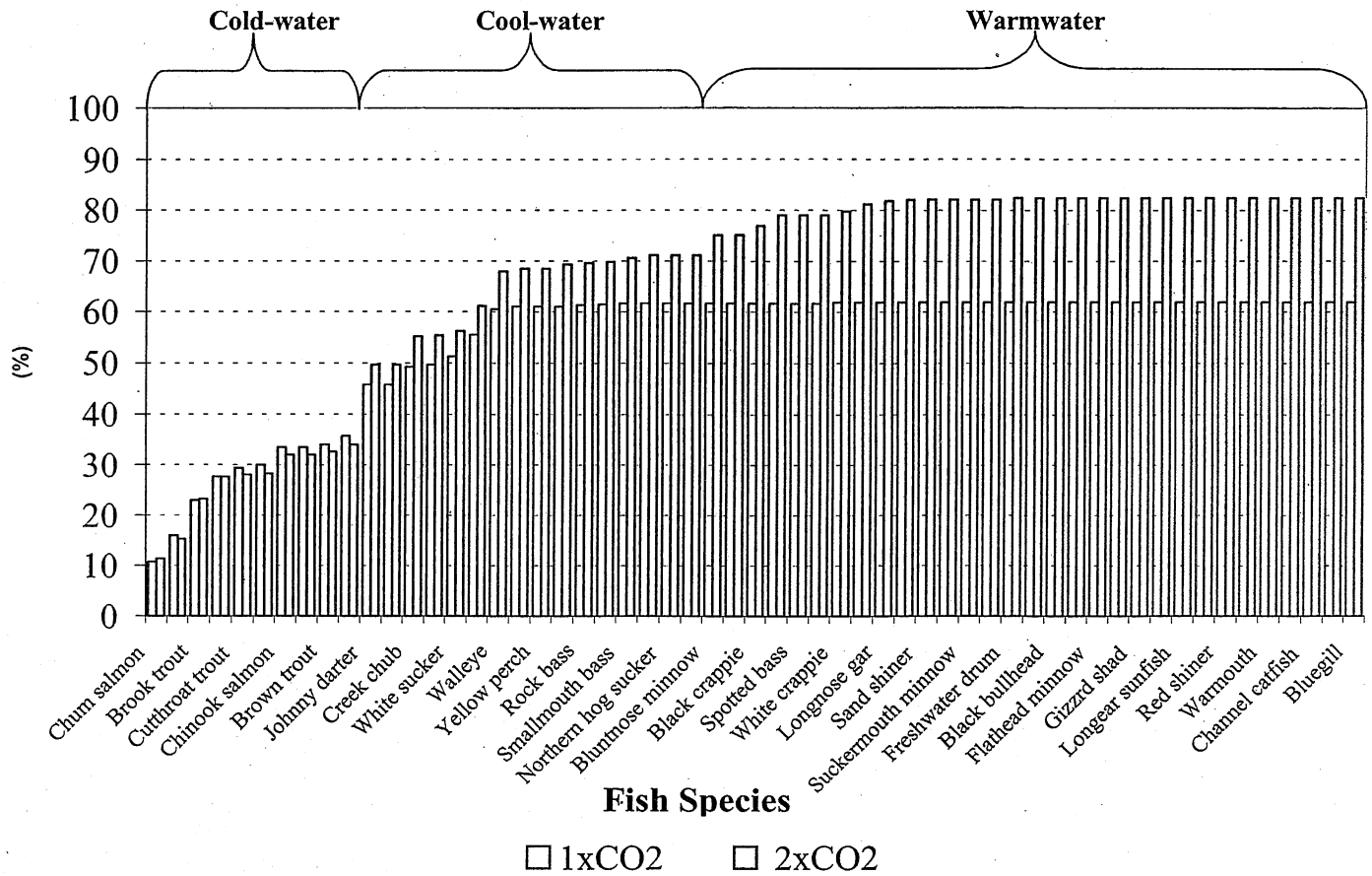


Figure 6. Suitable thermal habitats of 57 fish species as a percentage of all records (764) under $1xCO_2$ and $2xCO_2$ climate conditions. The minimum weekly temperature tolerance for all fishes is set equal to 2 °C.

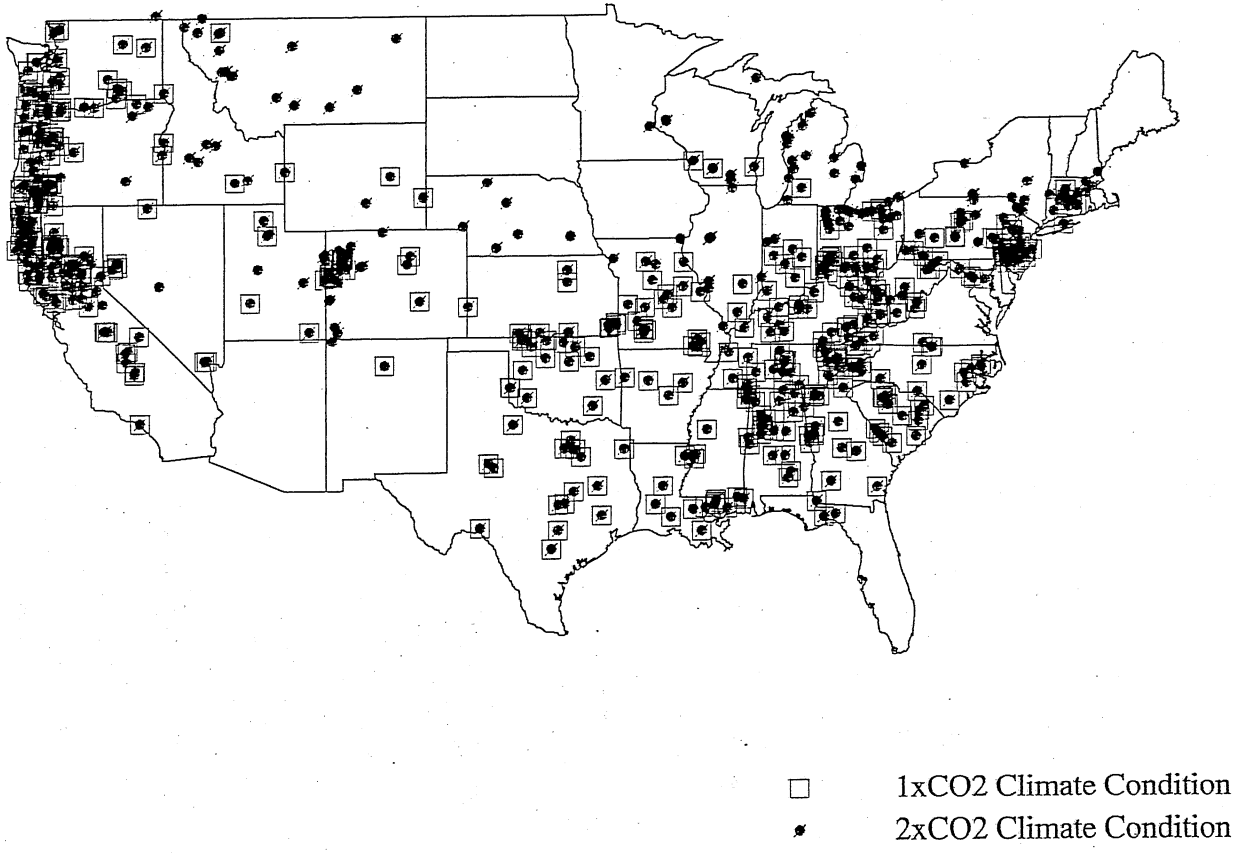


Figure 7. Stream gaging stations with suitable thermal regime for Largemouth Bass under past and $2xCO_2$ climate conditions. The minimum weekly temperature tolerance is set equal to 2 °C.

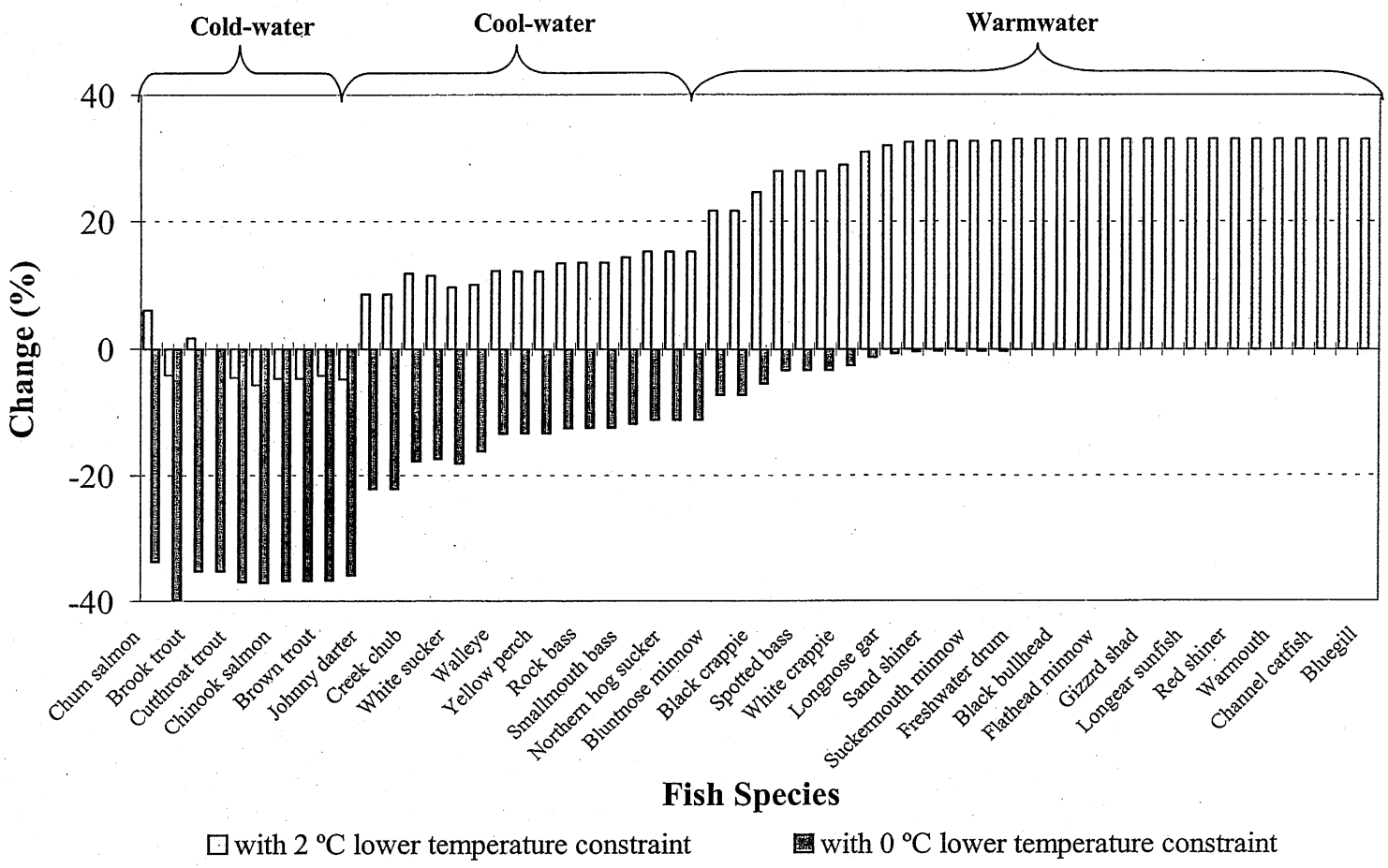


Figure 8. Changes in fish thermal habitat under the $2xCO_2$ climate scenario for lower temperature constraints of 0 °C and 2 °C. Changes are given as percentage of past conditions.

Maps

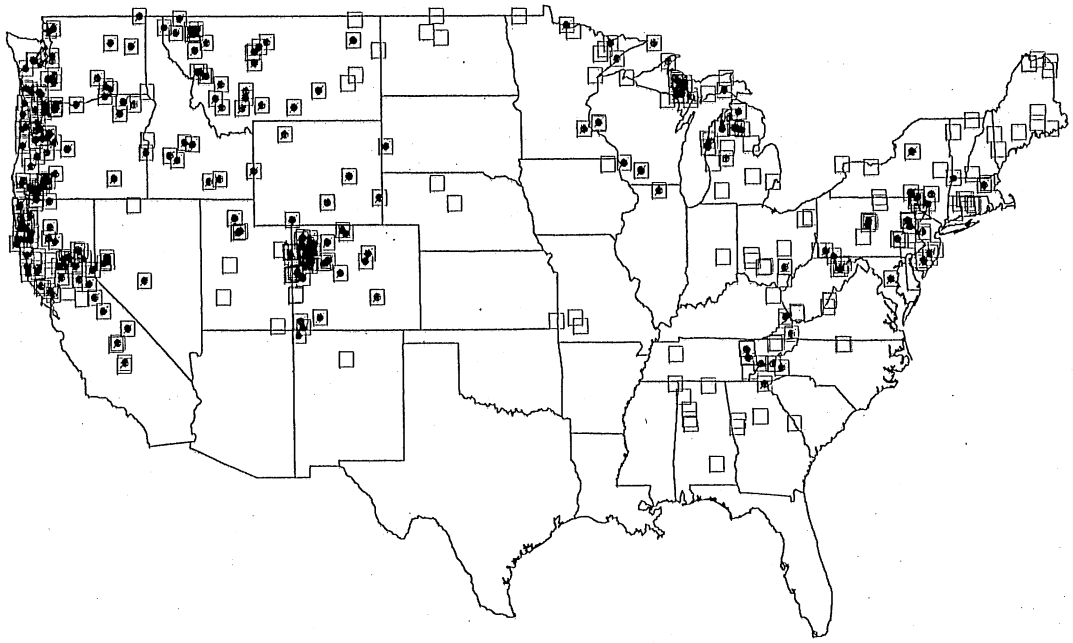
On the following pages, 57 maps are given, which display stream gaging stations with suitable thermal regimes for the 57 fish species of Table 2 under past/current and $2xCO_2$ climate conditions. The maps give potential habitat at a stream gaging station and do not indicate that a fish species is actually present at that station. The minimum weekly temperature tolerance is set equal to 0 °C or 2 °C for all fish species. The maps follow the same order as the list of fish species in Table 2. In addition, there are 15 summary maps. In these summary maps, the cold-water fish habitat changes are shown using only 0 °C as the minimum weekly temperature tolerance. For cool-water fishes, both 0 °C and 2 °C, and for warm-water fishes only 2 °C as the minimum weekly temperature tolerances are used. The summary maps give the changes as percentages calculated using two different methods.

In the first method, the changes in total number of fish stations under $2xCO_2$ climate conditions were reported as a percentage of the total number of fish stations under past/current conditions. The term "fish stations" stands for the number of stream gaging stations, which are thermally suitable habitat for a fish species in a state. If a state exhibited less than or equal to two stations as suitable habitat for a guild, i.e. 20 fish stations for cold-water fishes, 32 for cool-water fishes and 62 for warm-water fishes, then it would be considered a state with insufficient data. Consequently, no result was reported for that state.

In the second method, initially the total number of stations used in this study and located in each state was determined. Then, for each state, the maximum suitable habitat in terms of the possible maximum number of fish stations was calculated, e.g. if there were 23 stream gaging stations in Minnesota, then, for 10 cold-water fish species, there would be a maximum number of 230 fish stations in Minnesota. The percentage of the actual number of fish stations in every state with respect to the maximum number of fish stations of that state, under past/current conditions and $2xCO_2$ climate conditions, were calculated and presented in two different maps for each guild.

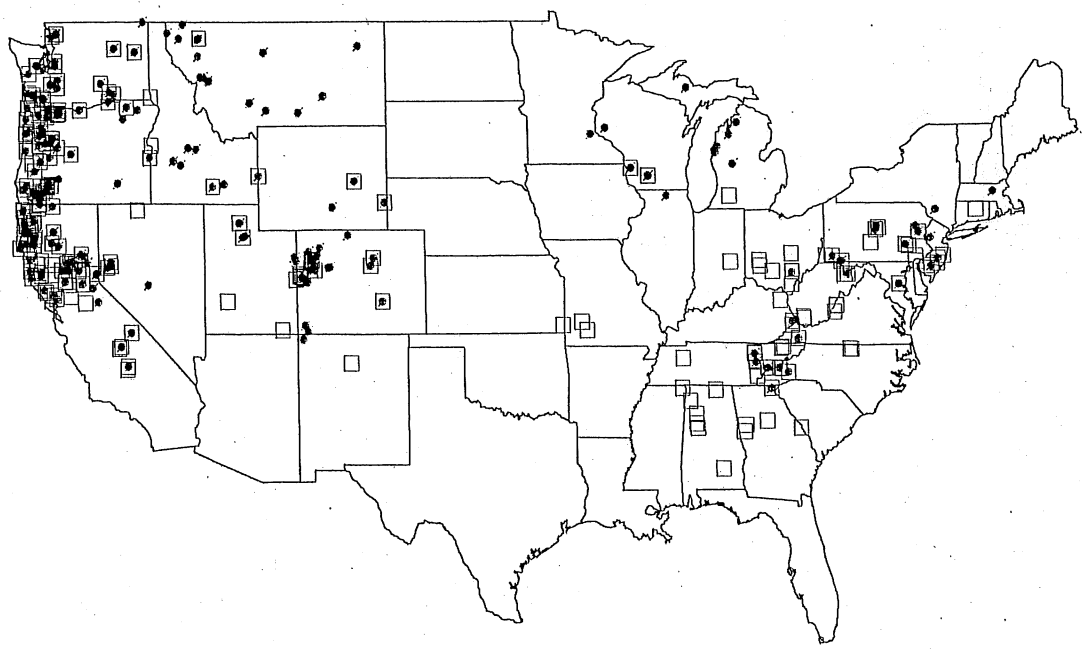
Cold-Water Fishes

Coho salmon



With 0 °C as the minimum temperature tolerance

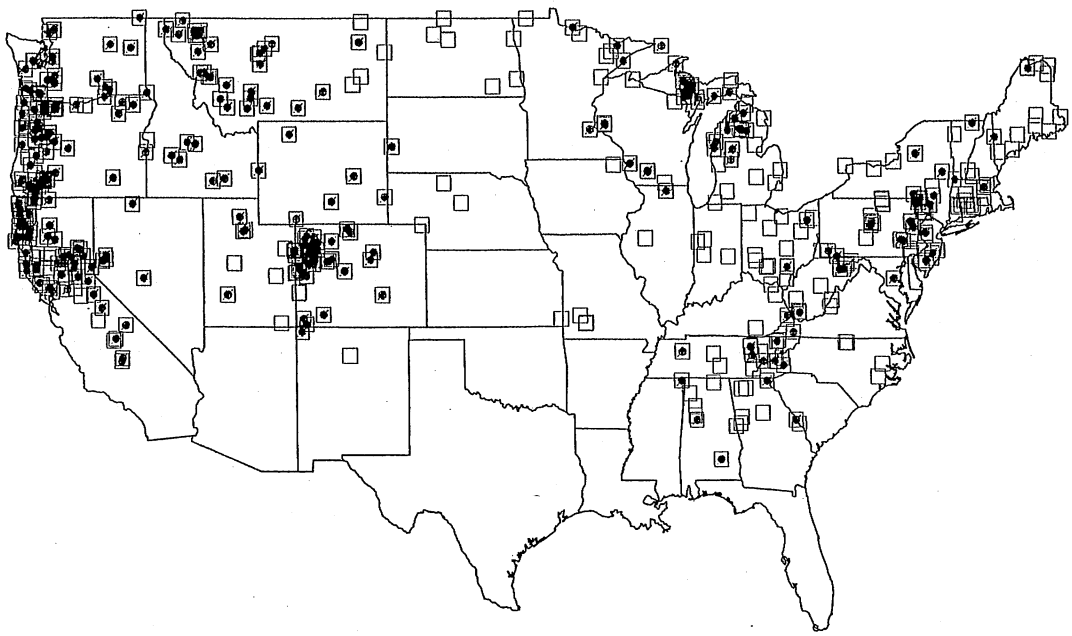
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

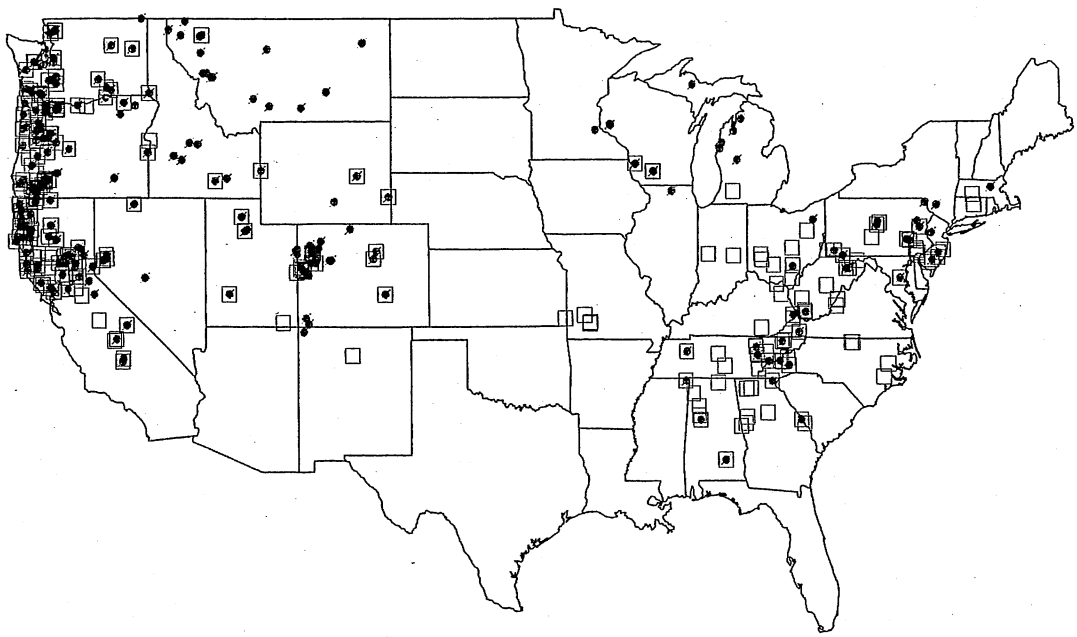
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Chinook salmon



With 0 °C as the minimum temperature tolerance

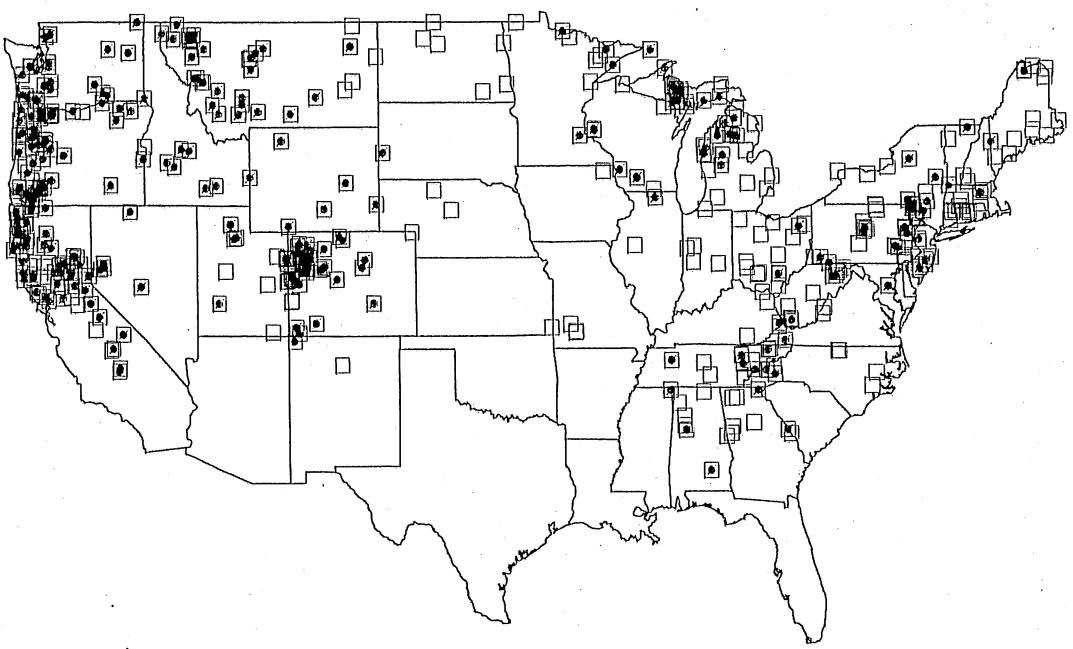
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition



With 2 °C as the minimum temperature tolerance

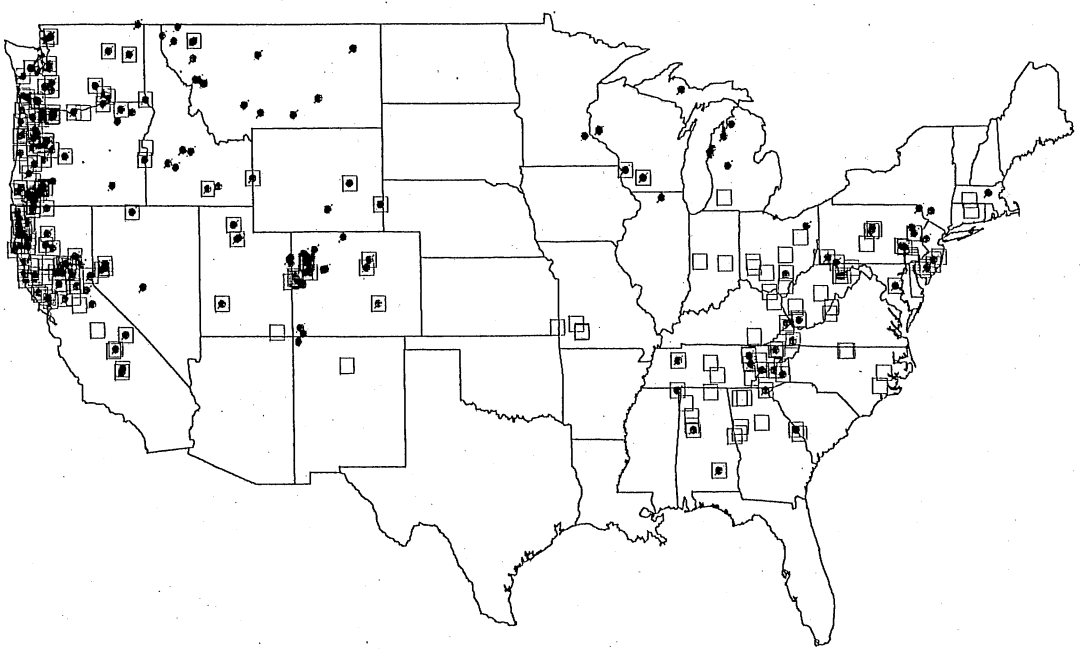
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

Rainbow trout



With 0 °C as the minimum temperature tolerance

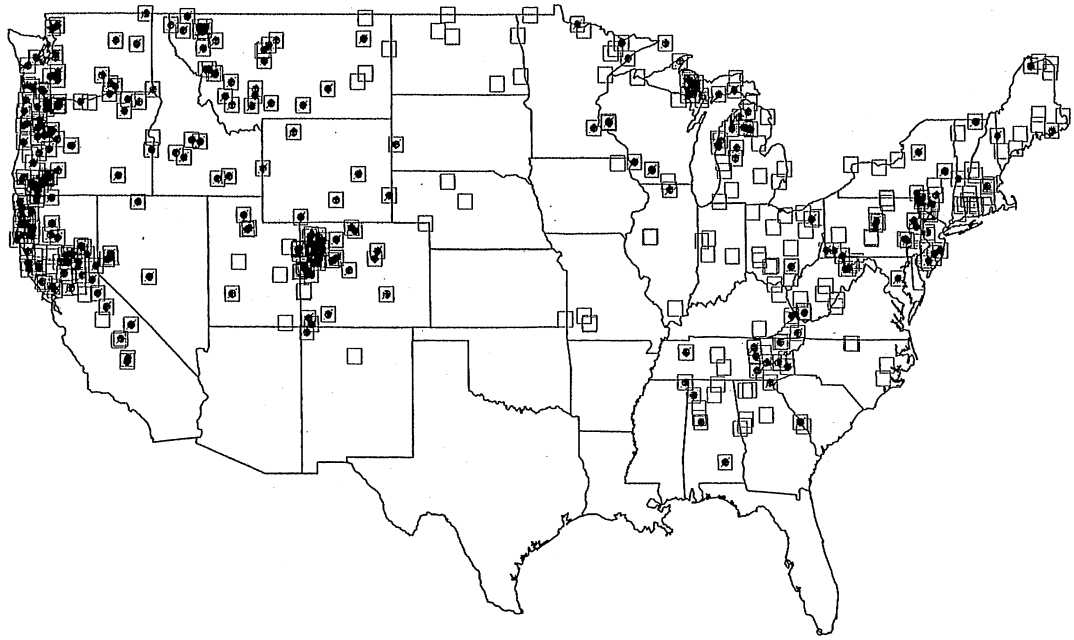
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

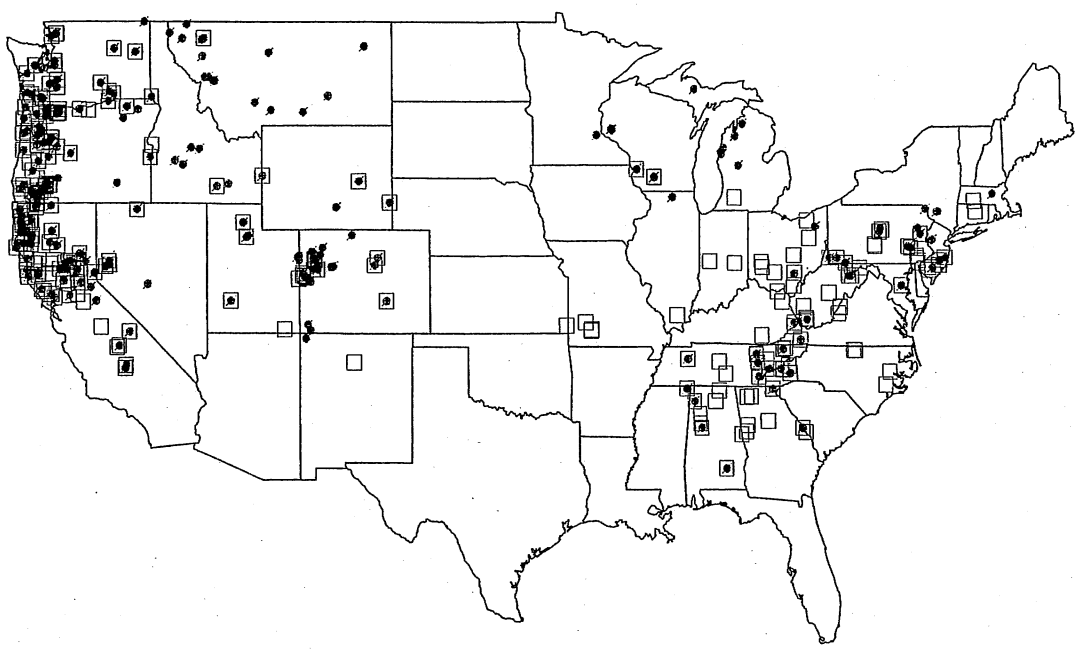
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Brown trout



With 0 °C as the minimum temperature tolerance

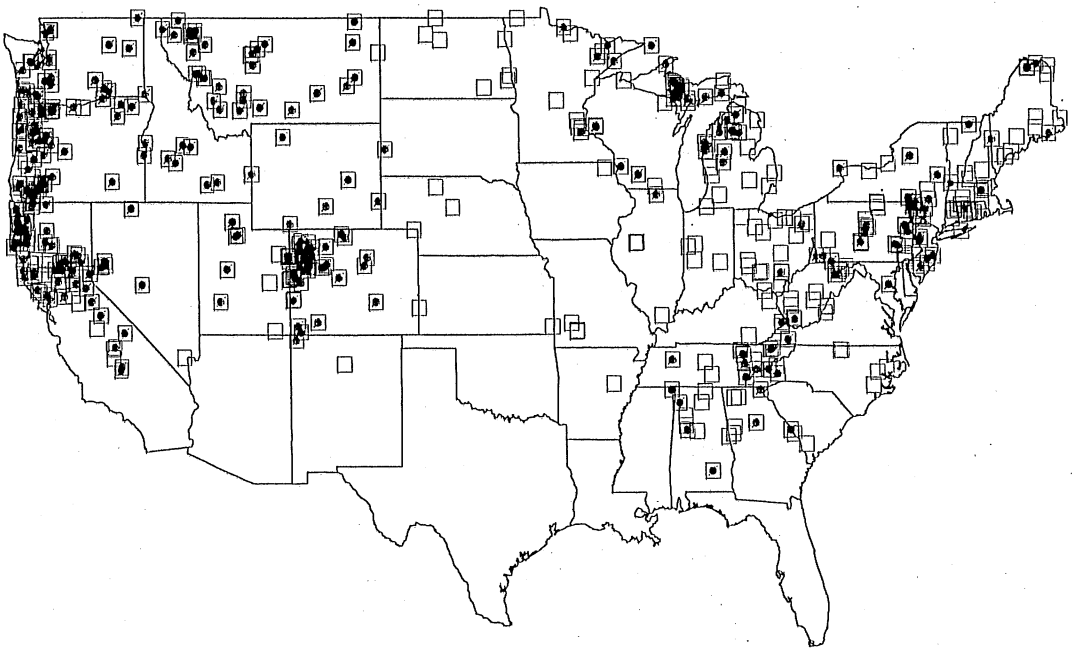
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

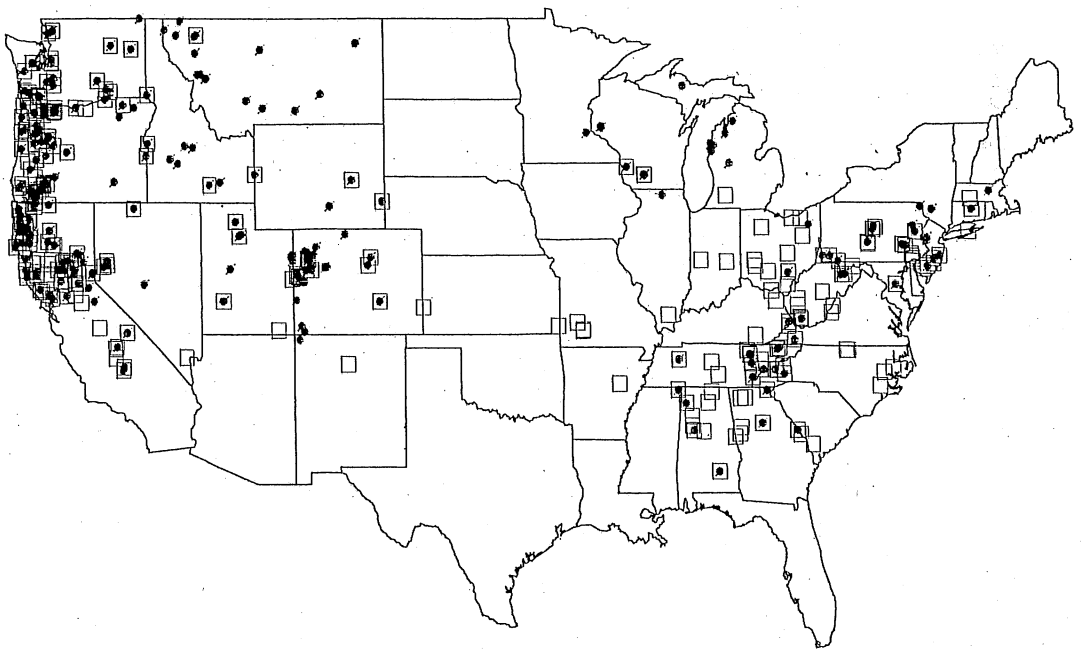
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Mottled sculpin



With 0 °C as the minimum temperature tolerance

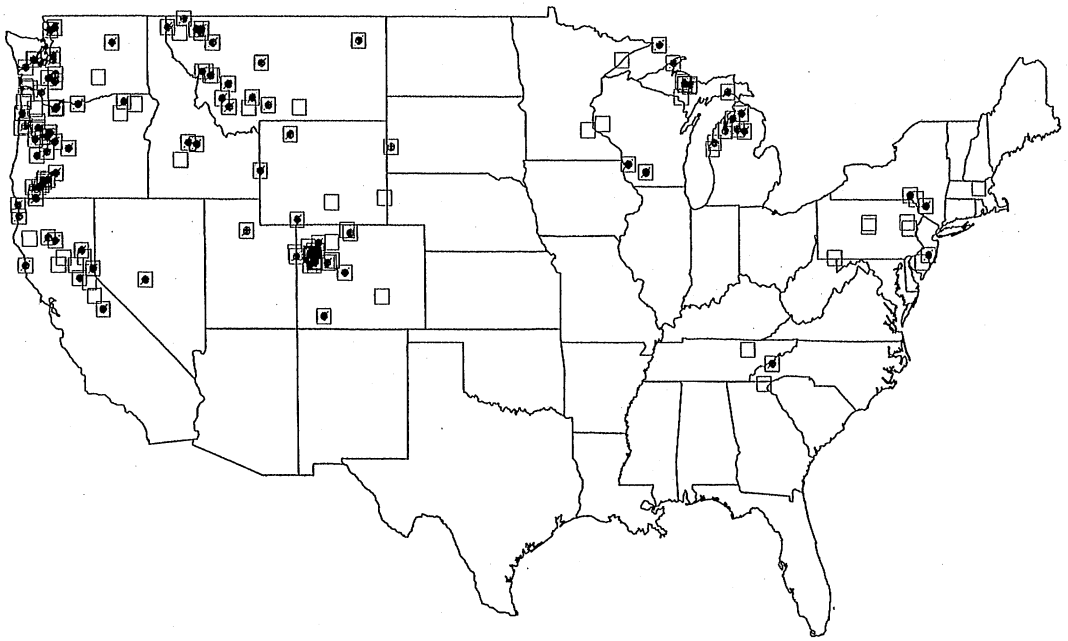
□ $1xCO_2$ Climate Condition
* $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

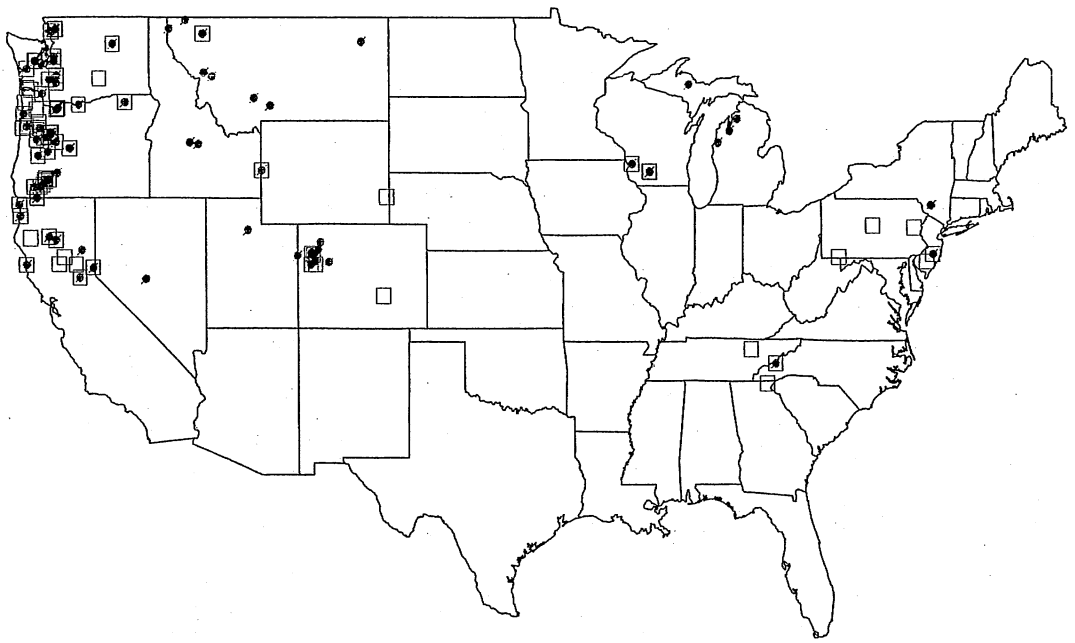
□ $1xCO_2$ Climate Condition
* $2xCO_2$ Climate Condition

Chum salmon



With 0 °C as the minimum temperature tolerance

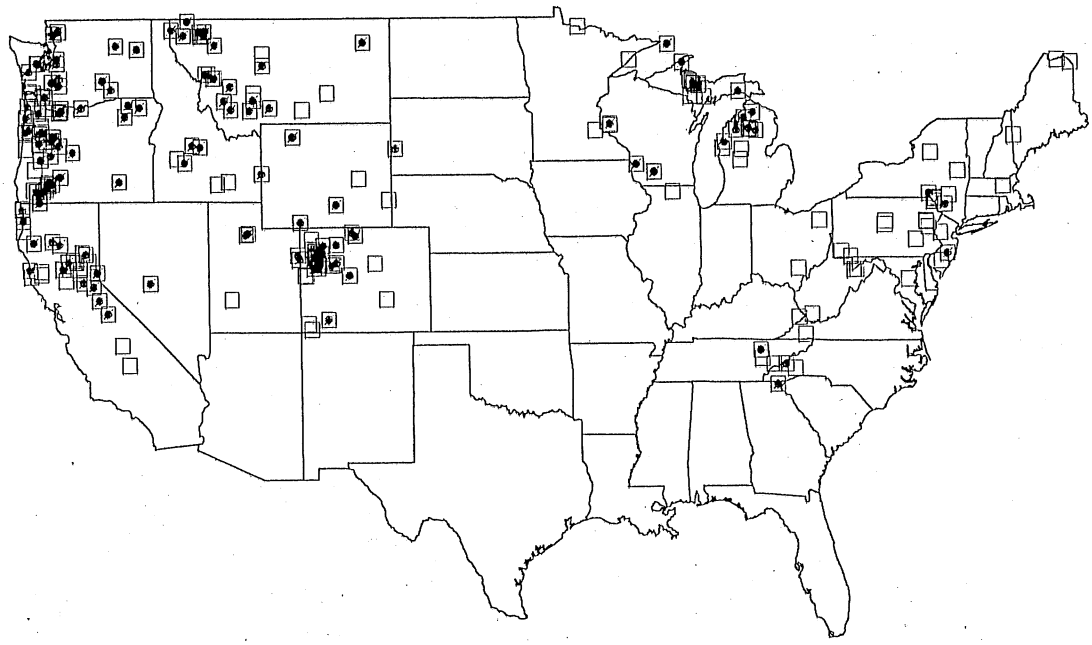
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition



With 2 °C as the minimum temperature tolerance

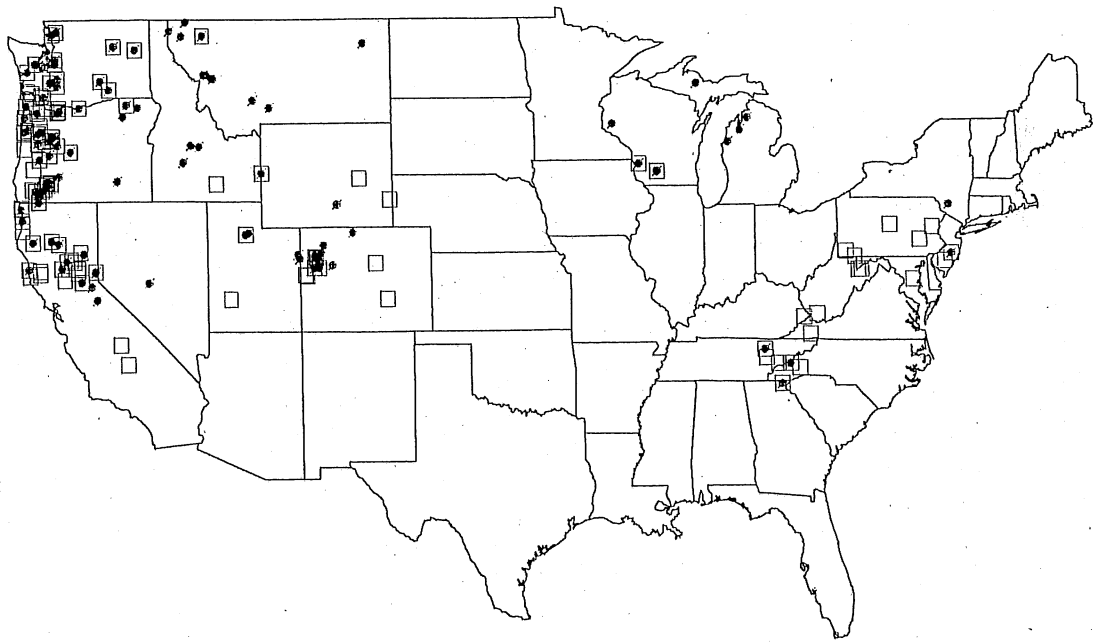
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

Pink salmon



With 0 °C as the minimum temperature tolerance

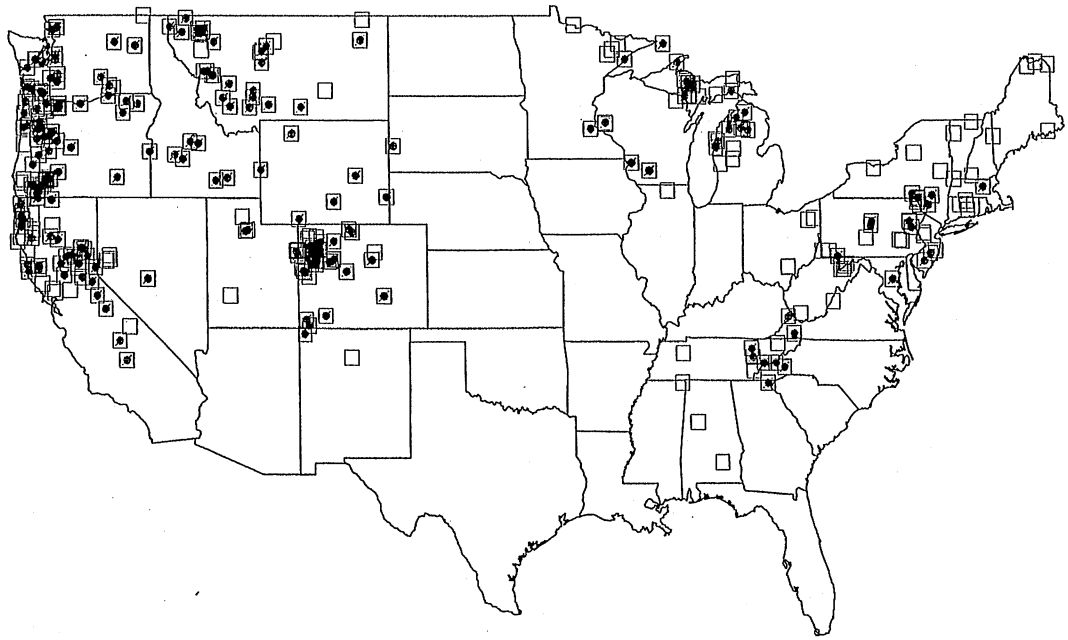
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

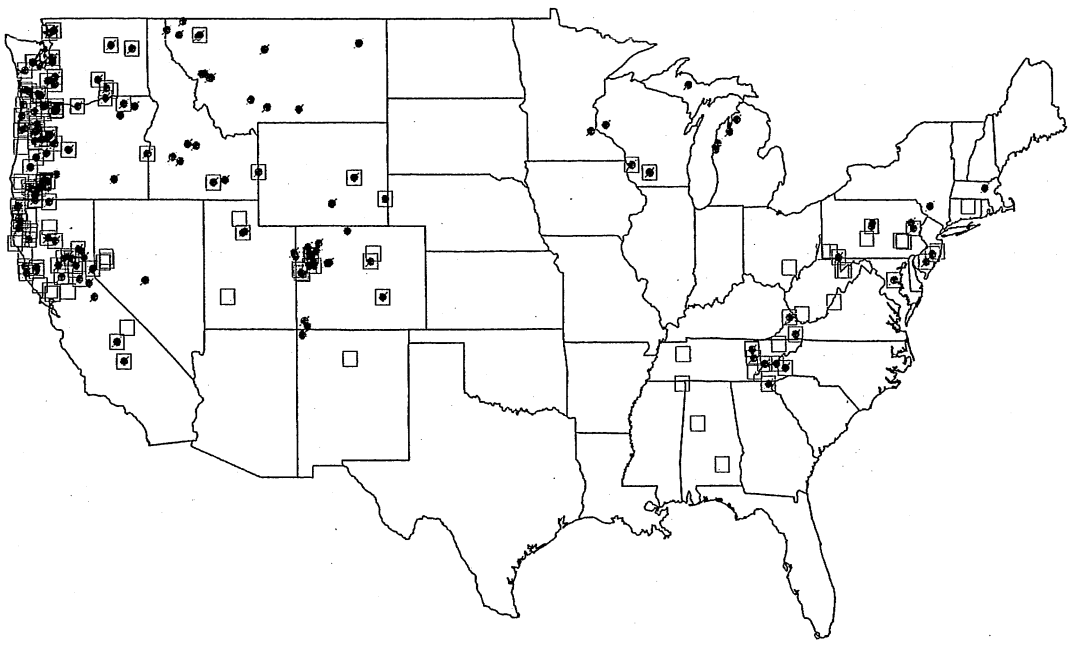
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Brook trout



With 0 °C as the minimum temperature tolerance

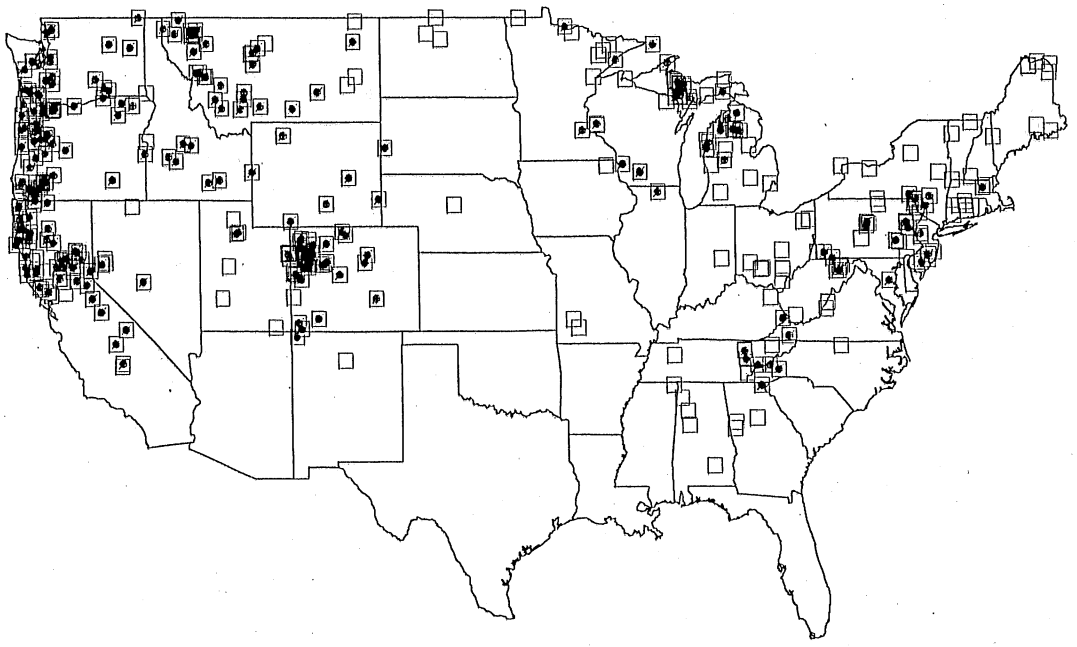
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition



With 2 °C as the minimum temperature tolerance

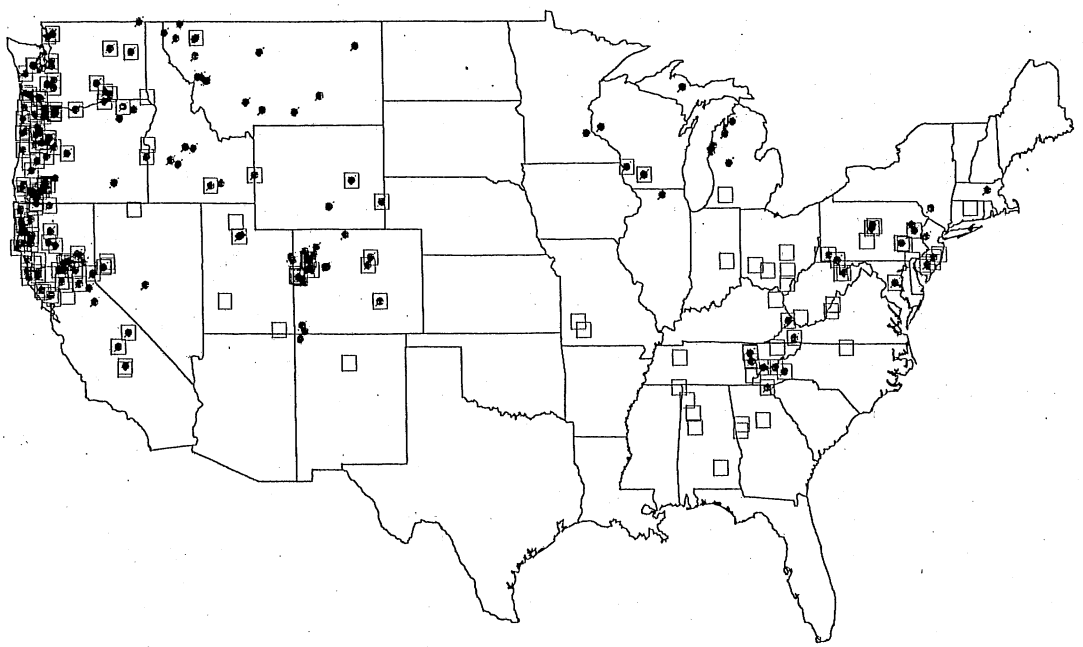
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

Mountain white fish



With 0 °C as the minimum temperature tolerance

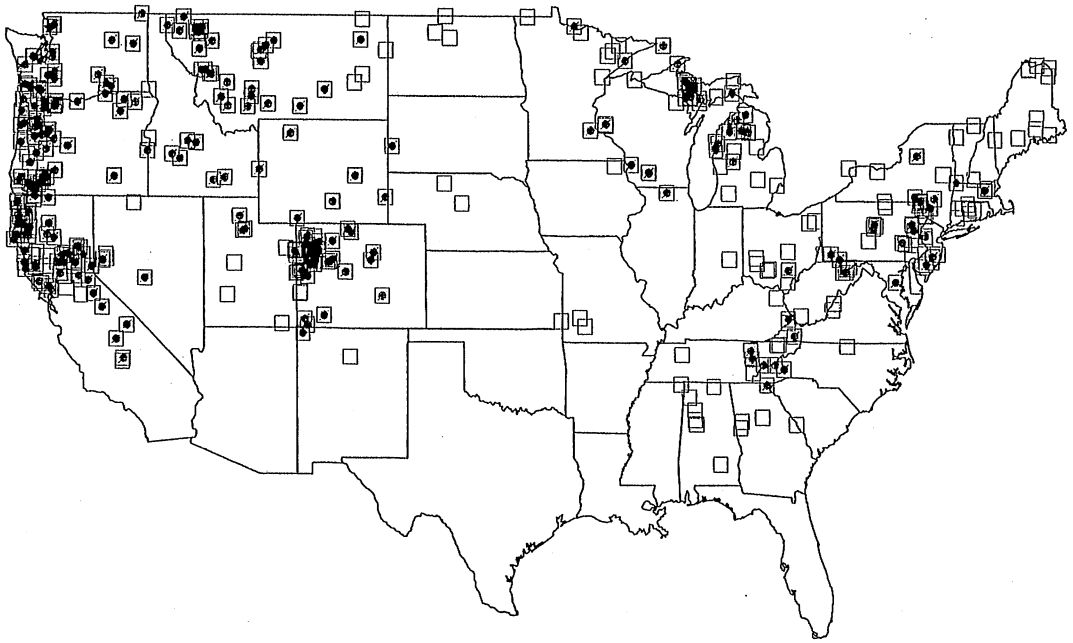
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition



With 2 °C as the minimum temperature tolerance

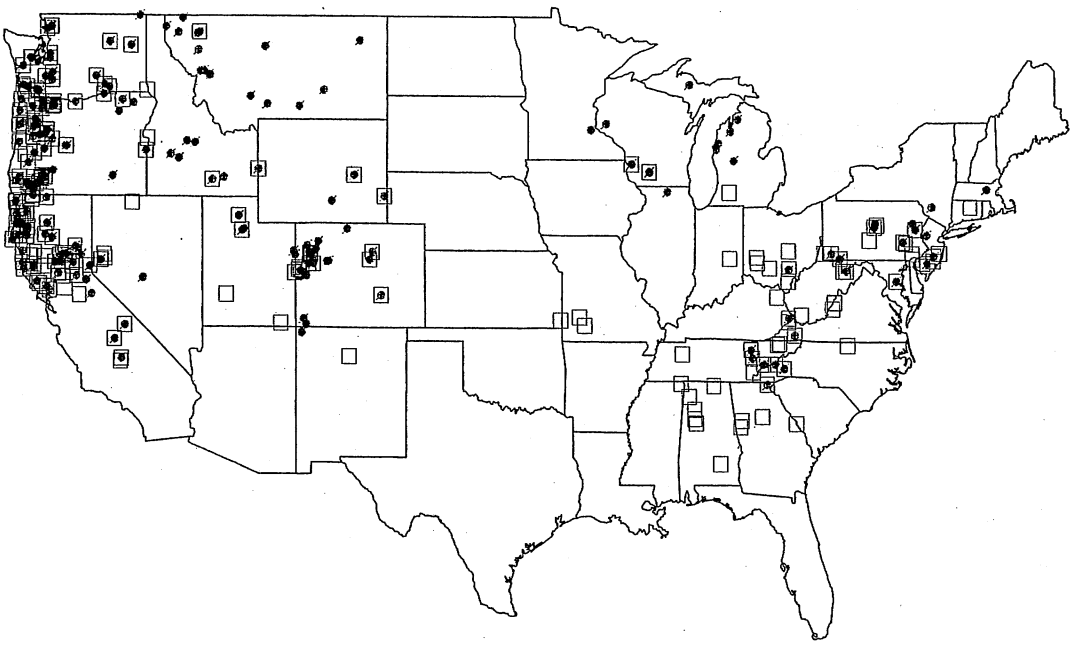
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

Cutthroat trout



With 0 °C as the minimum temperature tolerance

□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

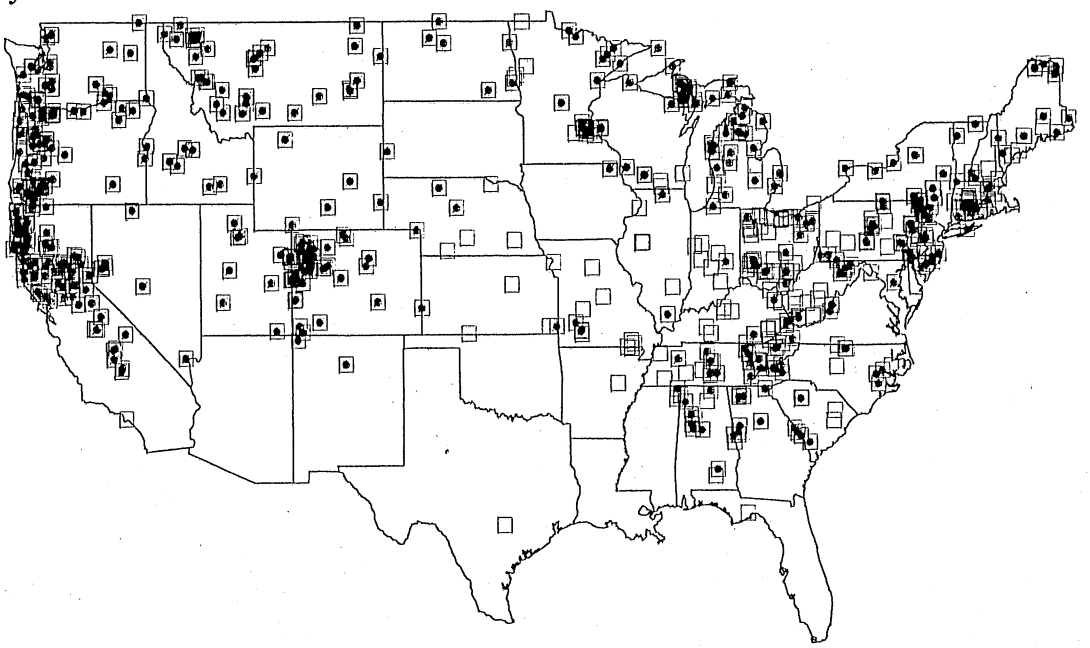


With 2 °C as the minimum temperature tolerance

□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

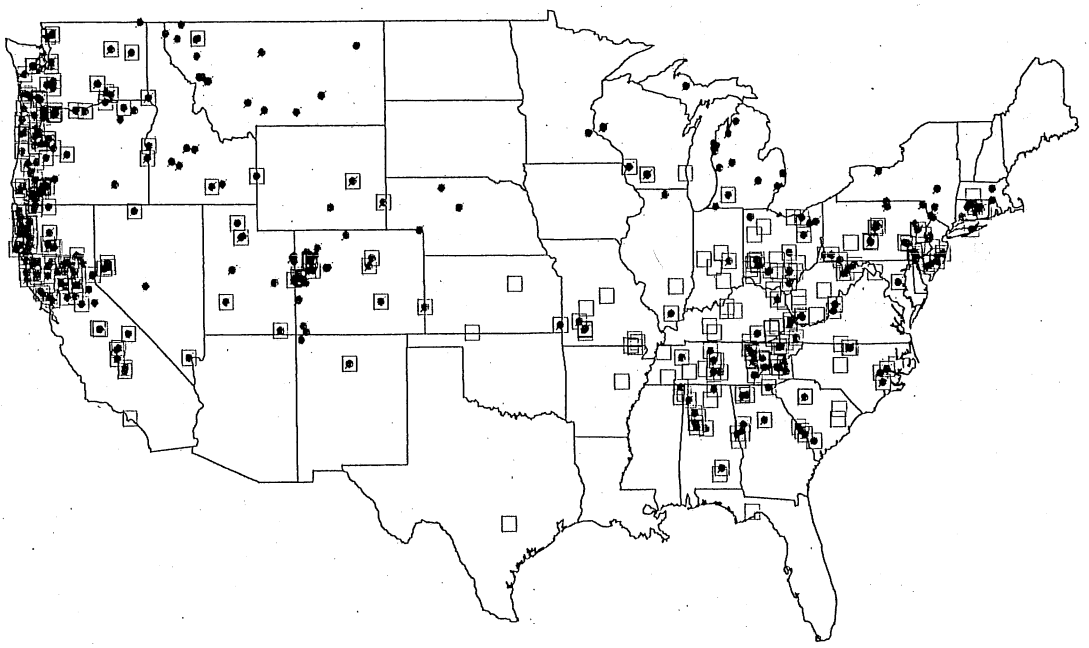
Cool-Water Fishes

Johnny darter



With 0 °C as the minimum temperature tolerance

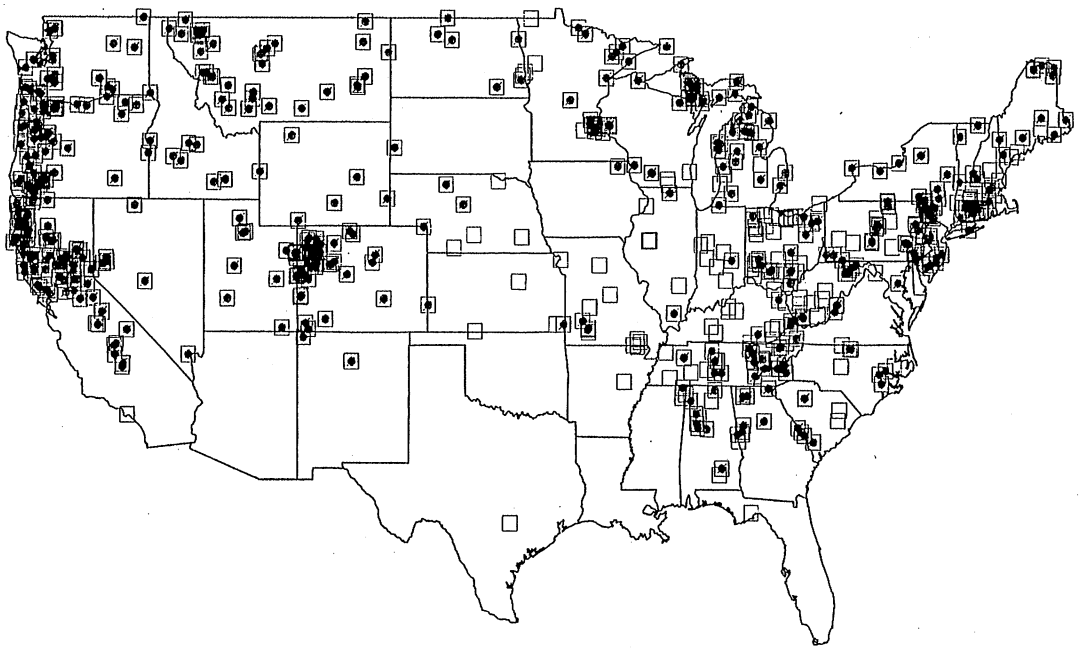
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

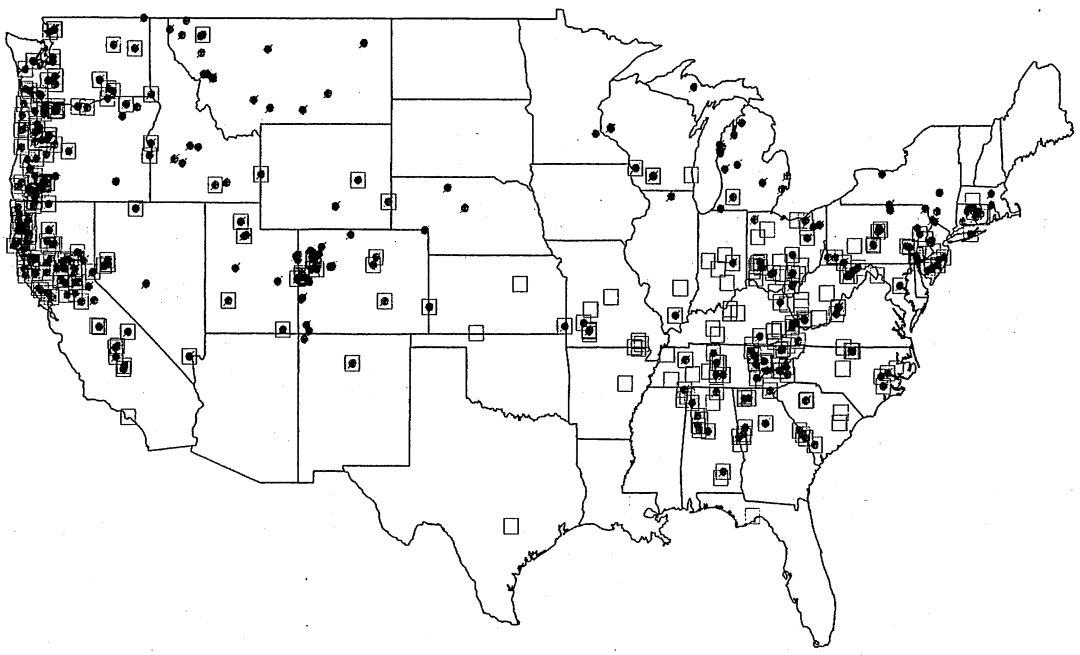
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Longnose dance



With 0 °C as the minimum temperature tolerance

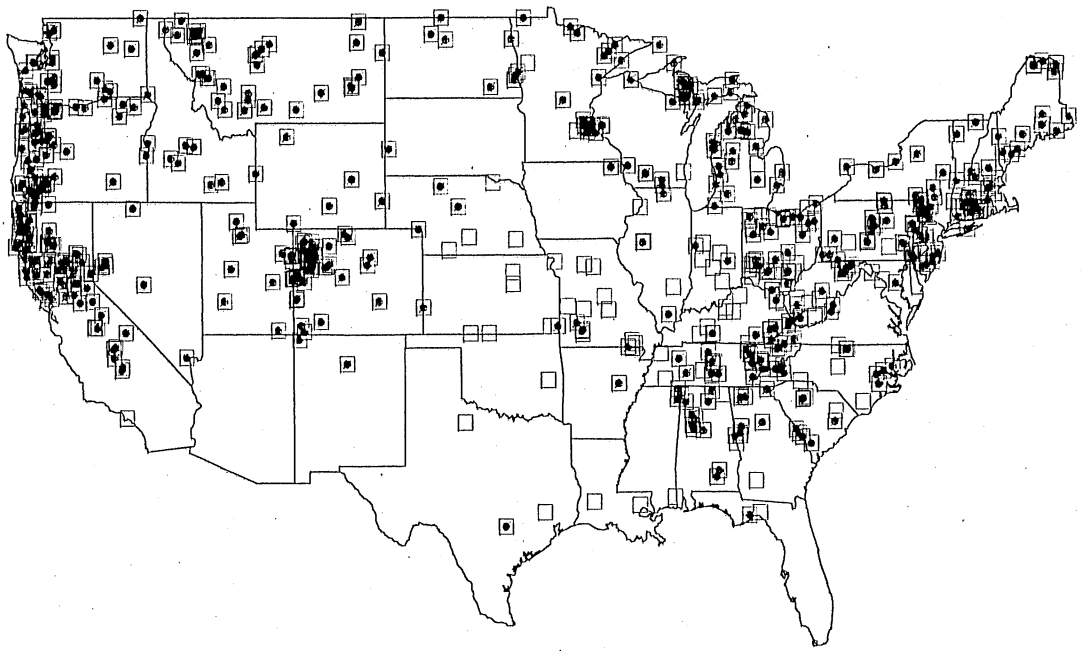
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition



With 2 °C as the minimum temperature tolerance

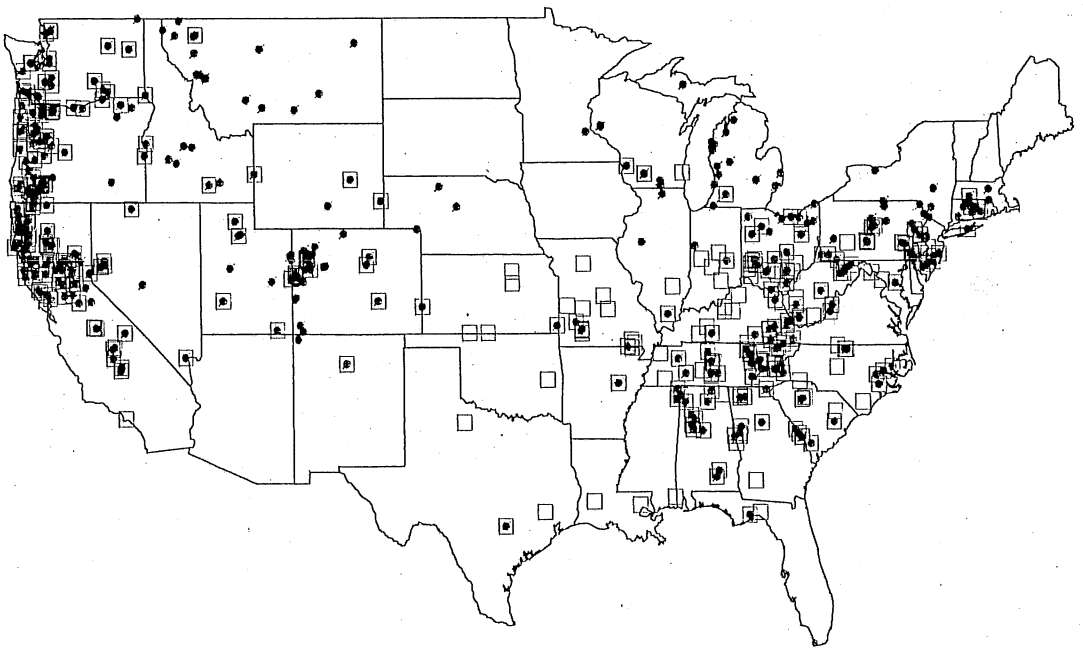
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

Creek chub



With 0 °C as the minimum temperature tolerance

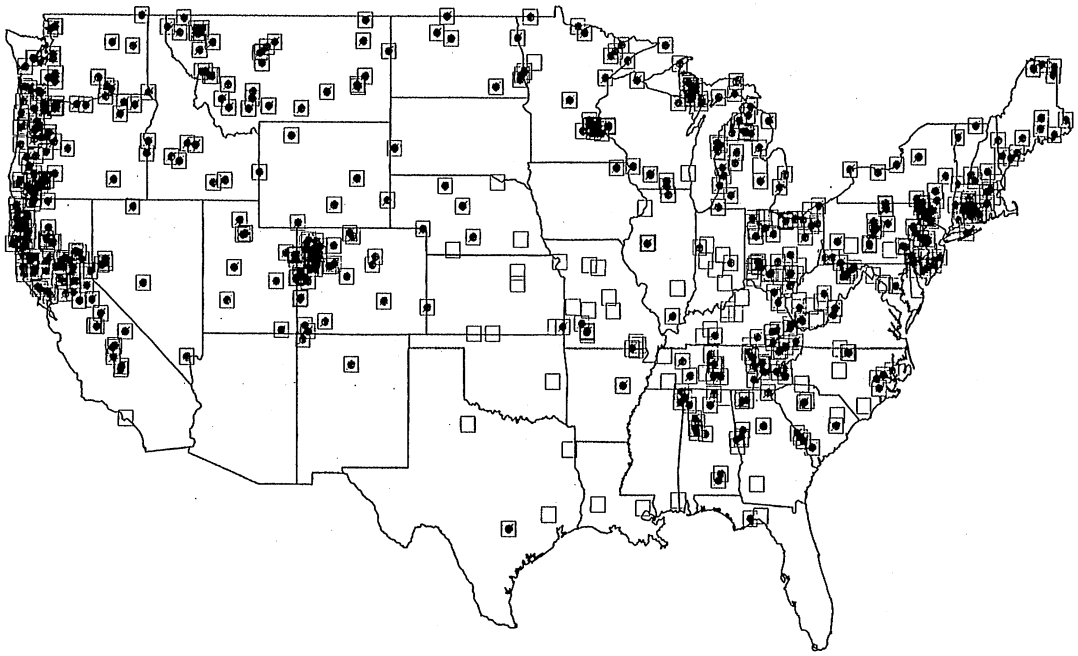
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

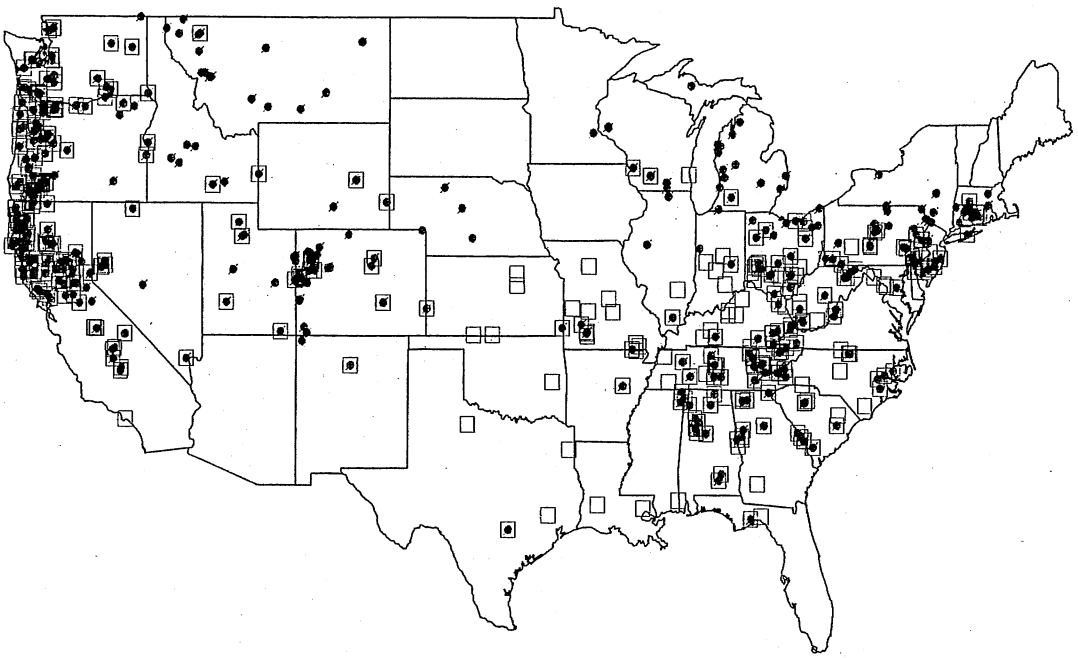
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Blacknose dance



With 0 °C as the minimum temperature tolerance

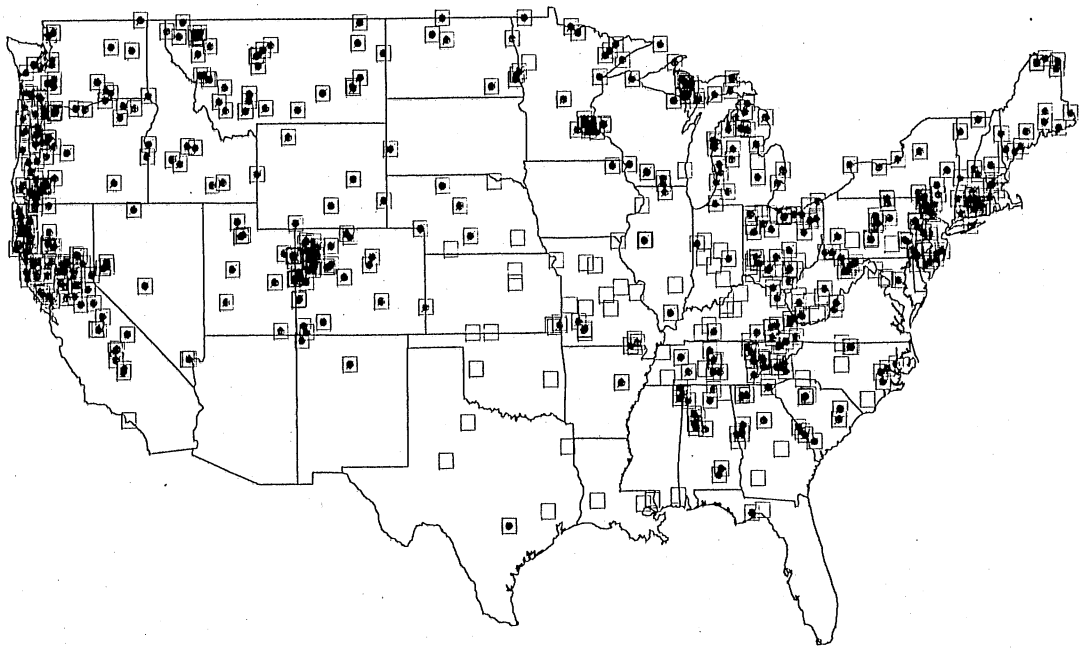
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

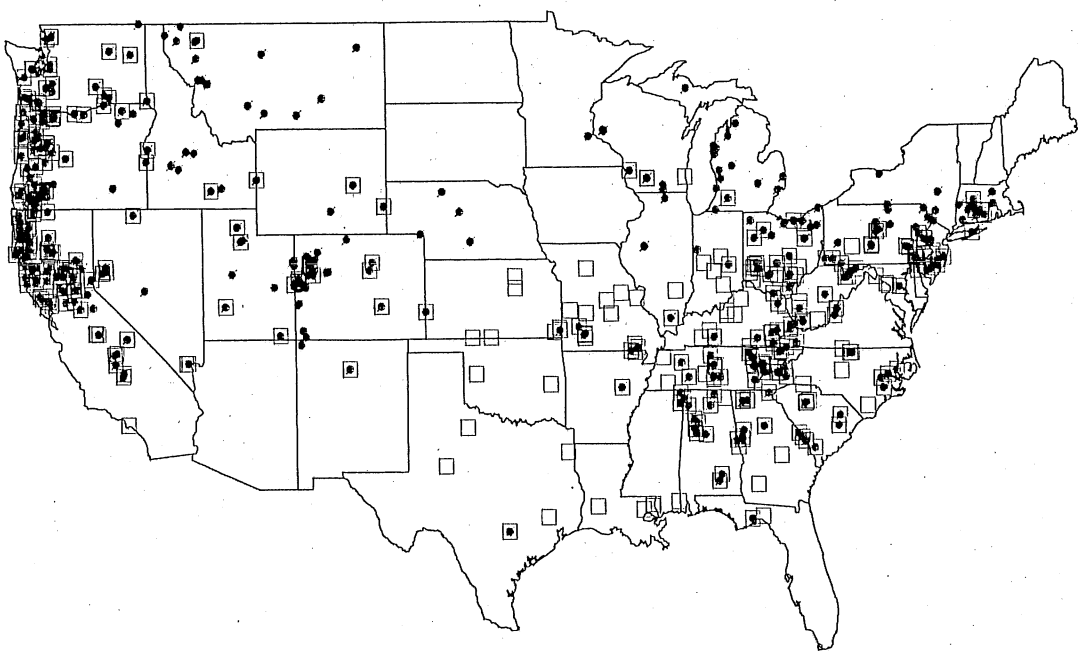
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

White sucker



With 0 °C as the minimum temperature tolerance

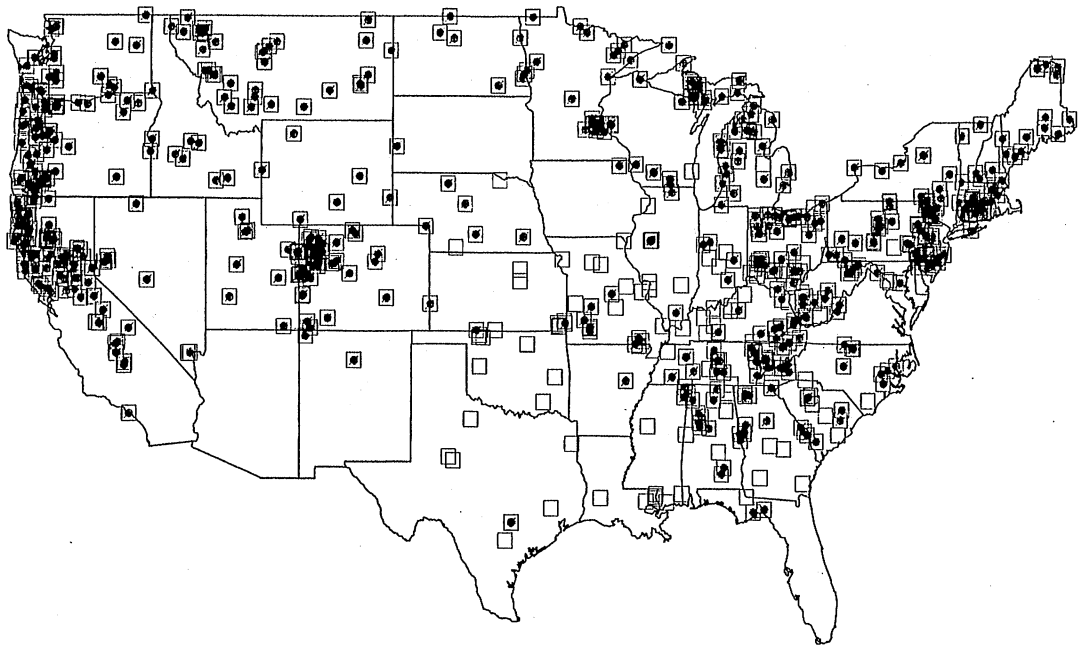
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

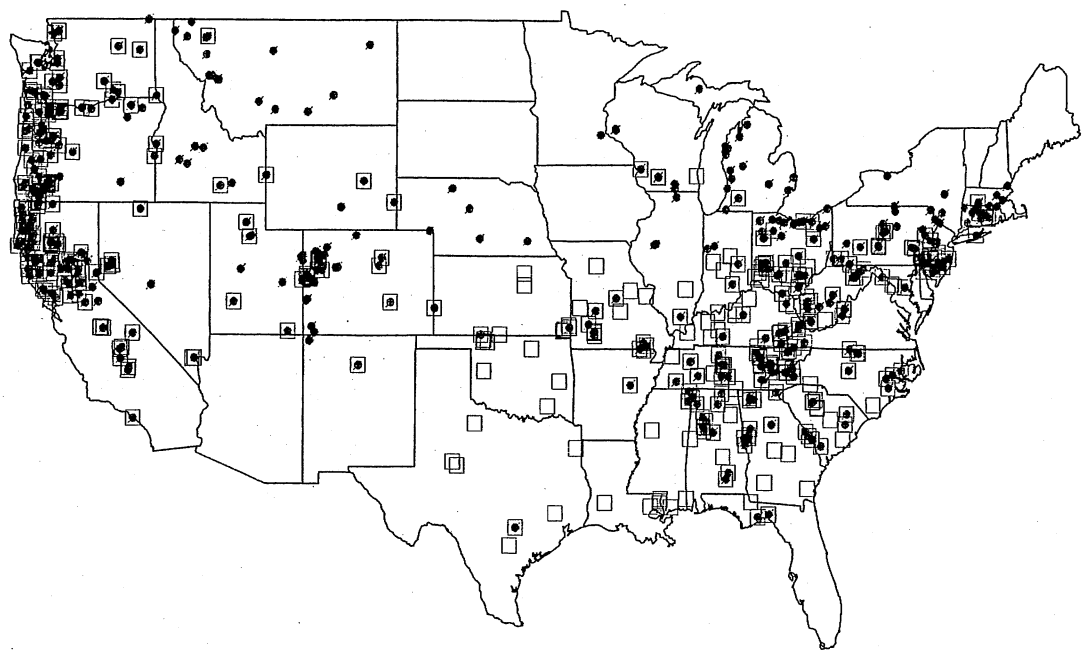
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Northern pike



With 0 °C as the minimum temperature tolerance

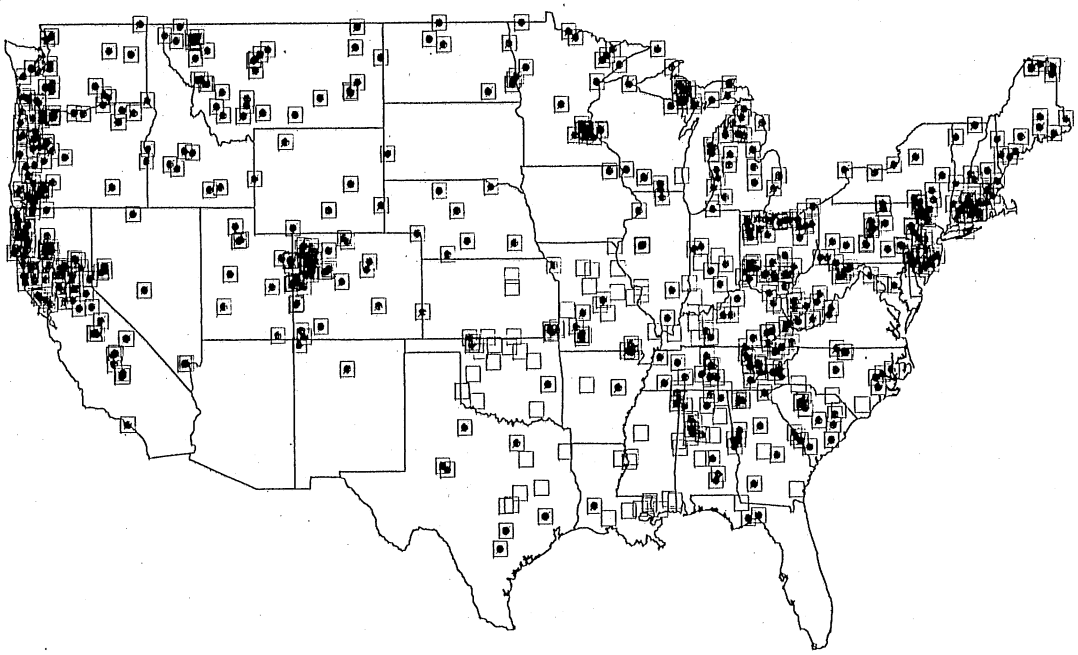
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

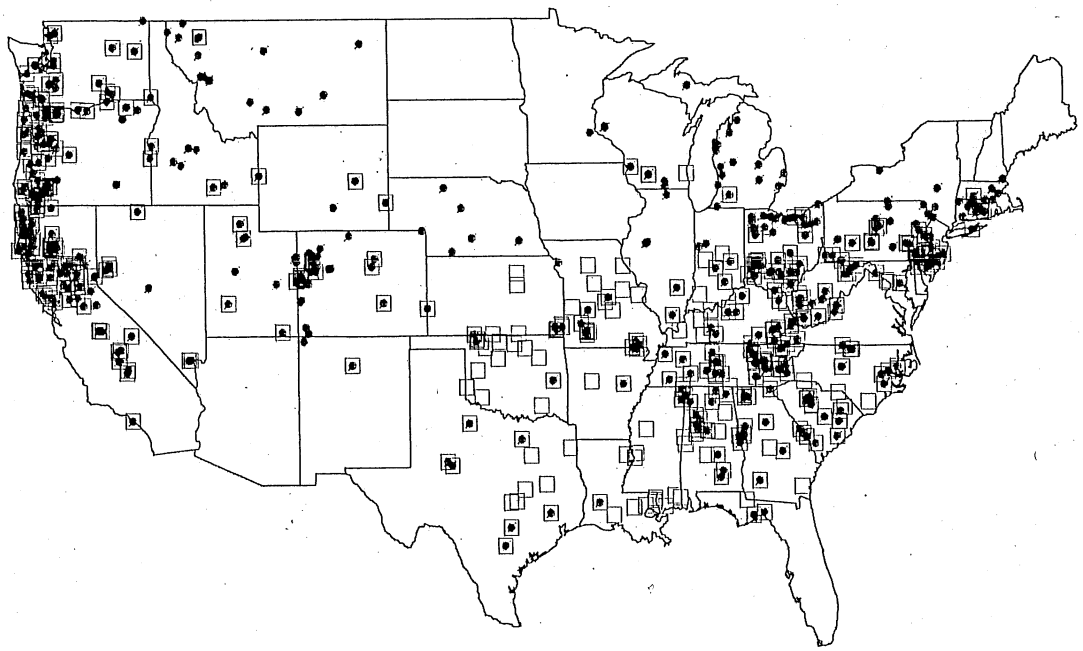
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Walleye



With 0 °C as the minimum temperature tolerance

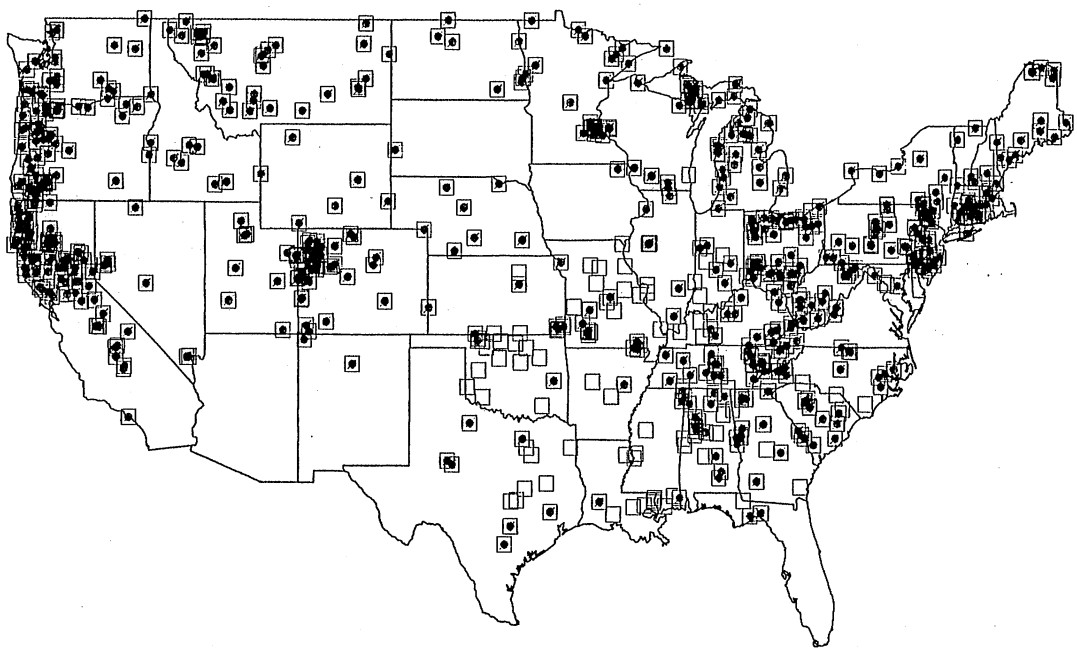
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition



With 2 °C as the minimum temperature tolerance

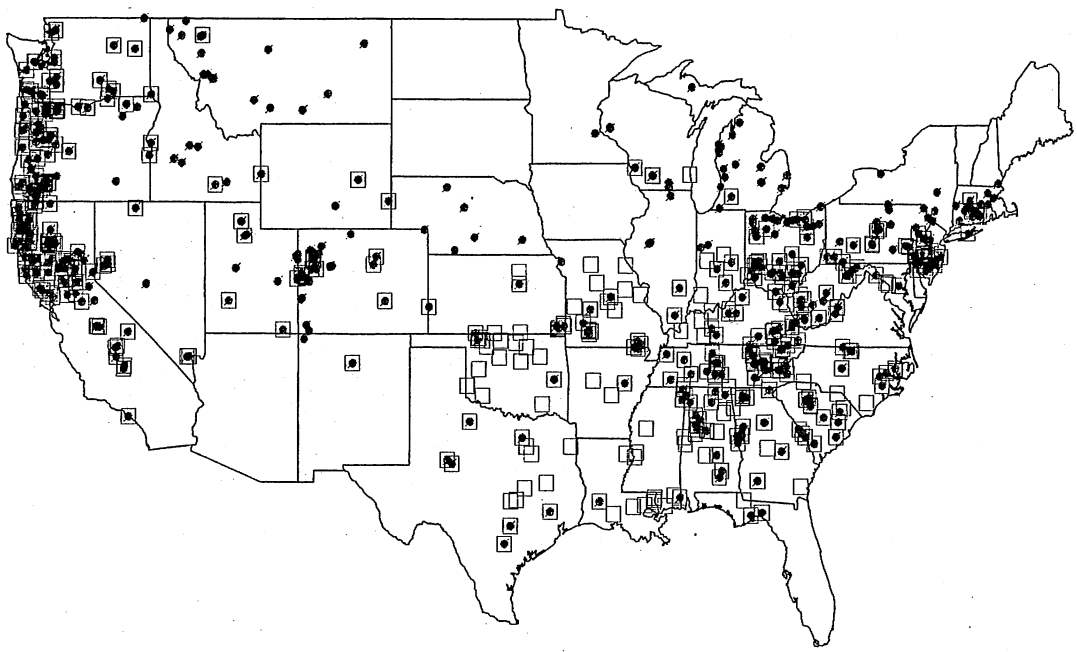
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

Pumpkinseed



With 0 °C as the minimum temperature tolerance

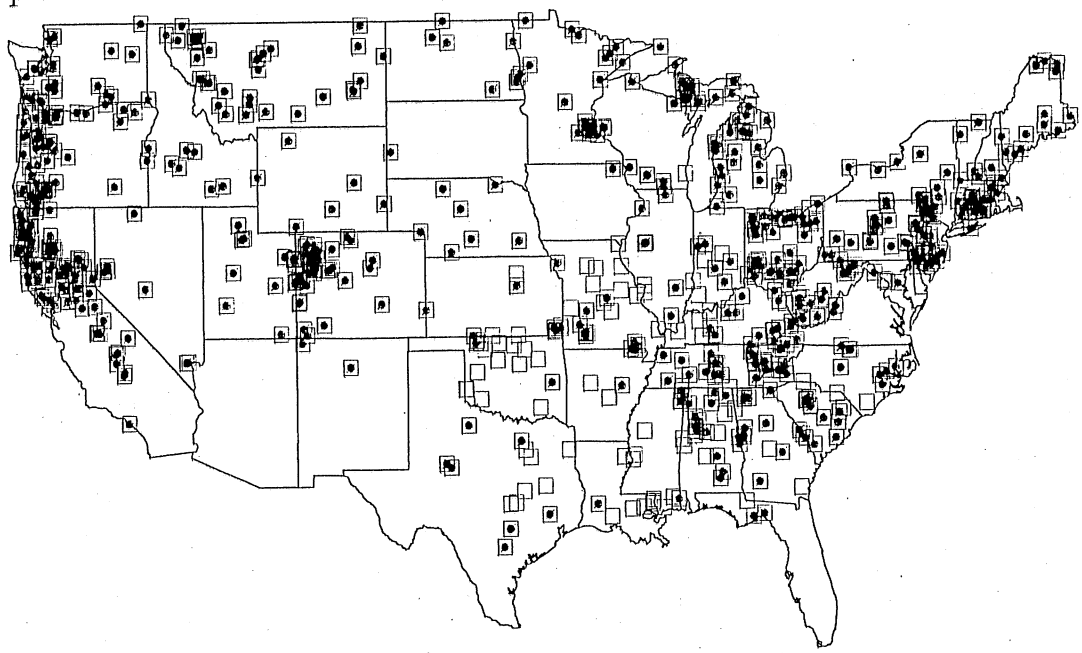
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

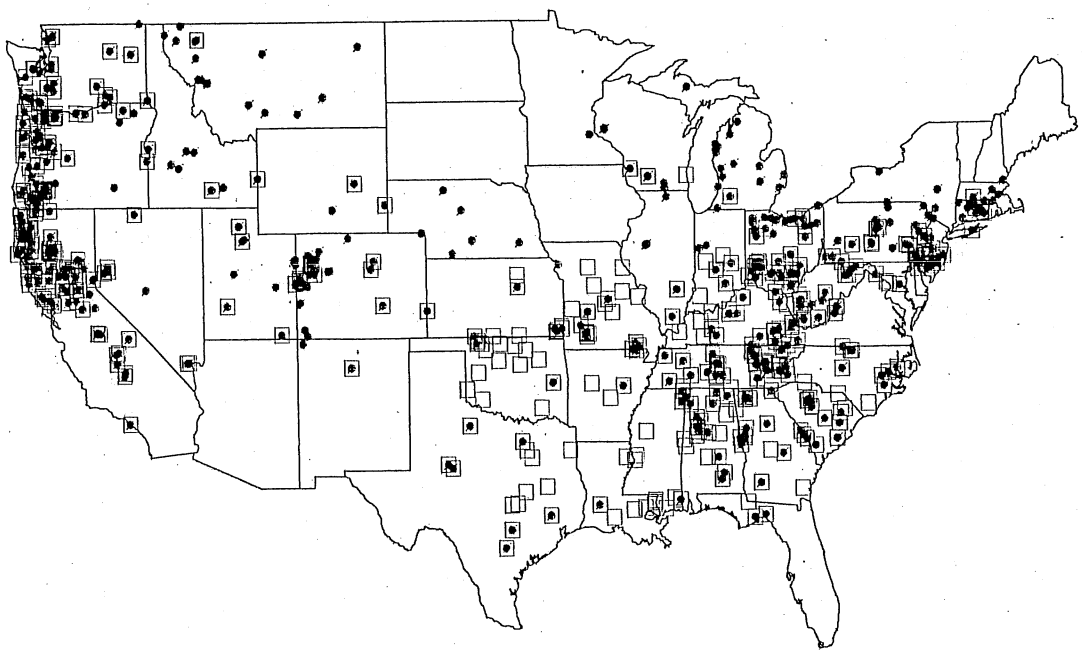
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Yellow perch



With 0 °C as the minimum temperature tolerance

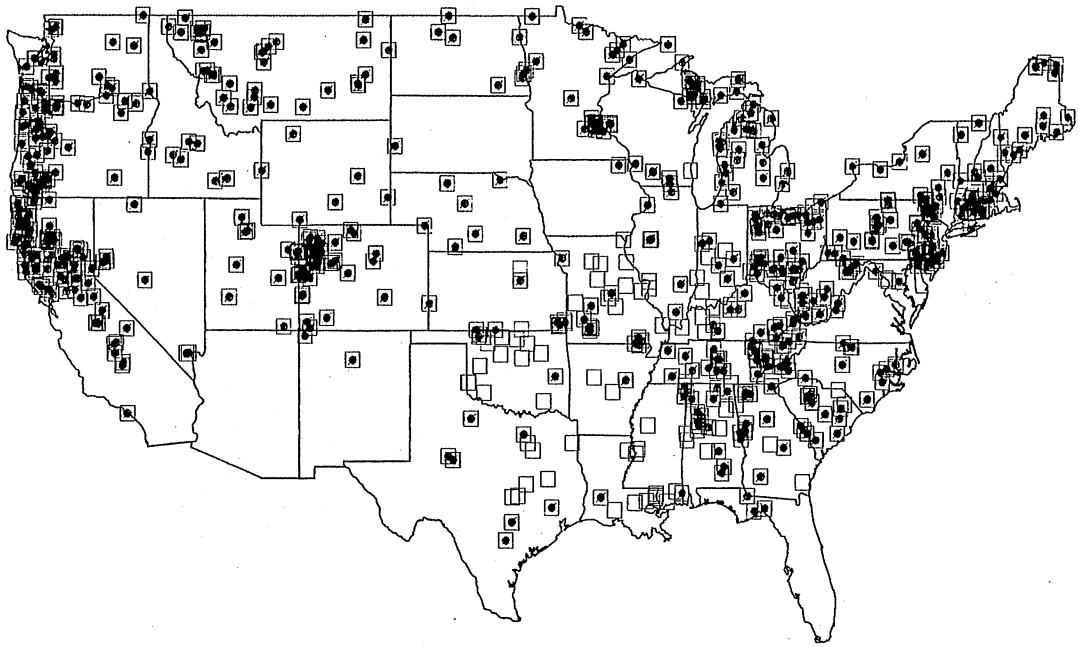
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

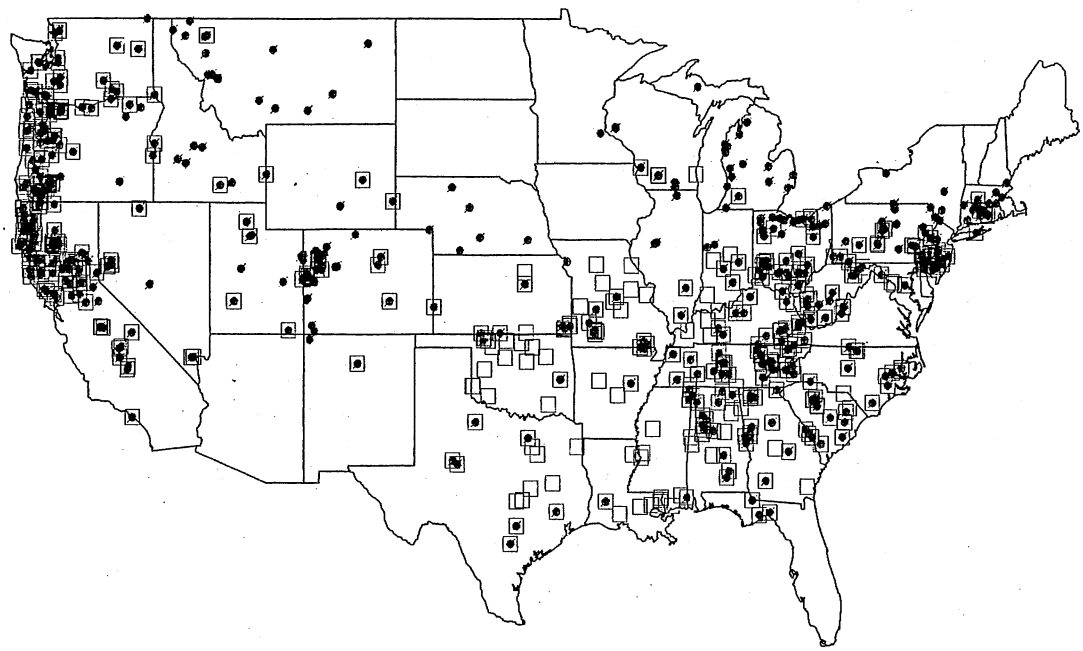
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Common shiner



With 0 °C as the minimum temperature tolerance

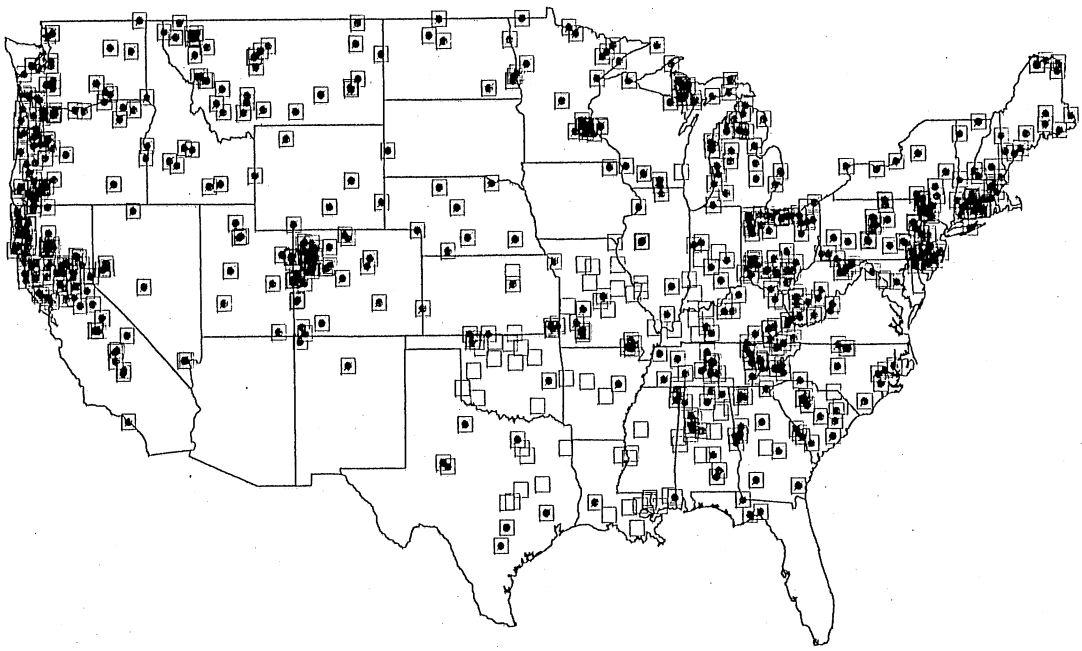
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

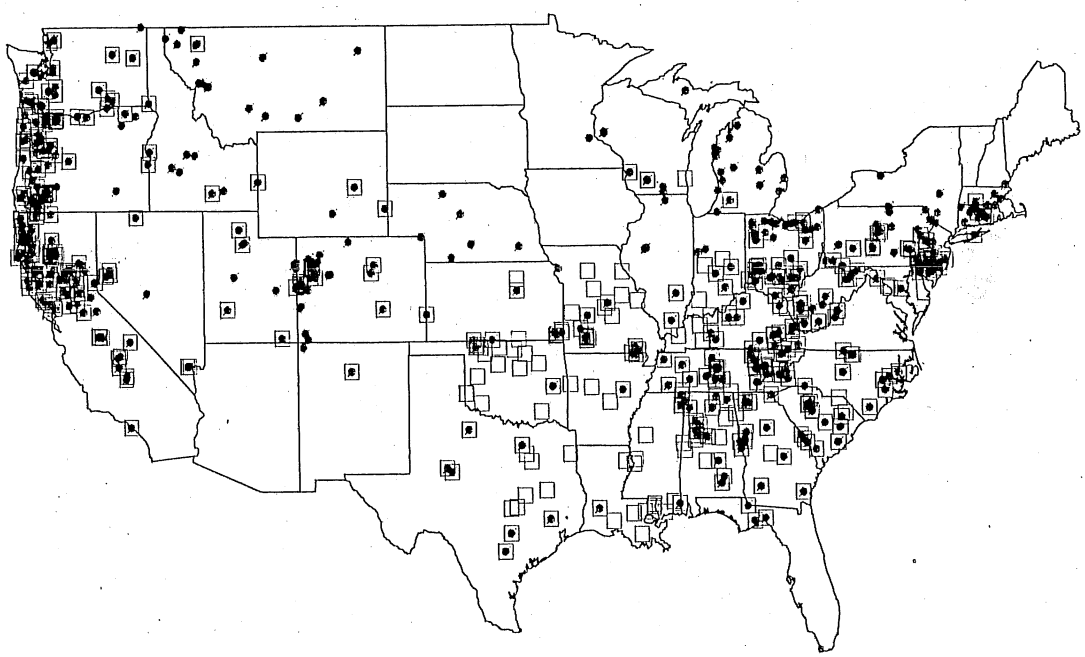
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Rock bass



With 0 °C as the minimum temperature tolerance

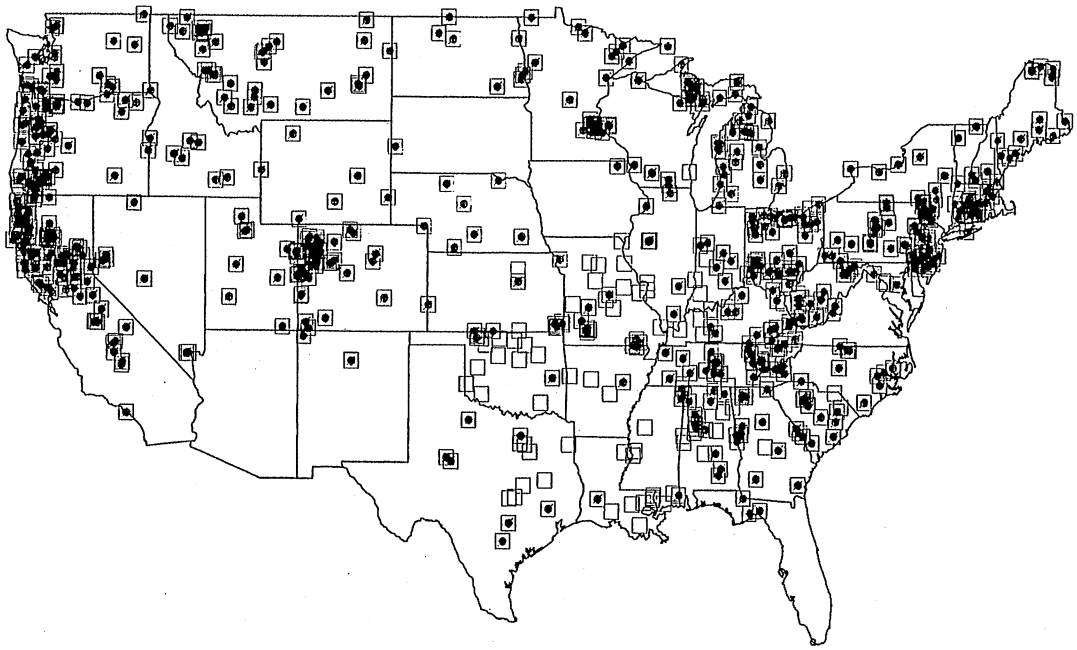
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

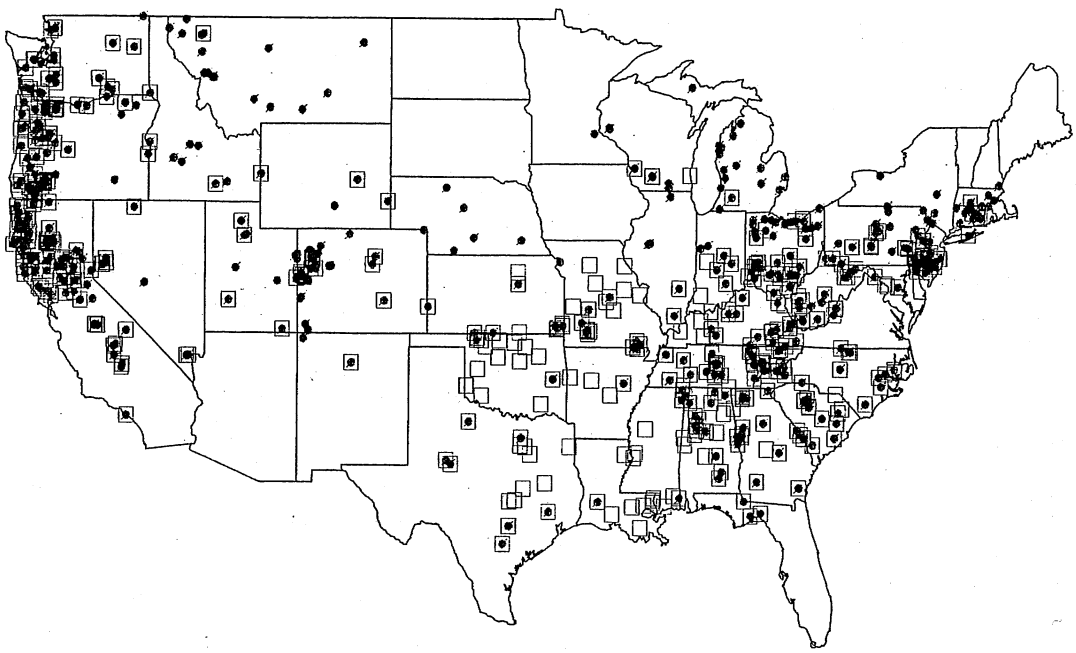
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Brown bullhead



With 0 °C as the minimum temperature tolerance

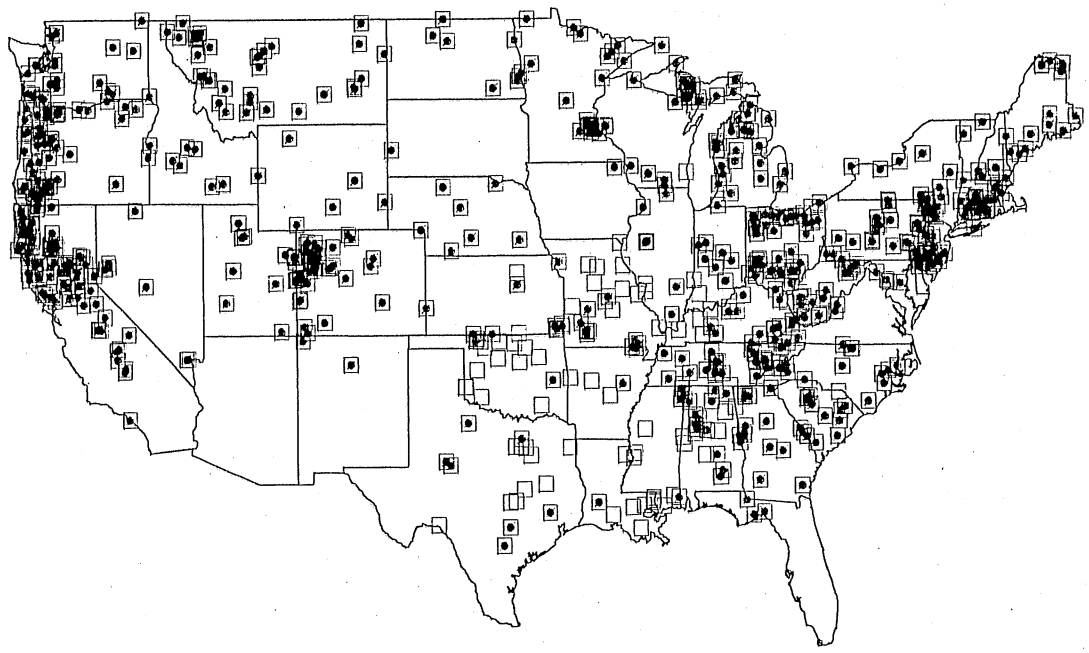
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

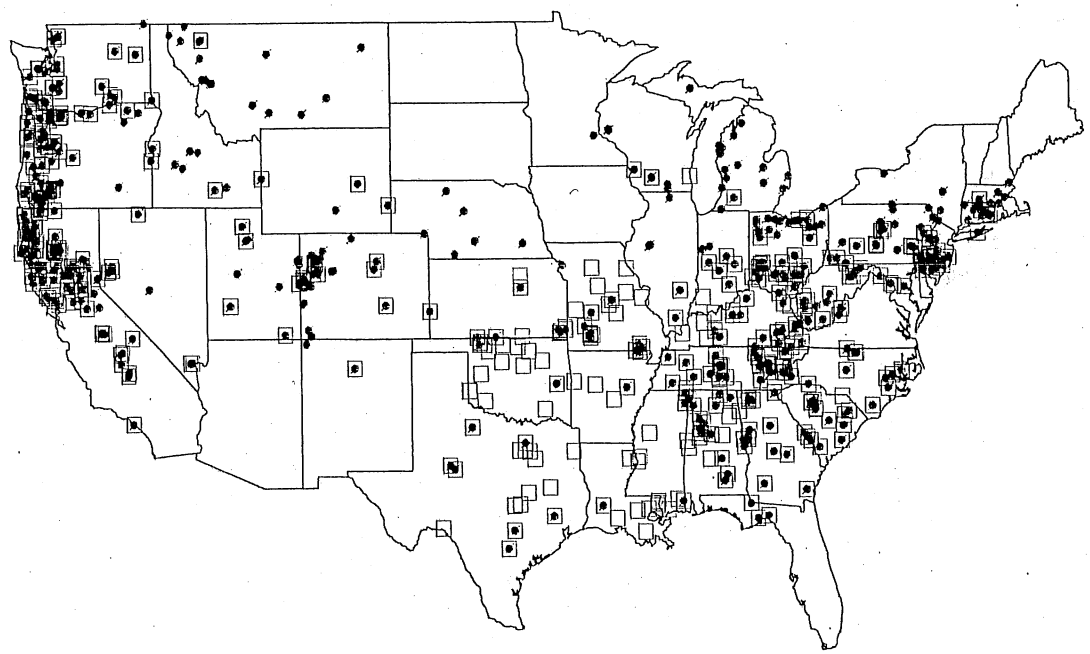
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Smallmouth bass



With 0 °C as the minimum temperature tolerance

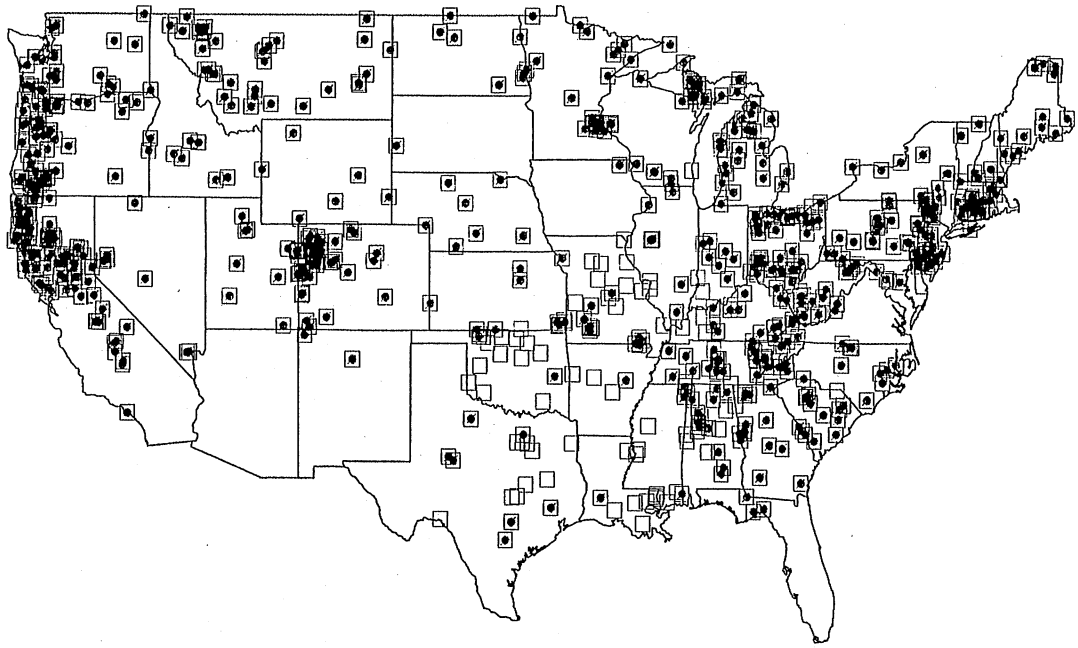
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

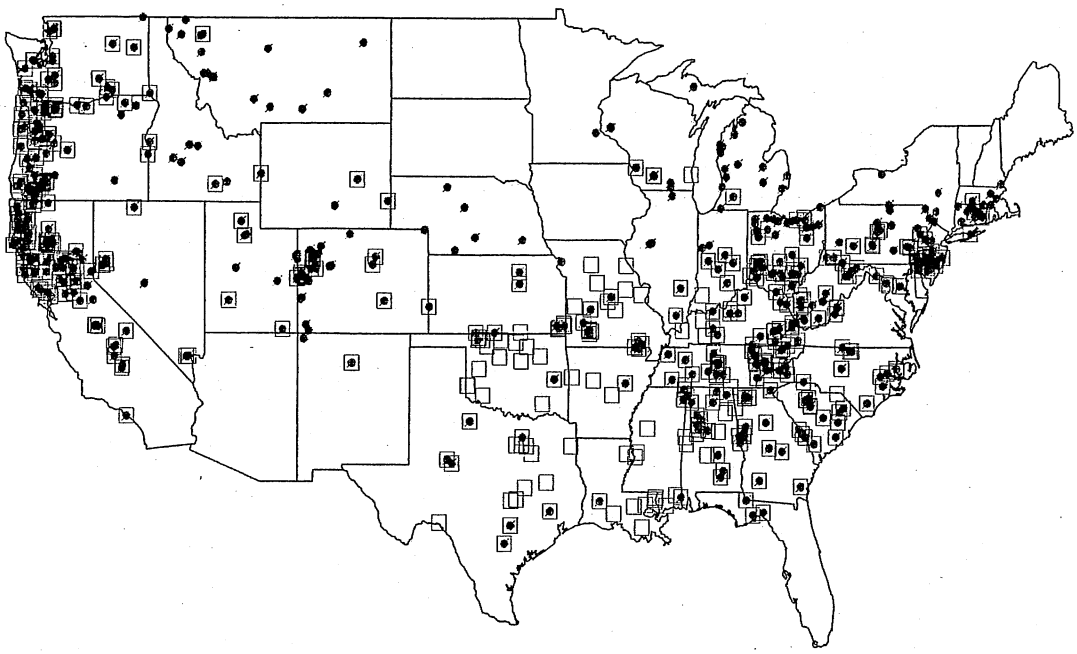
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Golden redhorse



With 0 °C as the minimum temperature tolerance

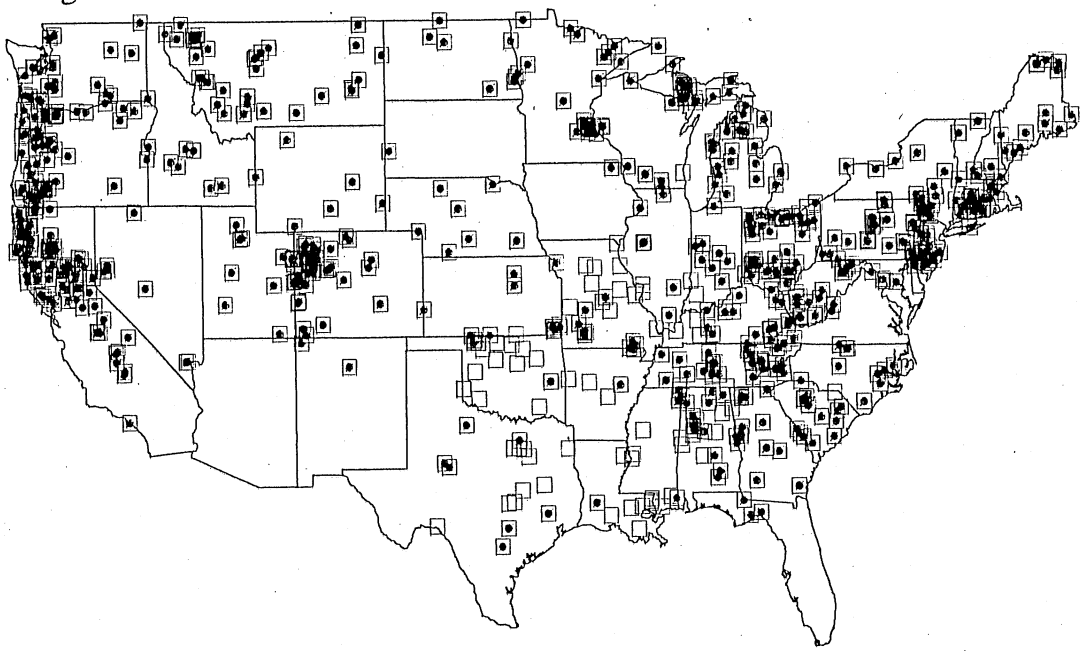
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

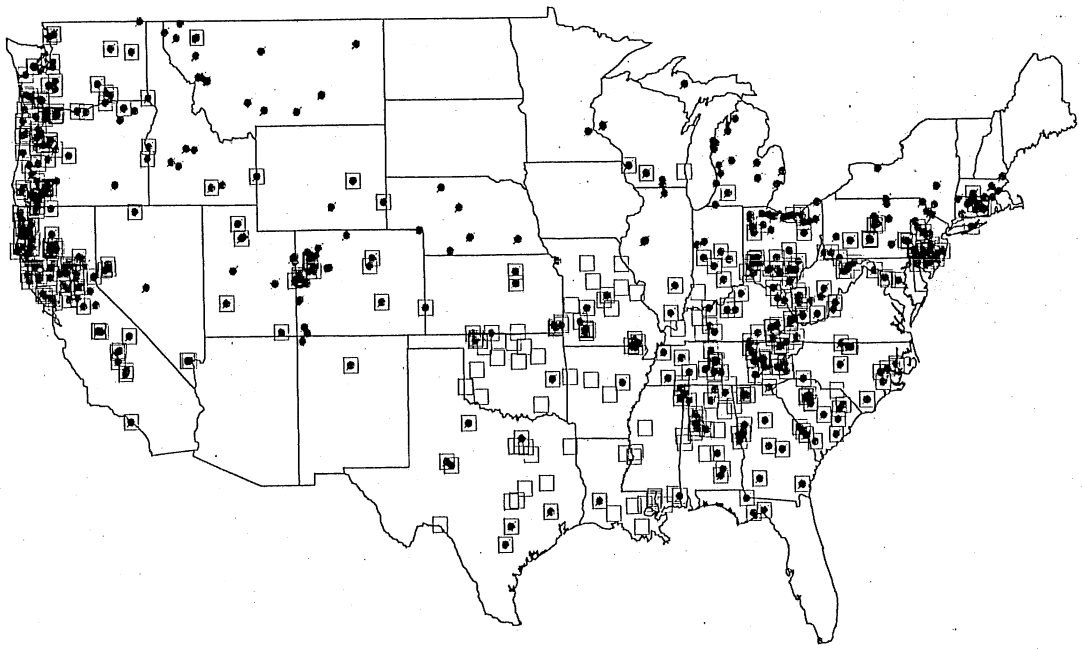
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Northern hog sucker



With 0 °C as the minimum temperature tolerance

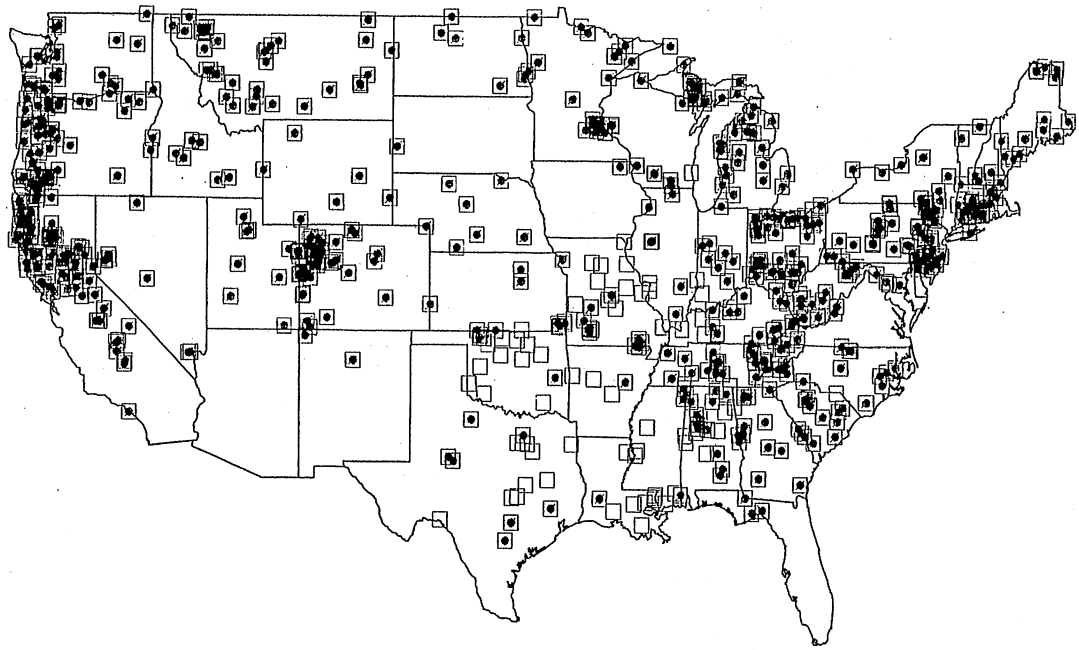
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

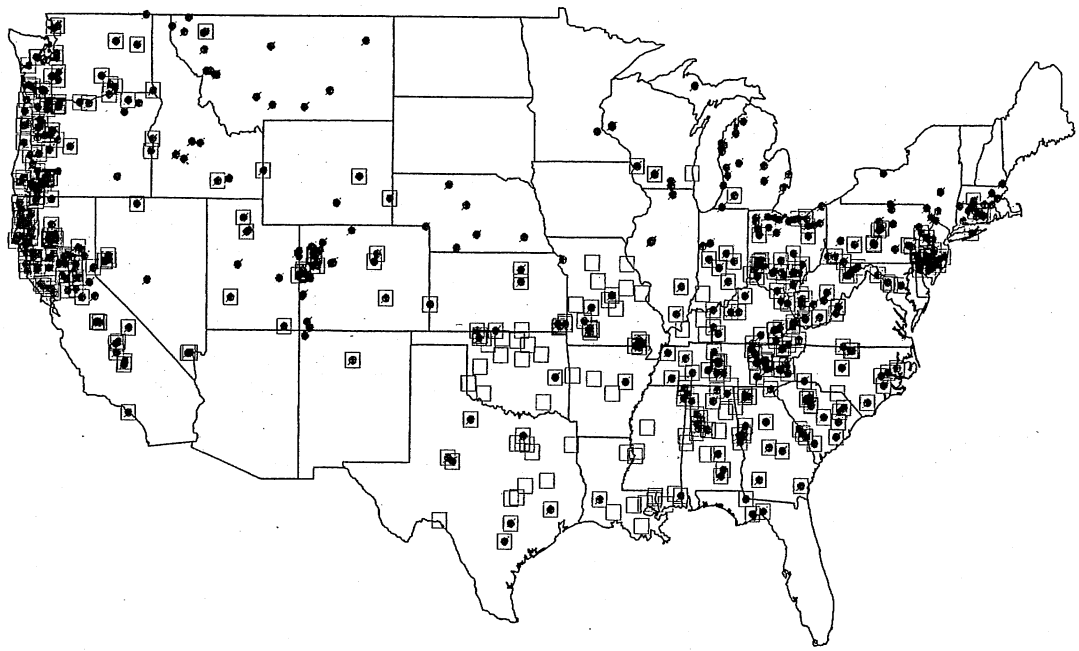
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Silver red horse



With 0 °C as the minimum temperature tolerance

□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

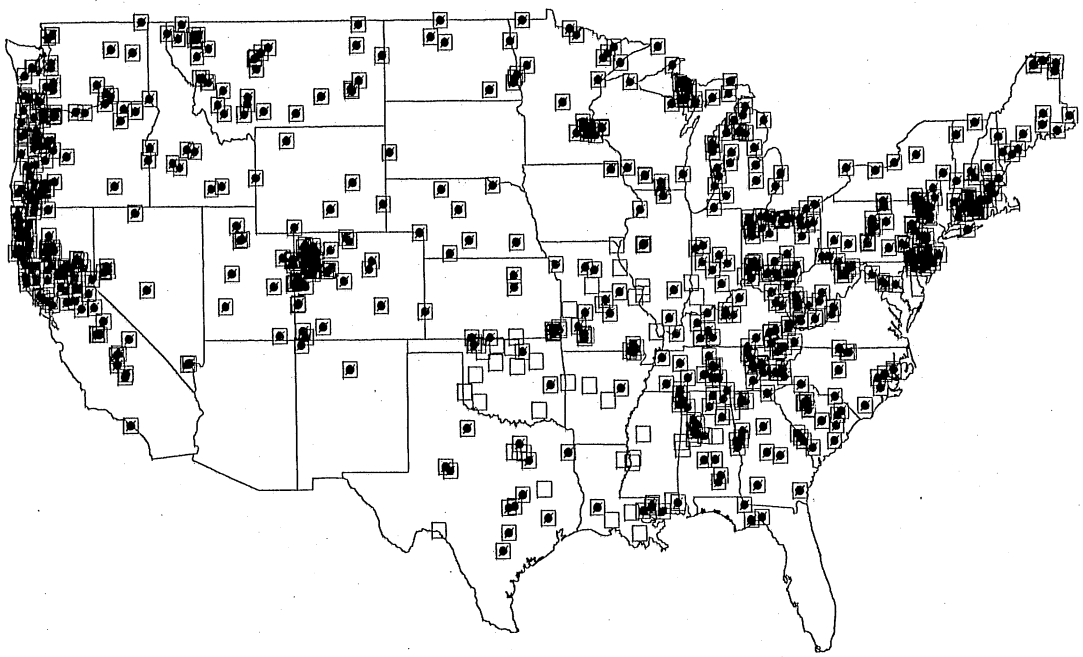


With 2 °C as the minimum temperature tolerance

□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

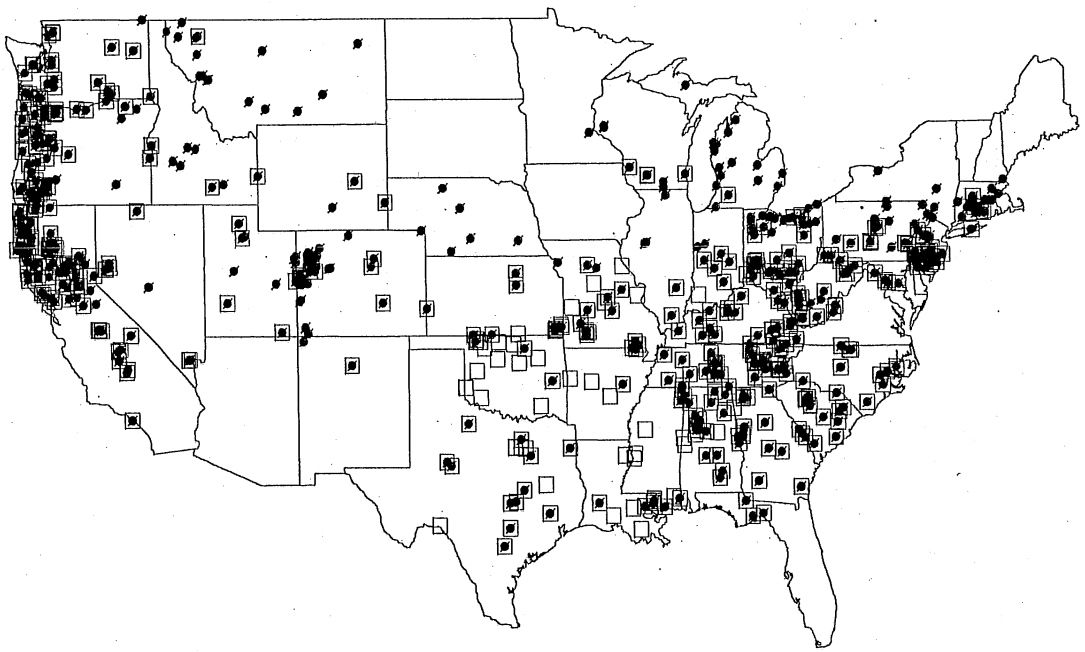
Warm-Water Fishes

Bluntnose Minnow



With 0 °C as the minimum temperature tolerance

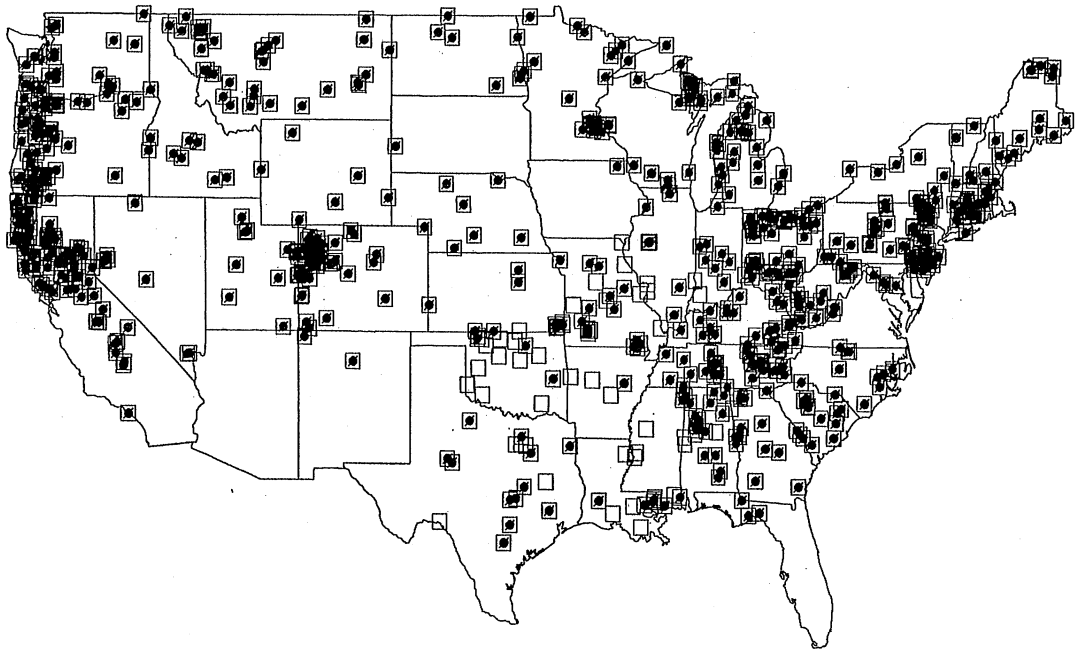
□ $1xCO_2$ Climate Condition
▪ $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

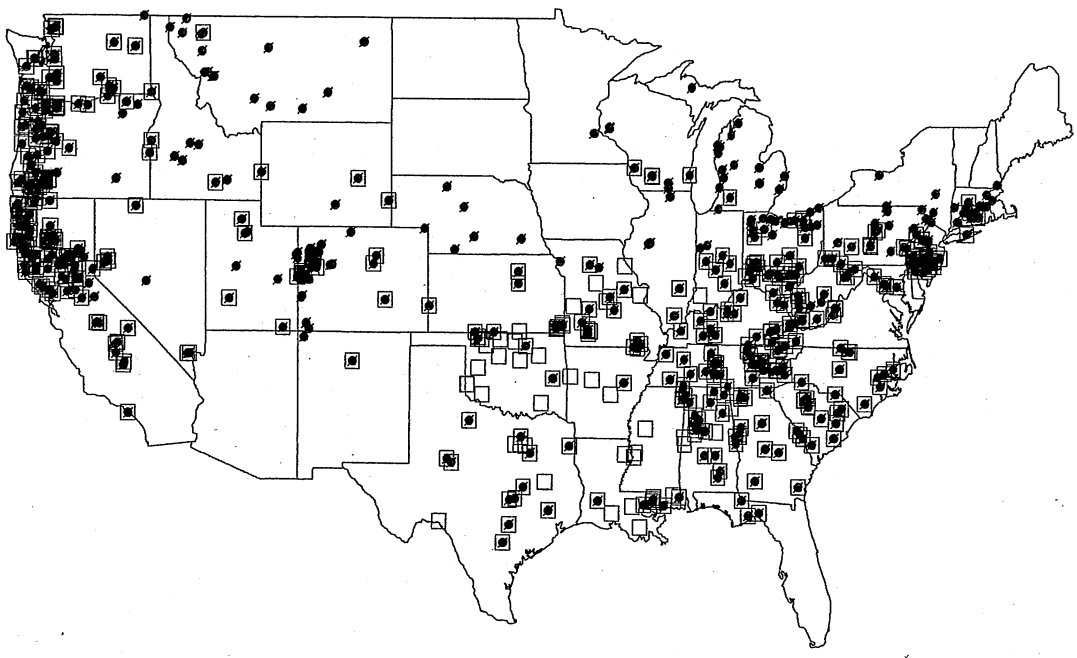
□ $1xCO_2$ Climate Condition
▪ $2xCO_2$ Climate Condition

Sauger



With 0 °C as the minimum temperature tolerance

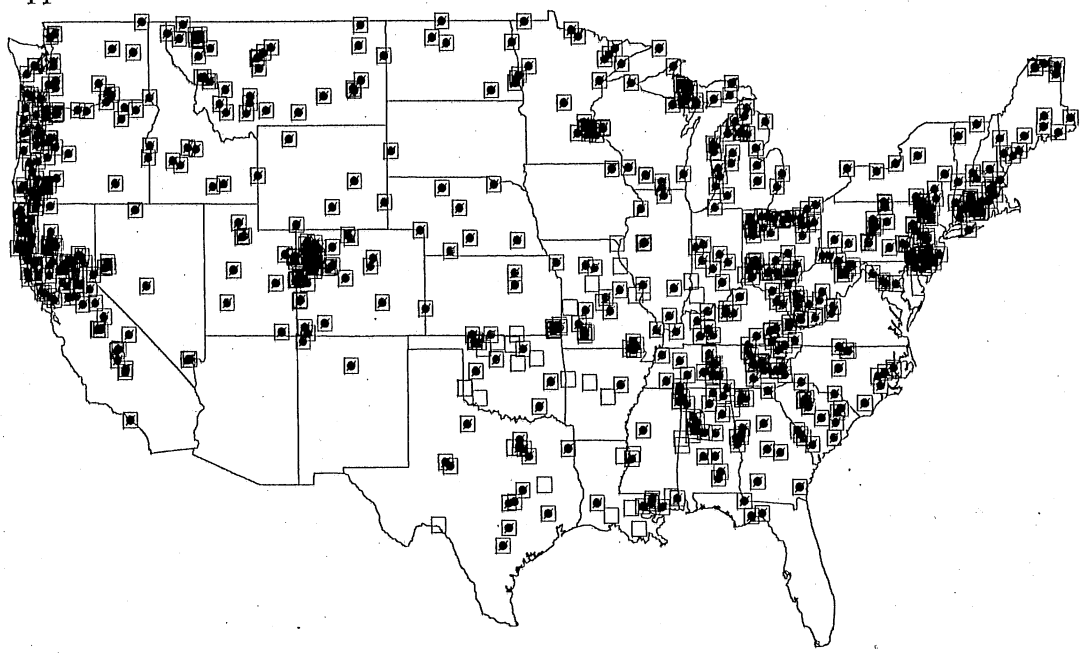
□ $1xCO_2$ Climate Condition
$2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

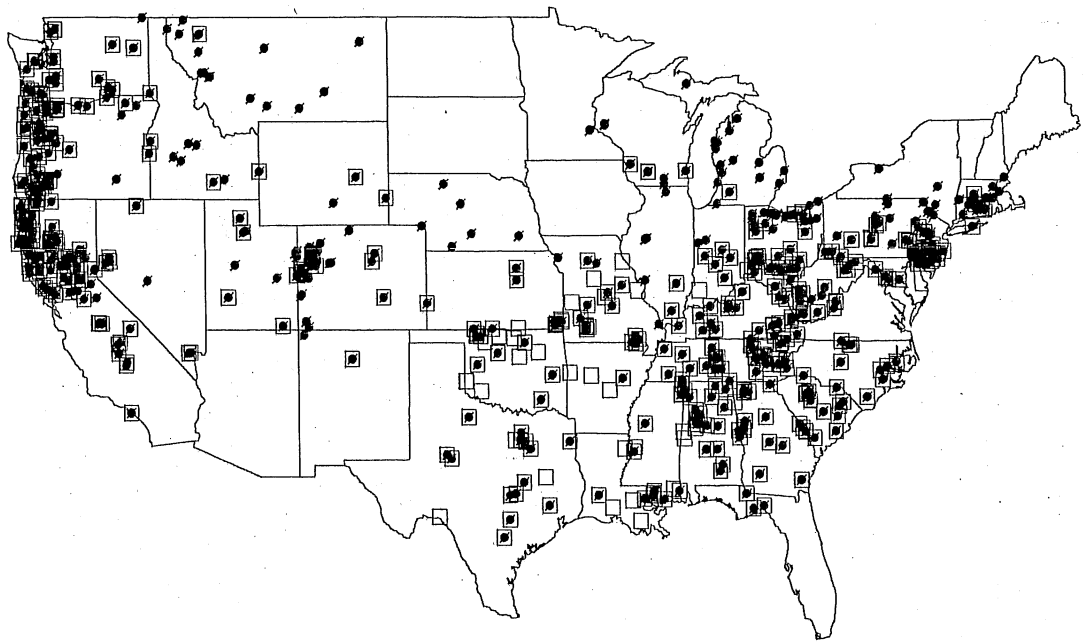
□ $1xCO_2$ Climate Condition
$2xCO_2$ Climate Condition

Black crappie



With 0 °C as the minimum temperature tolerance

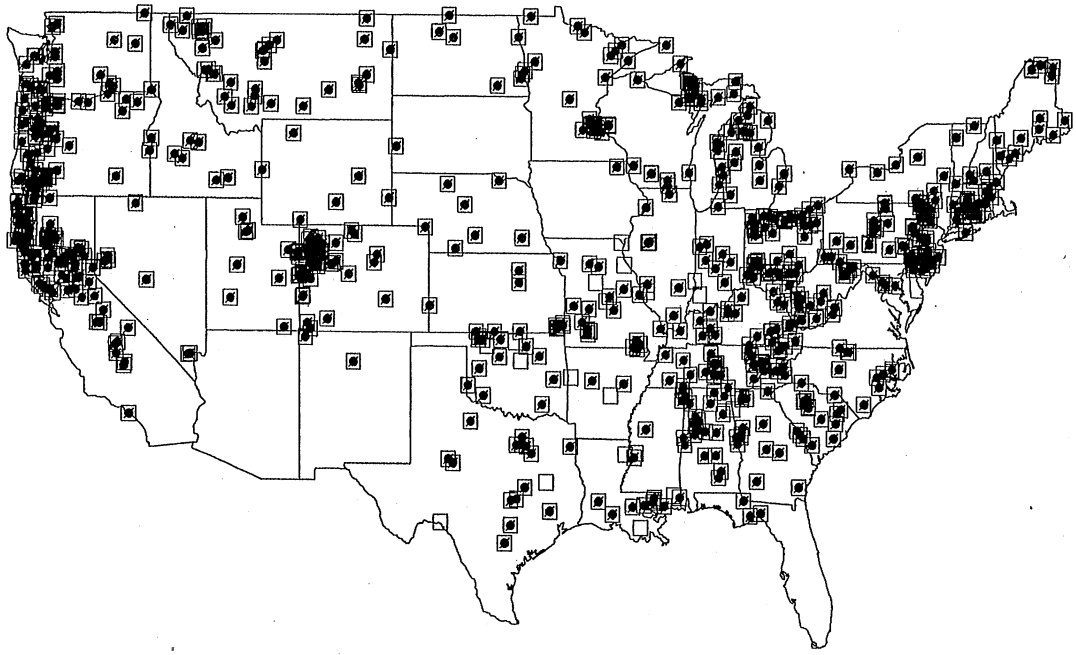
□ $1xCO_2$ Climate Condition
▪ $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

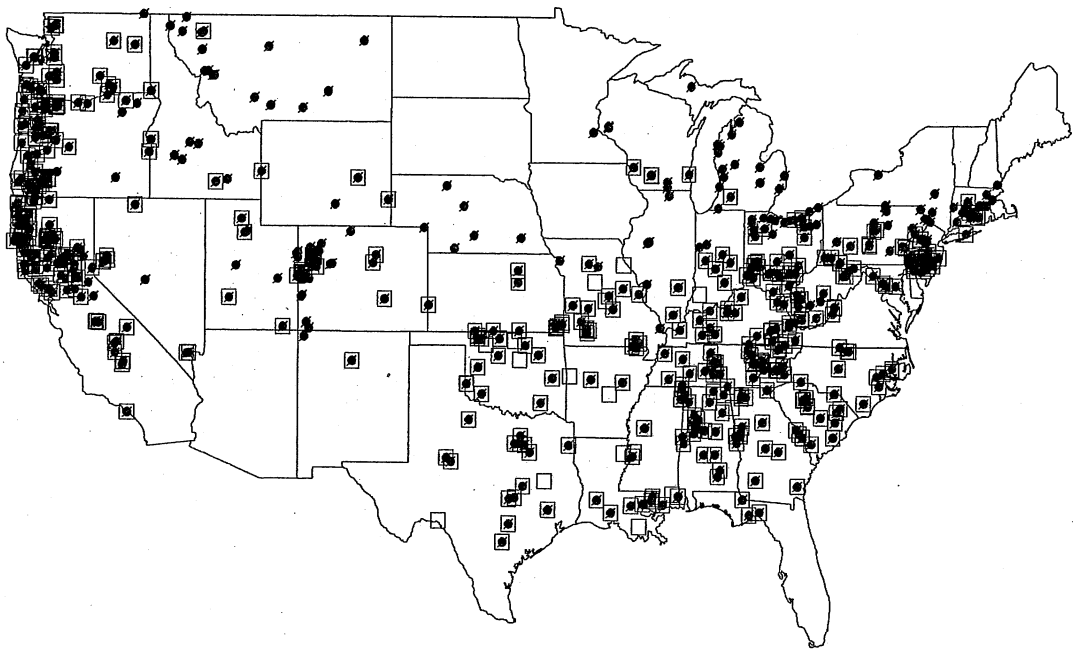
□ $1xCO_2$ Climate Condition
▪ $2xCO_2$ Climate Condition

Golden shiner



With 0 °C as the minimum temperature tolerance

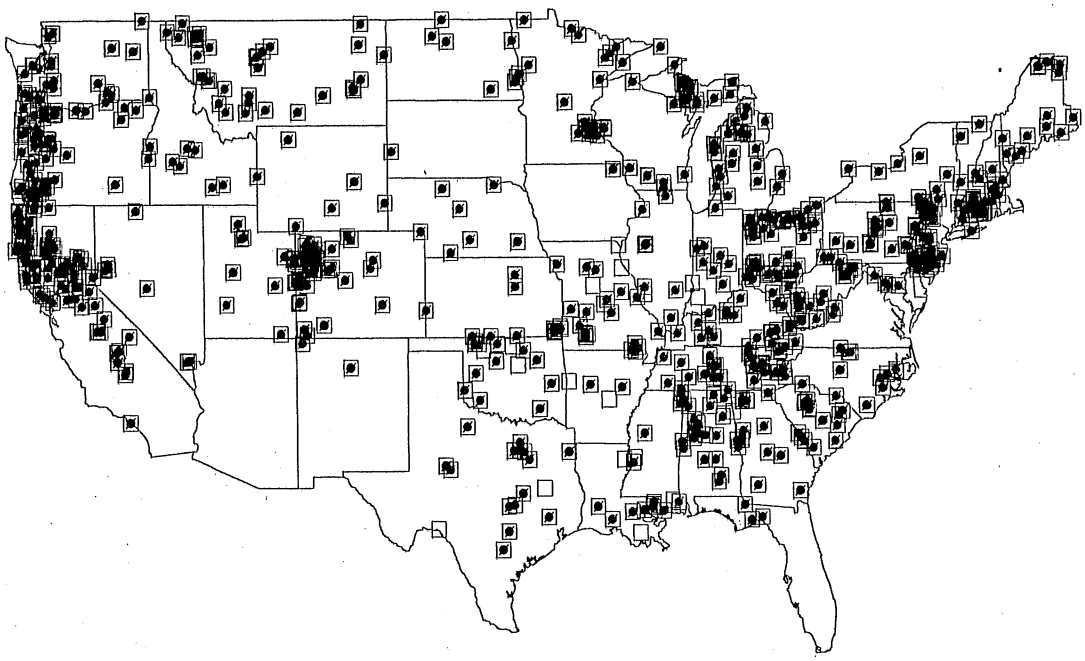
□ $1xCO_2$ Climate Condition
▪ $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

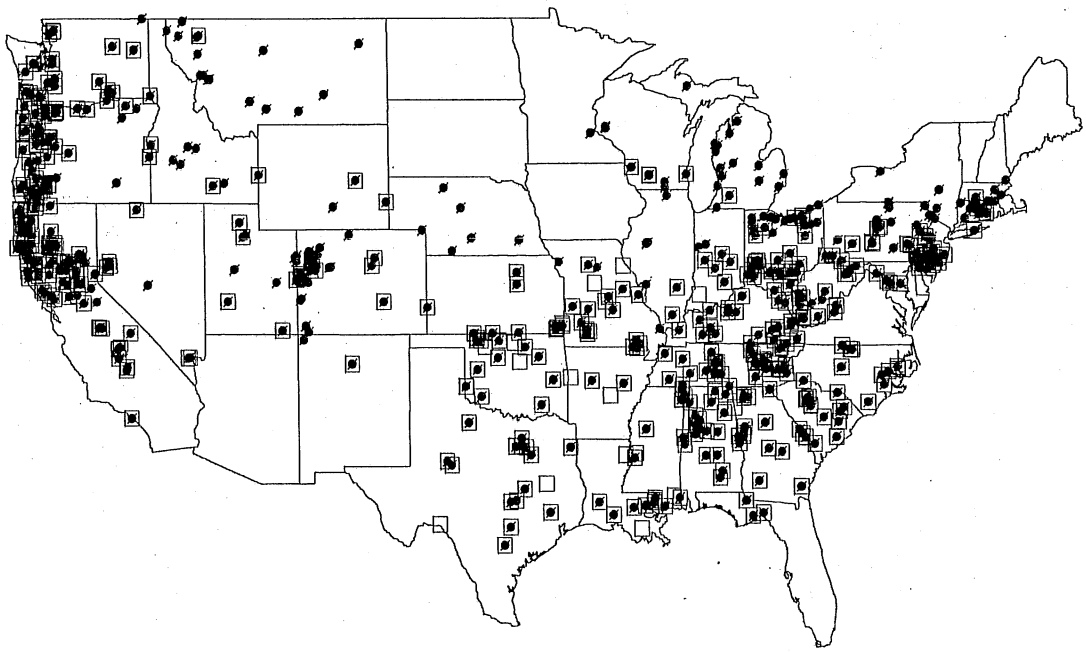
□ $1xCO_2$ Climate Condition
▪ $2xCO_2$ Climate Condition

Spotted bass



With 0 °C as the minimum temperature tolerance

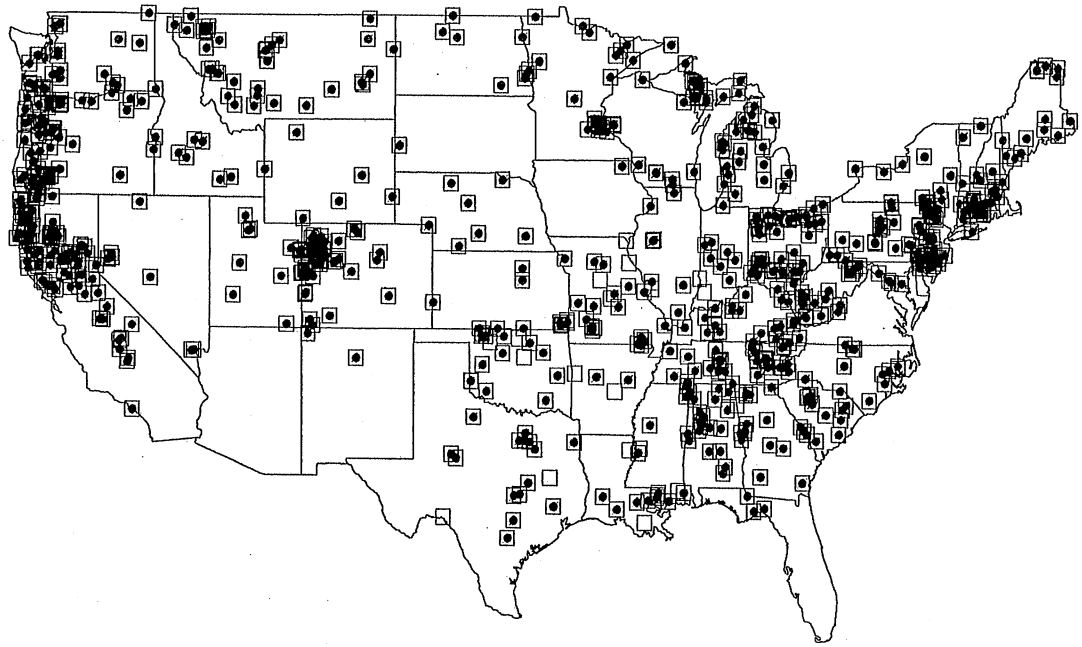
□ $1xCO_2$ Climate Condition
▪ $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

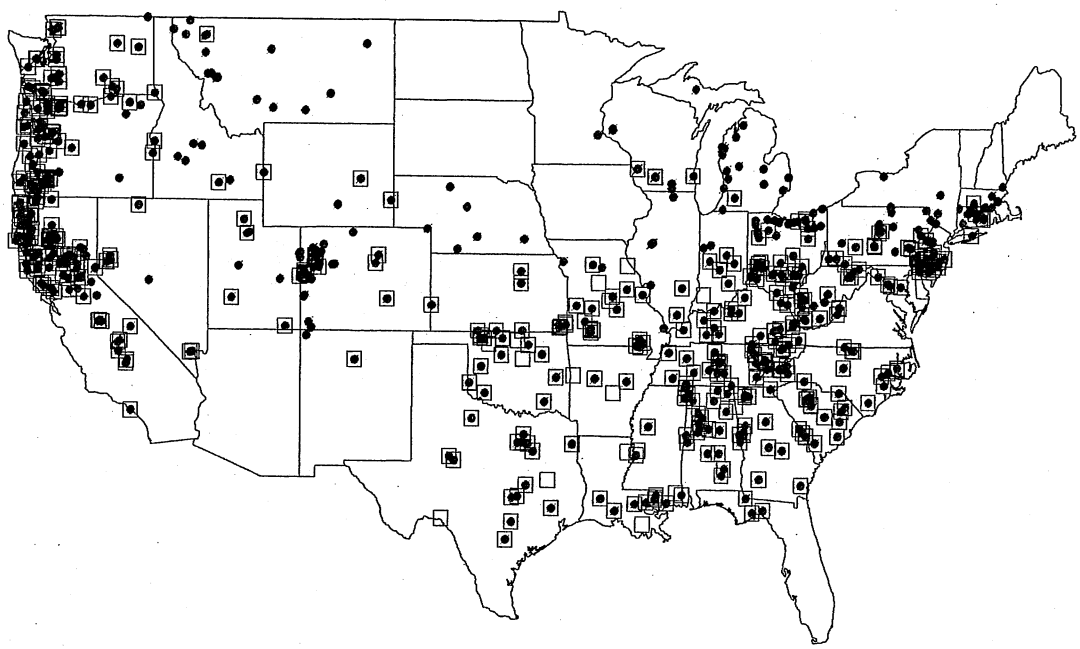
□ $1xCO_2$ Climate Condition
▪ $2xCO_2$ Climate Condition

White pearch



With 0 °C as the minimum temperature tolerance

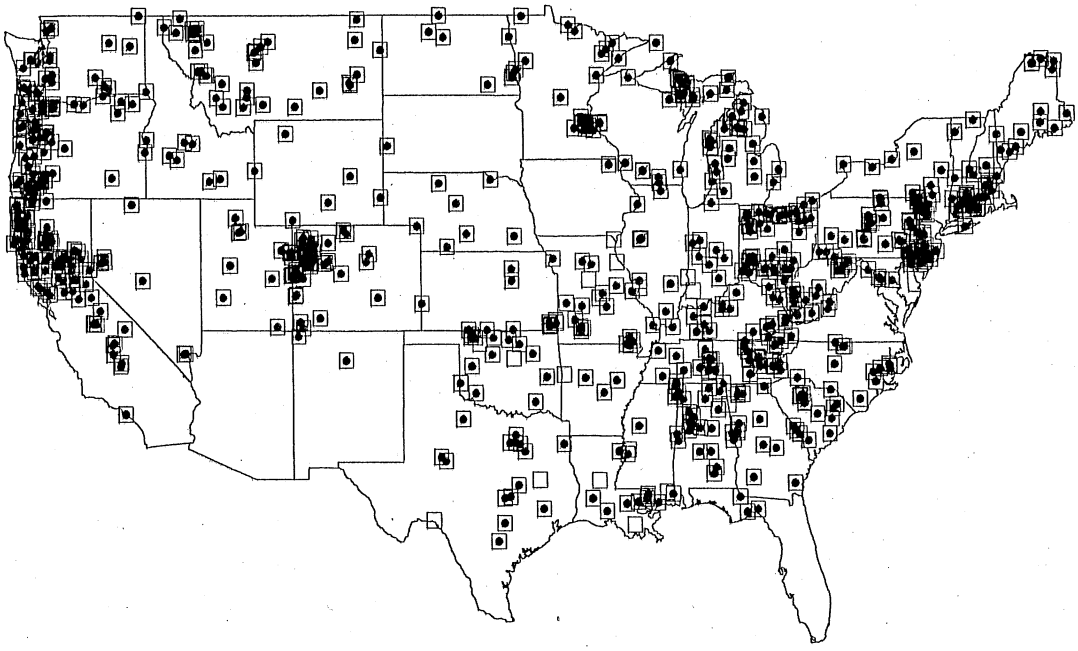
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

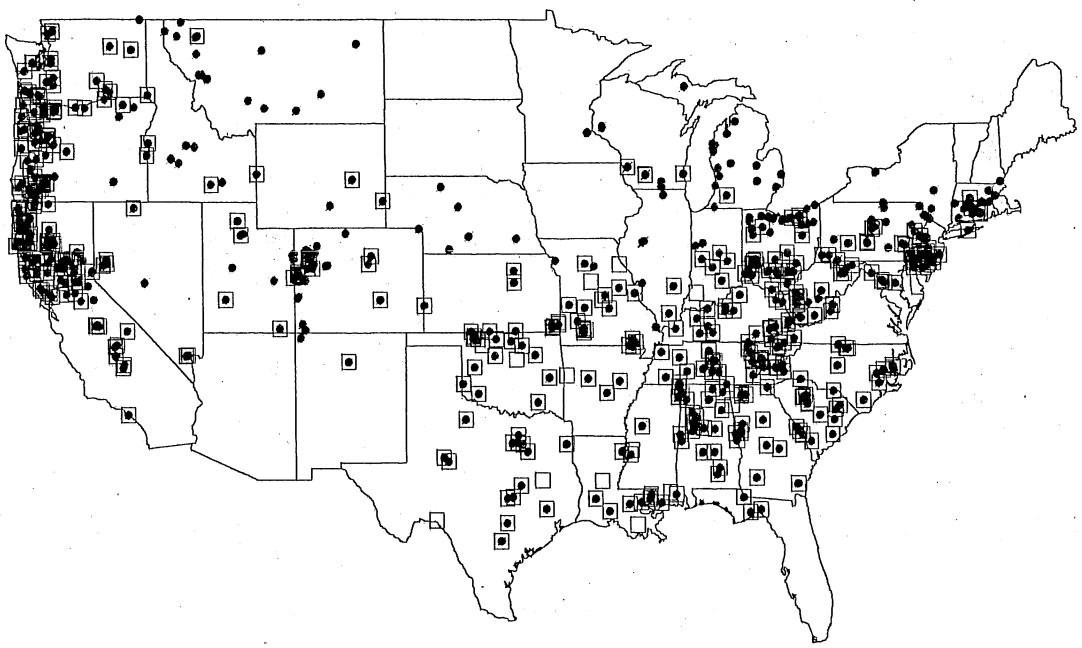
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

White crappie



With 0 °C as the minimum temperature tolerance

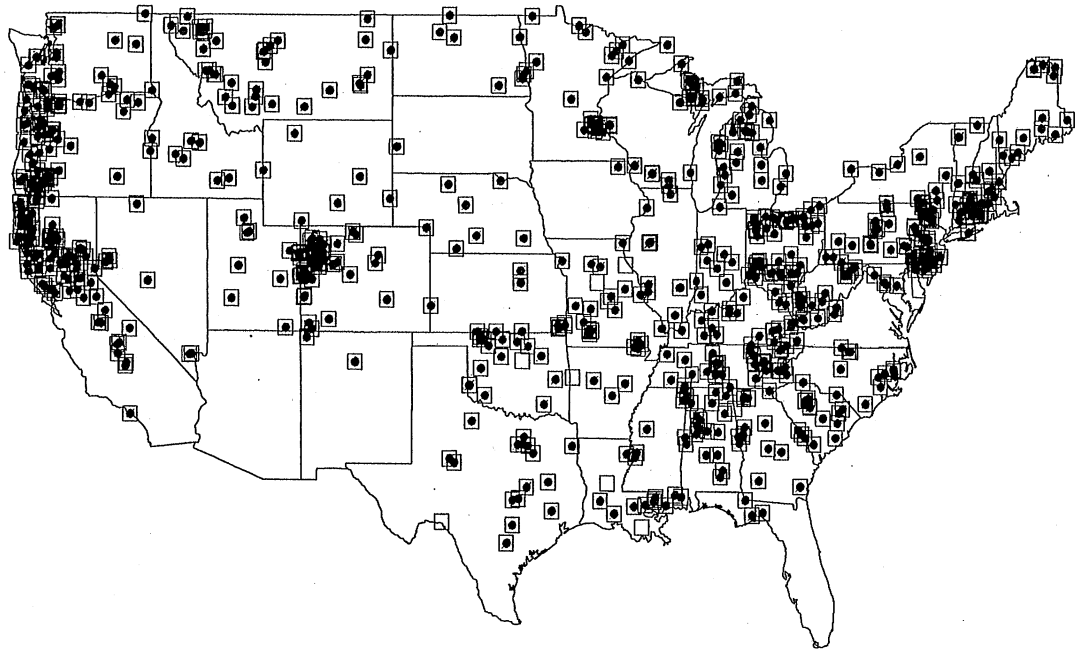
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

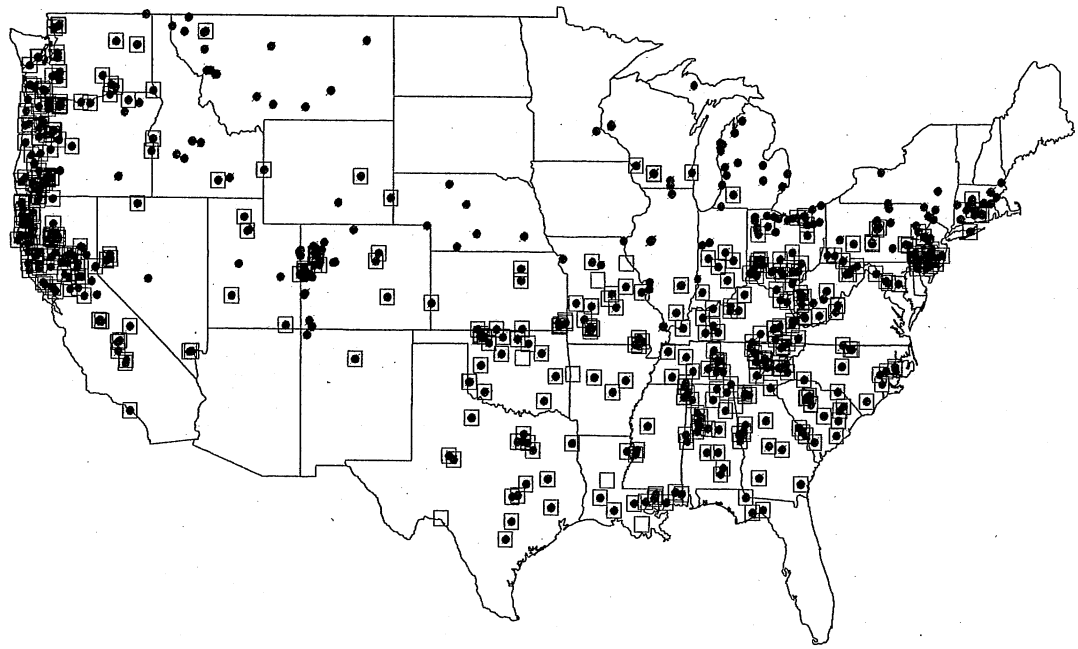
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

White bass



With 0 °C as the minimum temperature tolerance

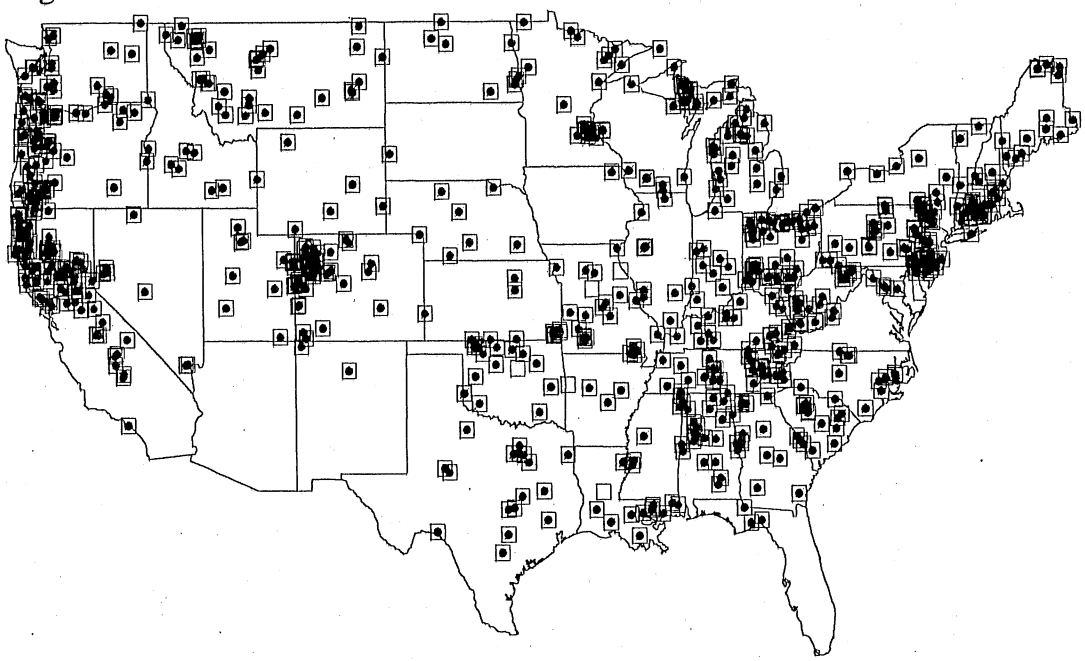
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

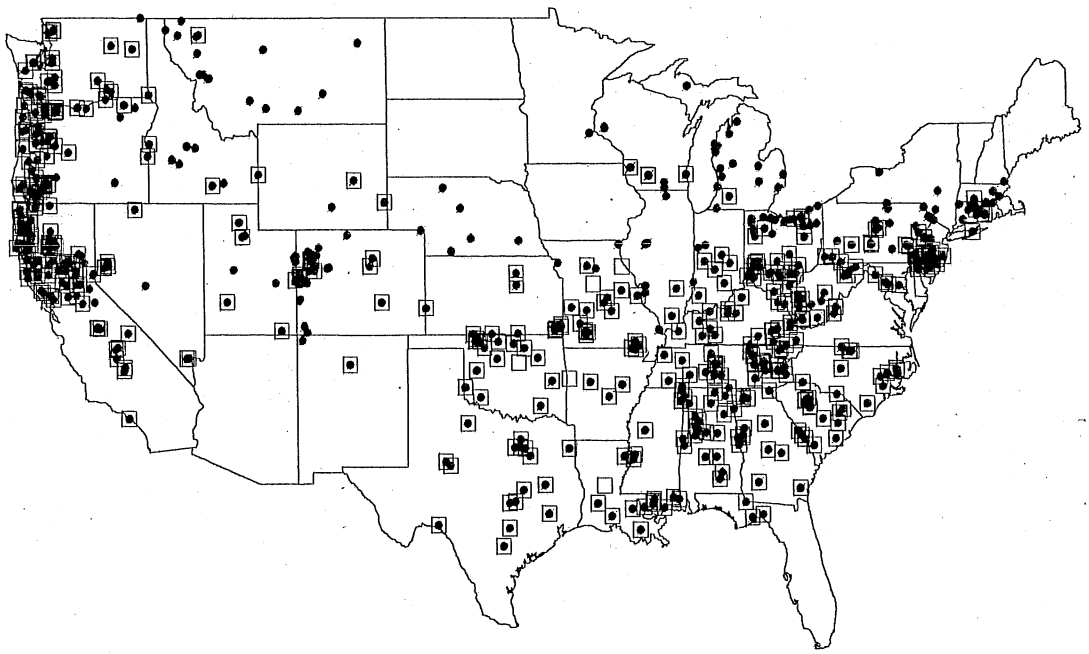
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Longnose gar



With 0 °C as the minimum temperature tolerance

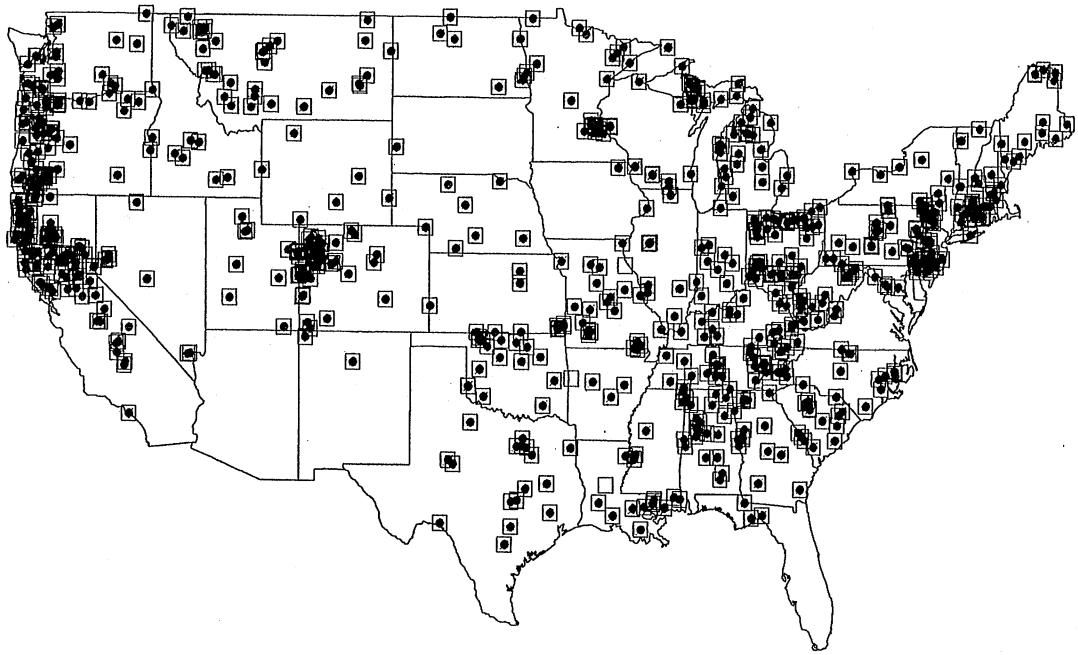
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

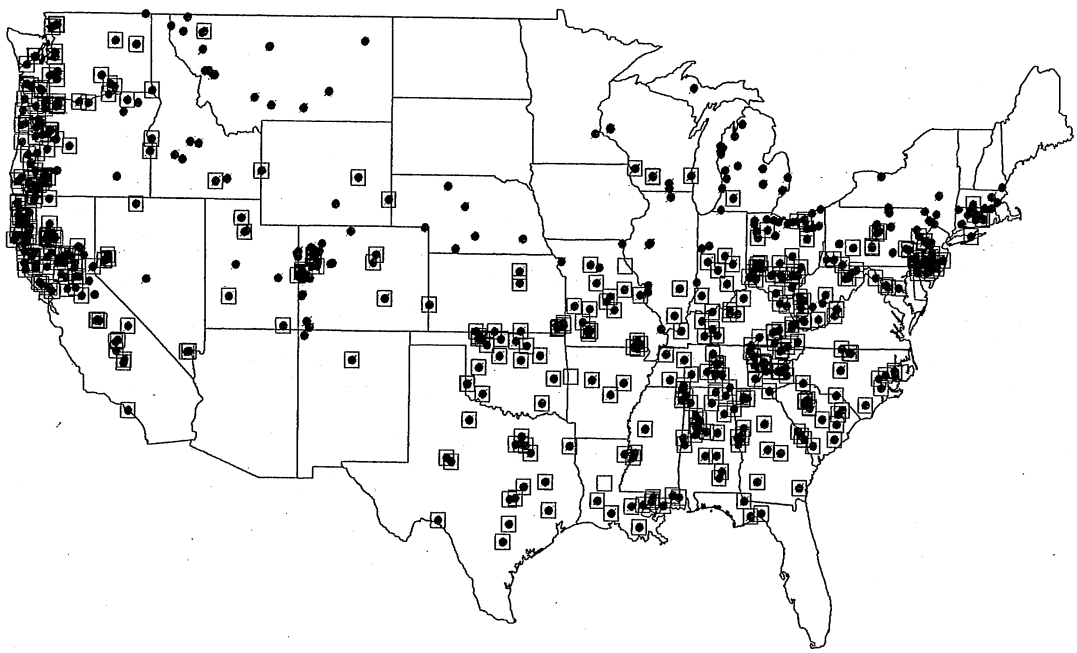
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Emrald shiner



With 0 °C as the minimum temperature tolerance

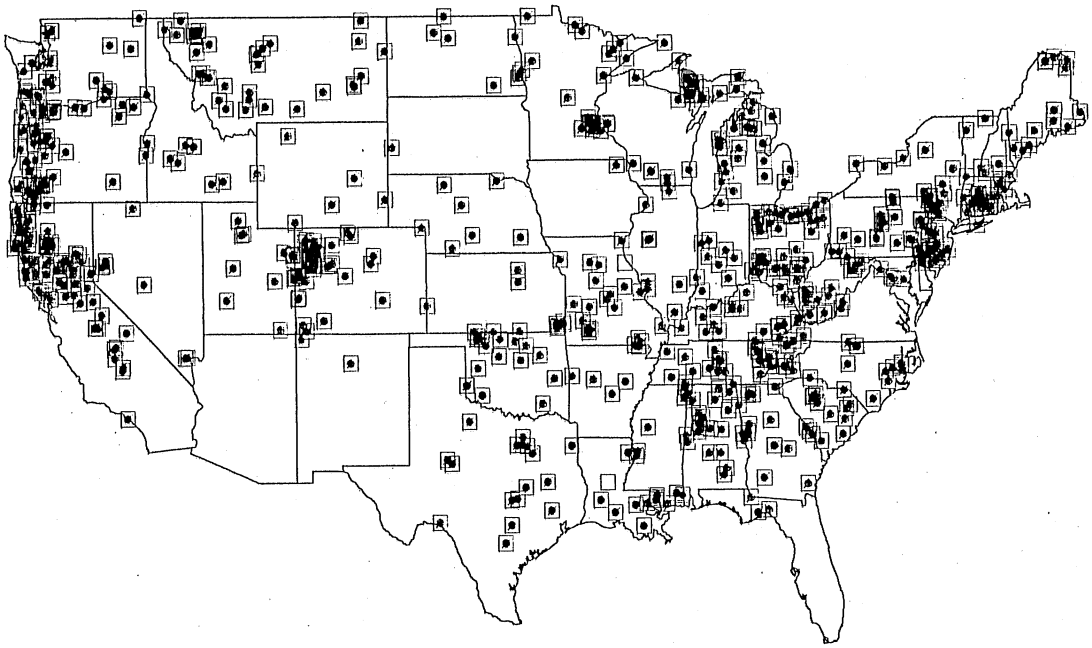
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

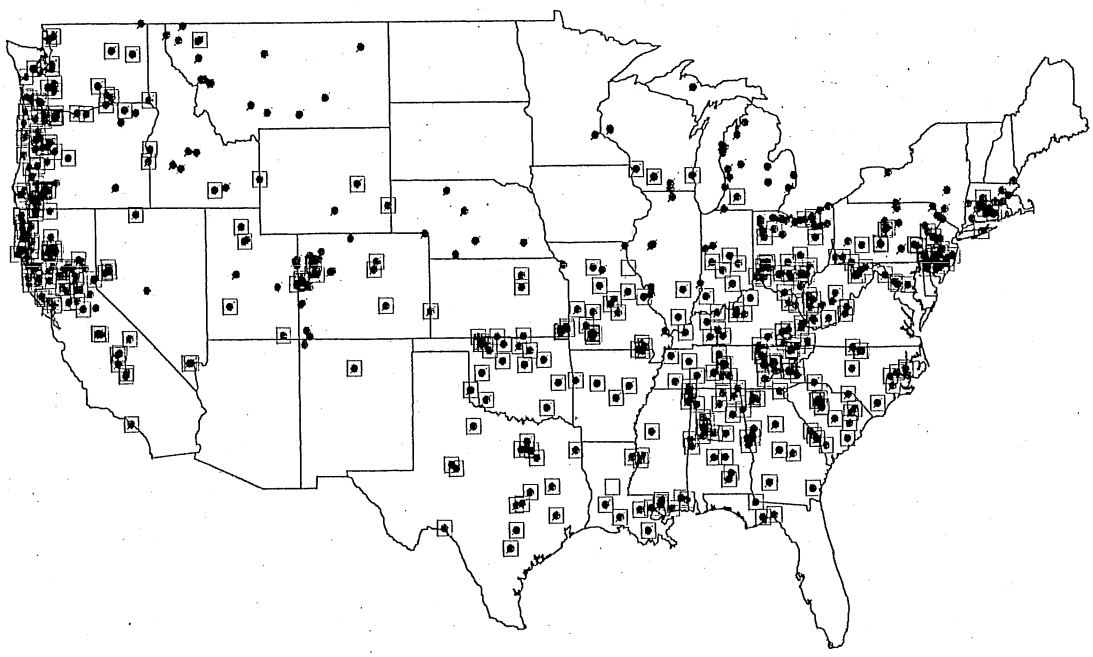
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Sand shiner



With 0 °C as the minimum temperature tolerance

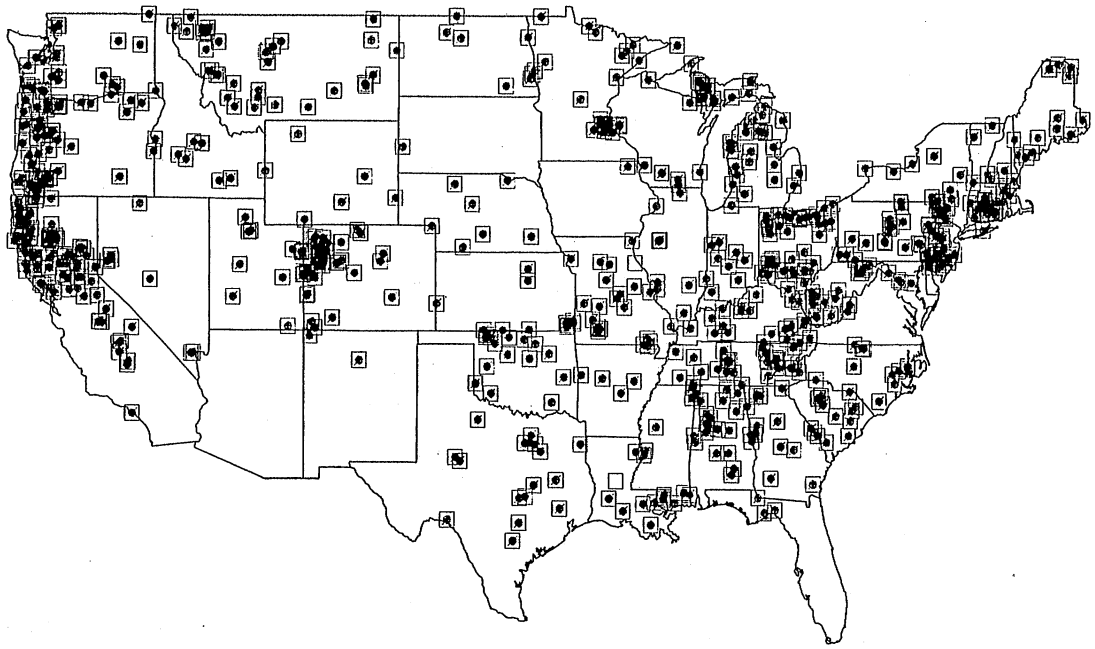
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

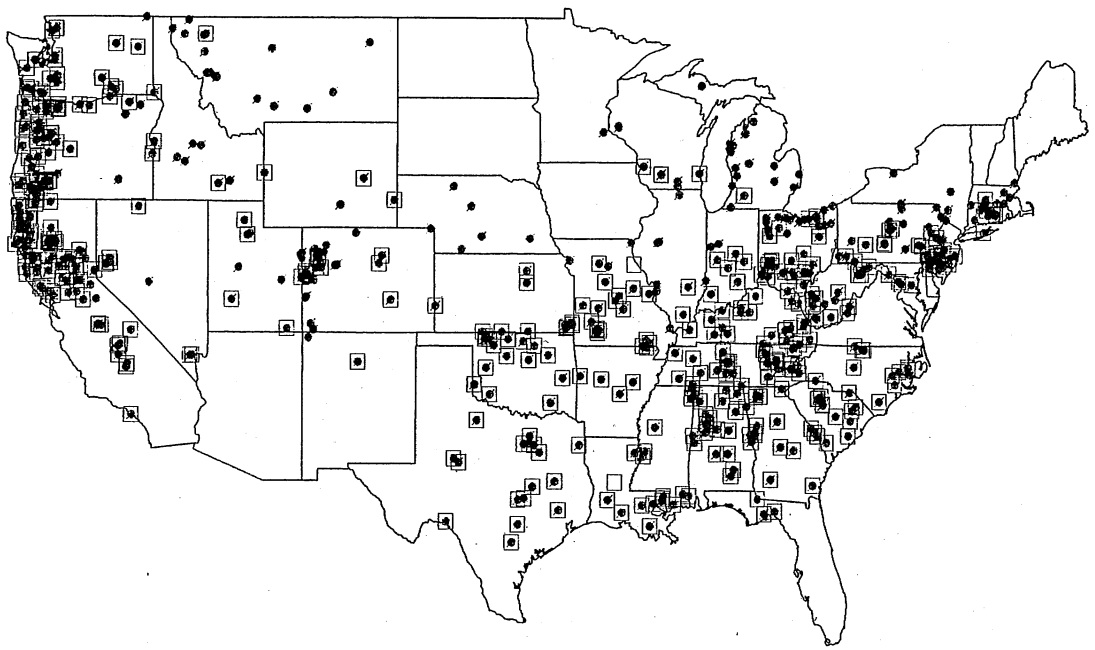
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

River carpsucker



With 0 °C as the minimum temperature tolerance

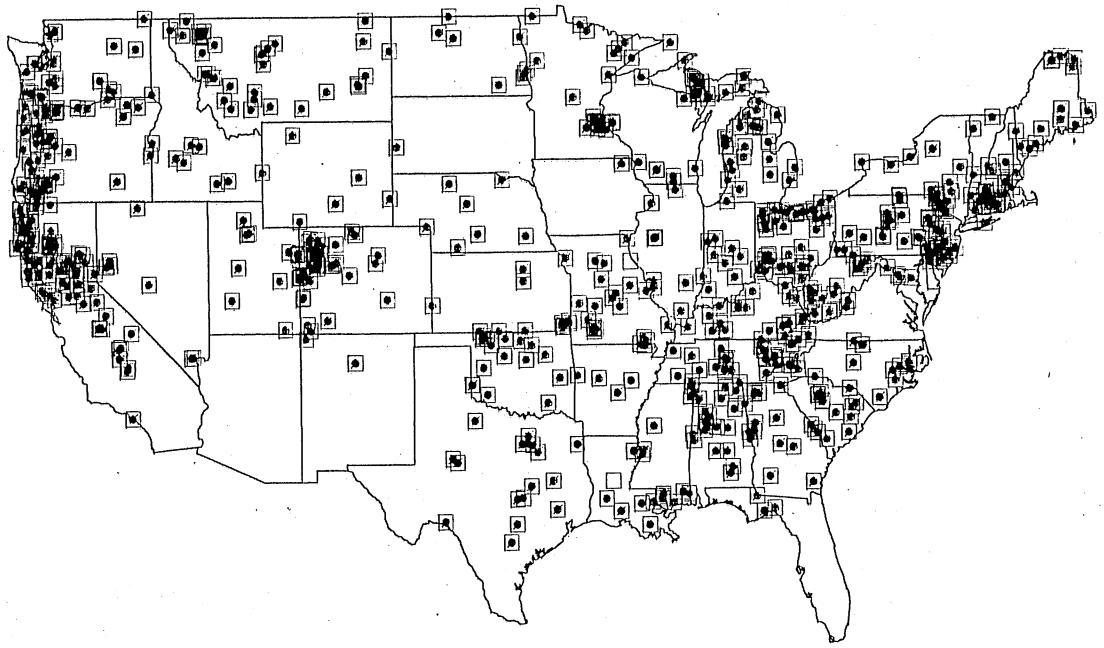
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition



With 2 °C as the minimum temperature tolerance

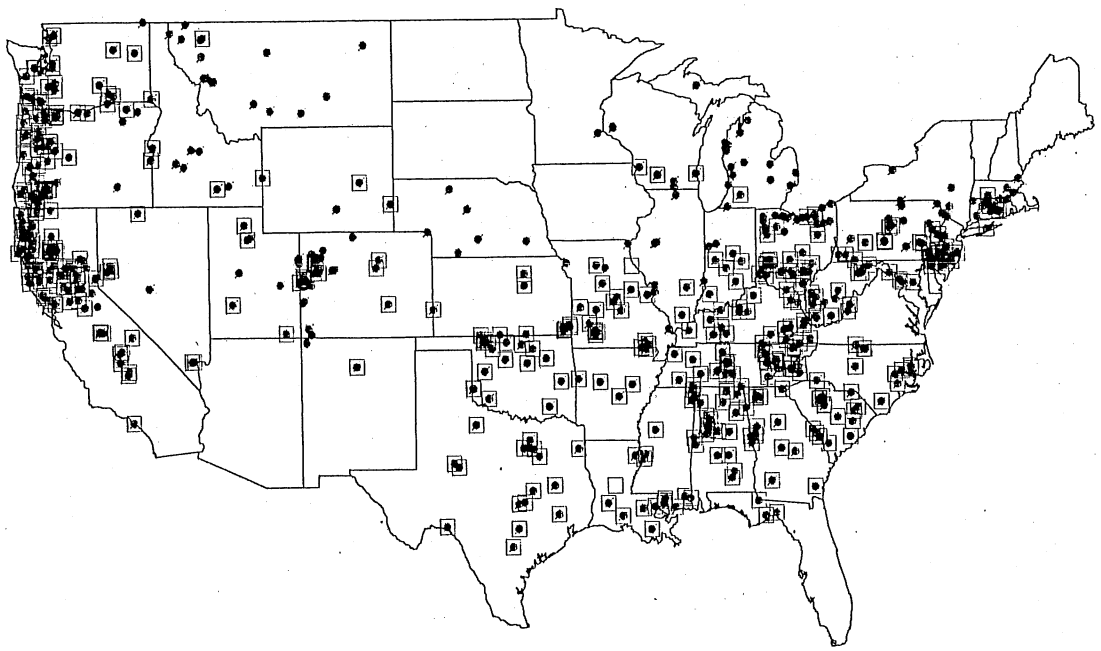
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

Suckermouth minnow



With 0 °C as the minimum temperature tolerance

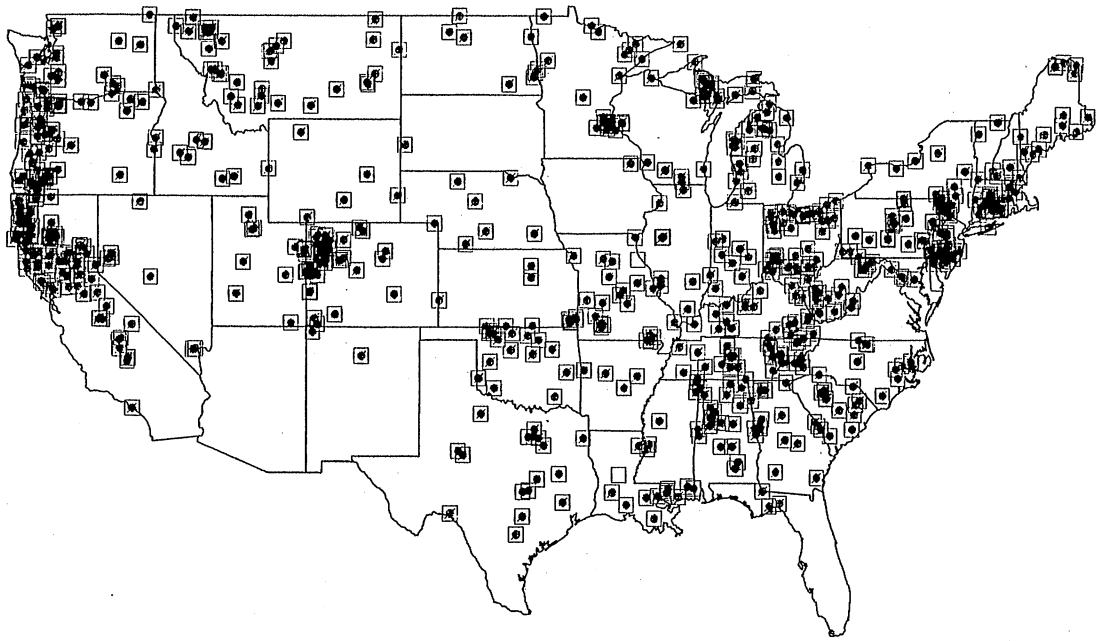
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

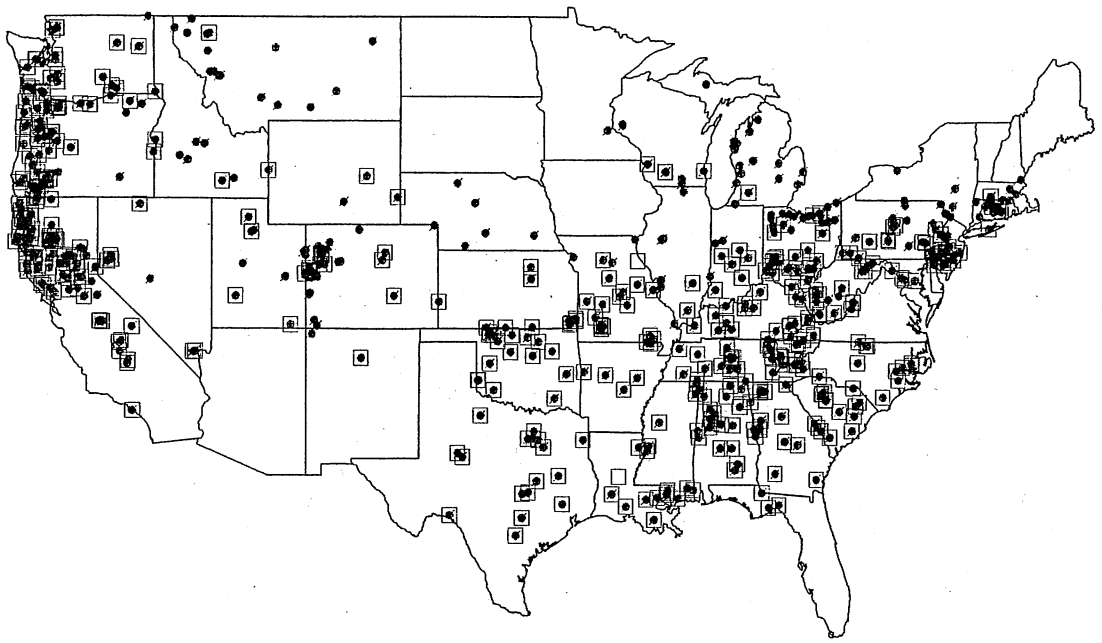
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Orange spotted sunfish



With 0 °C as the minimum temperature tolerance

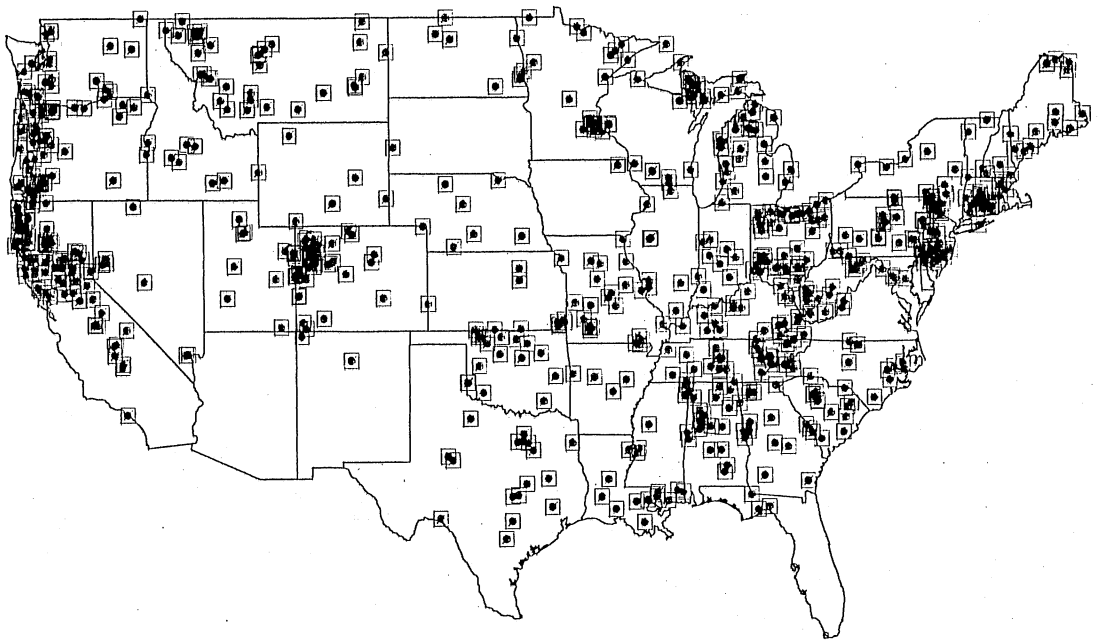
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

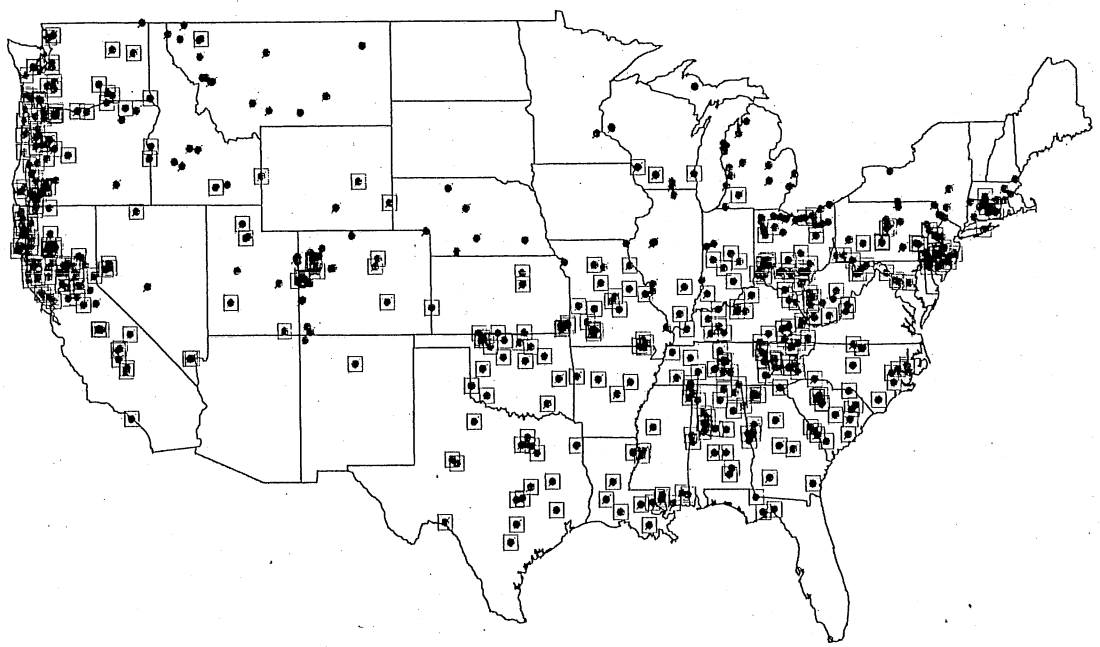
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Freshwater drum



With 0 °C as the minimum temperature tolerance

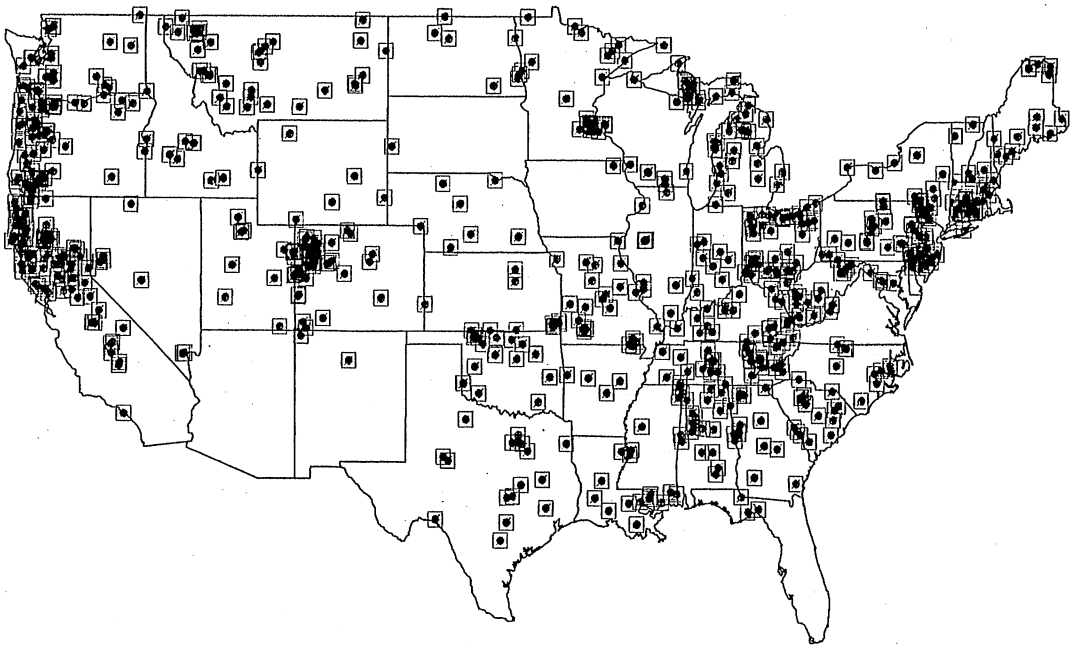
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

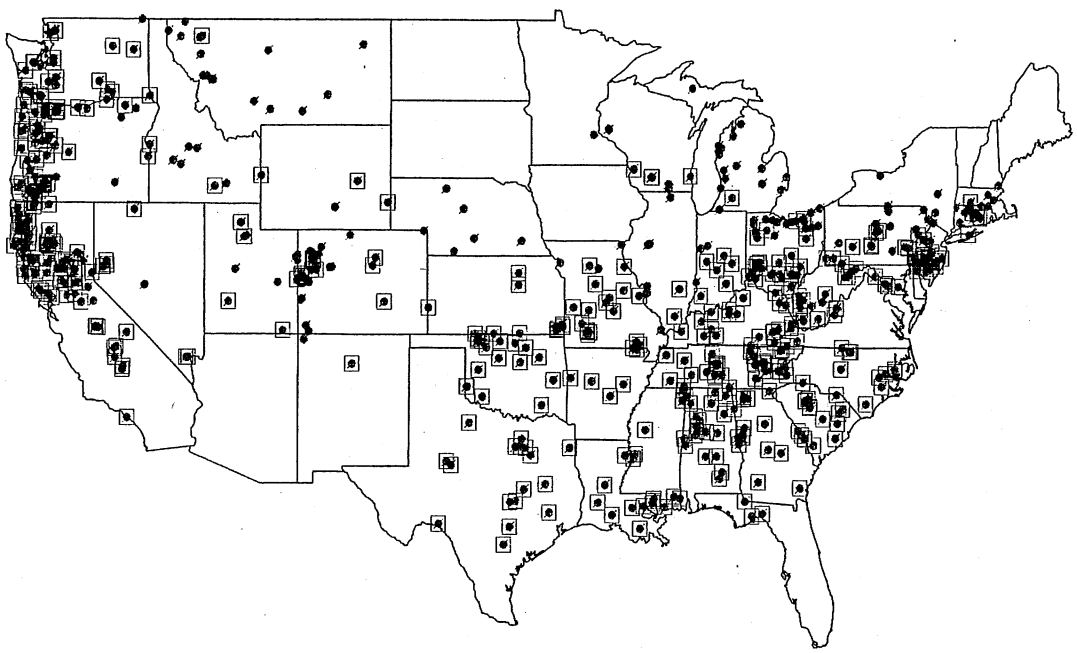
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Bullhead minnow



With 0 °C as the minimum temperature tolerance

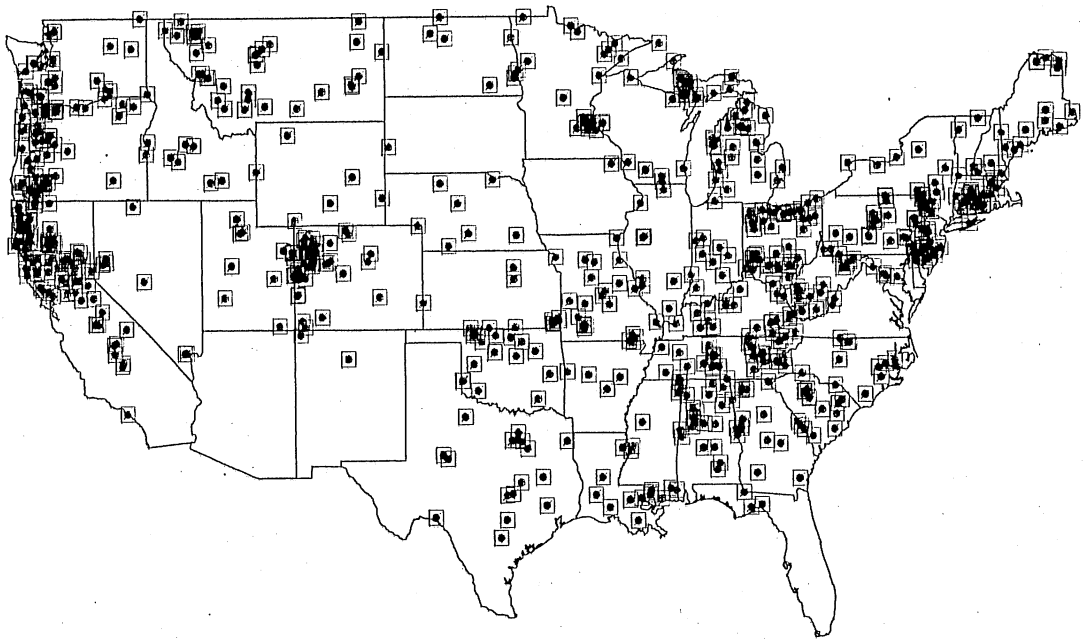
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

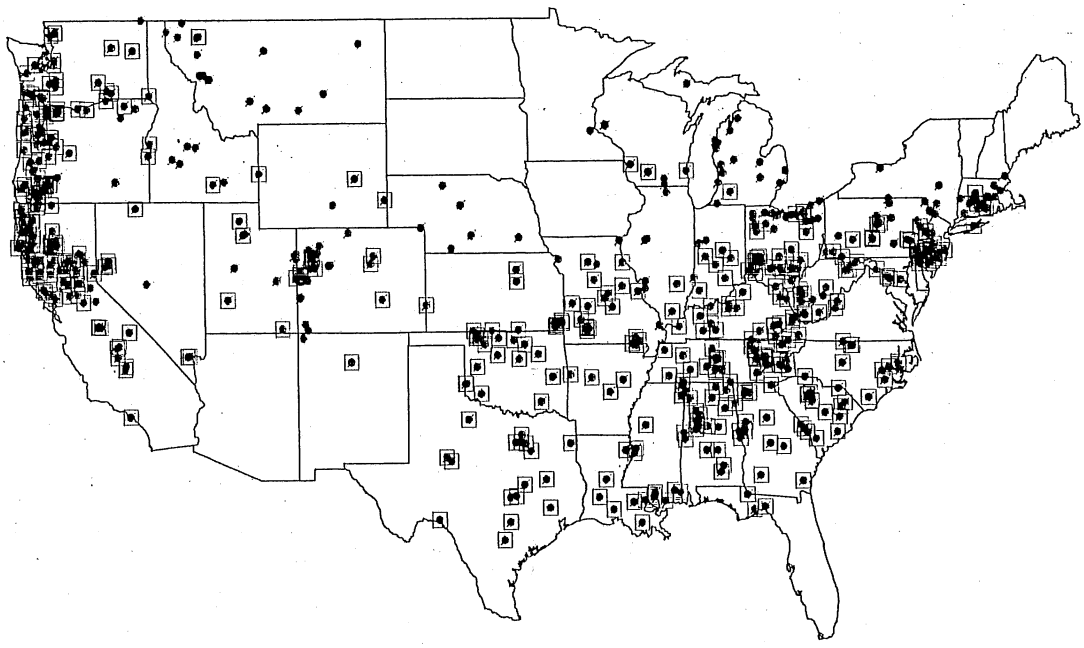
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Black bullhead



With 0 °C as the minimum temperature tolerance

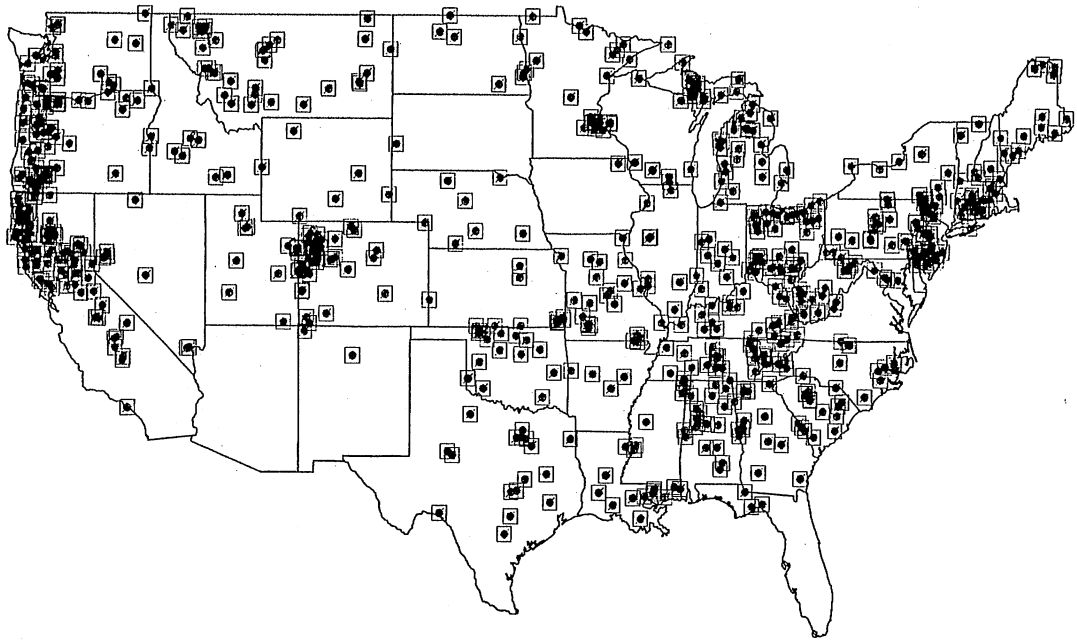
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

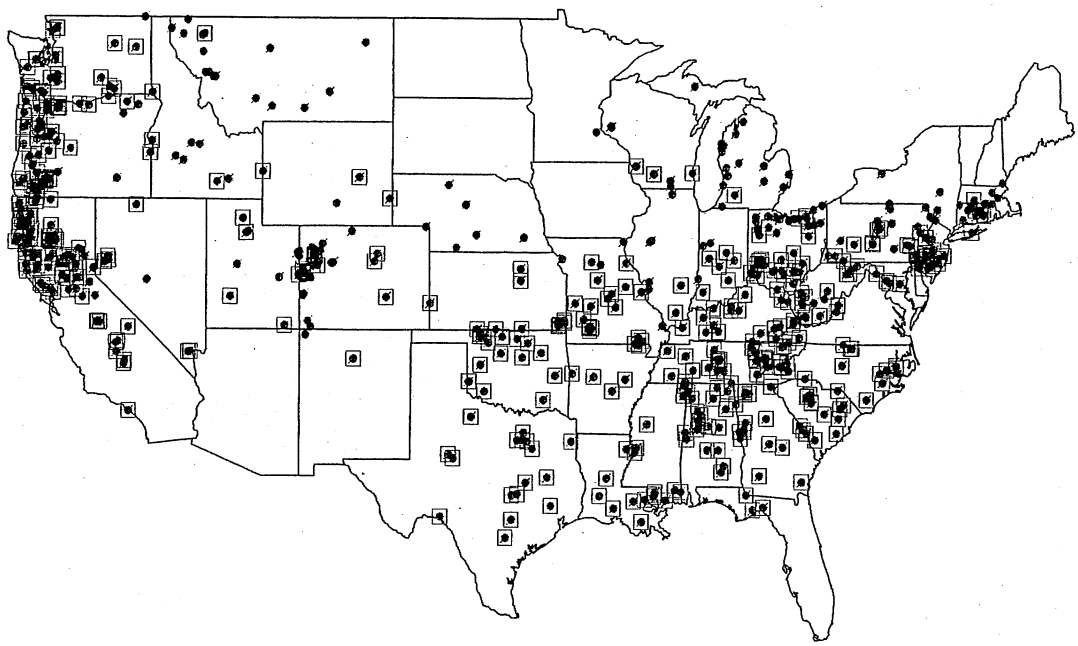
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Flathead catfish



With 0 °C as the minimum temperature tolerance

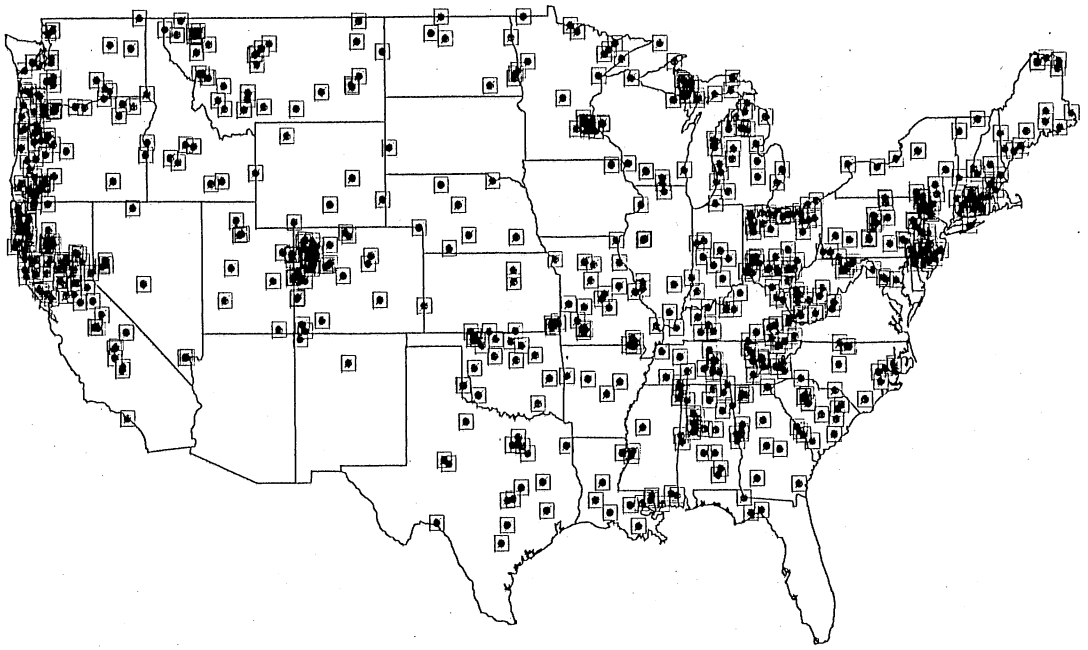
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

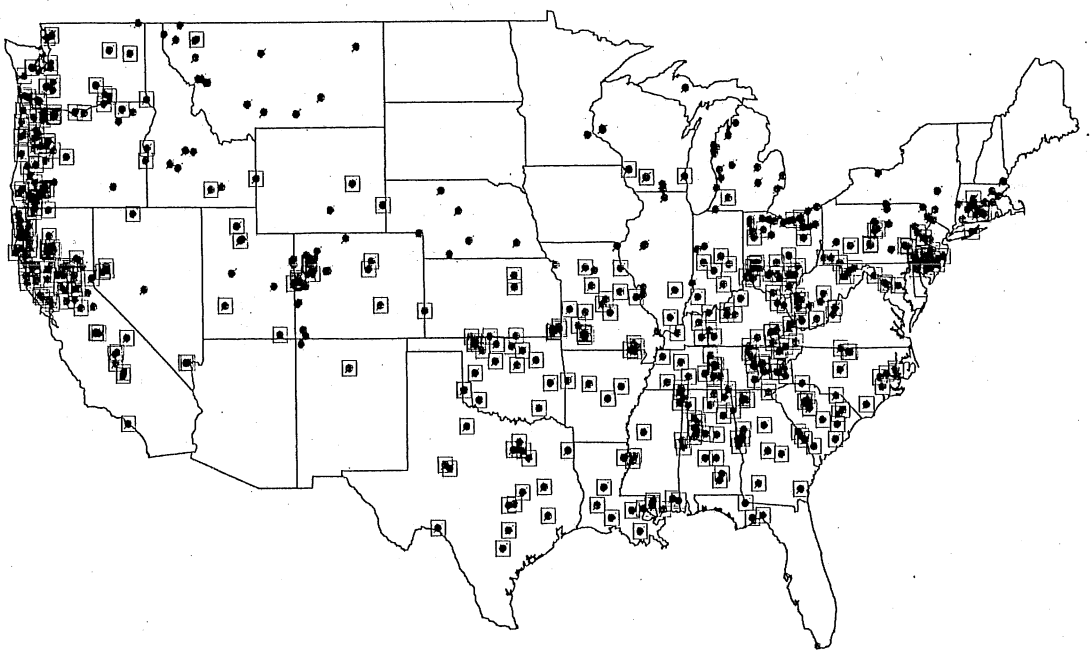
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Flathead minnow



With 0 °C as the minimum temperature tolerance

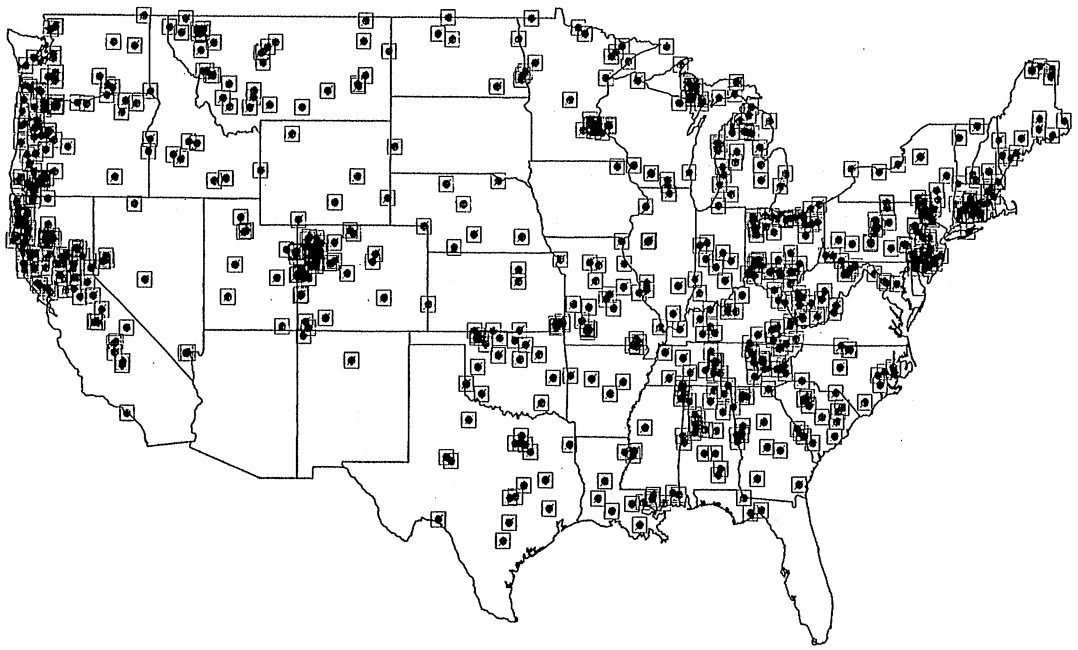
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition



With 2 °C as the minimum temperature tolerance

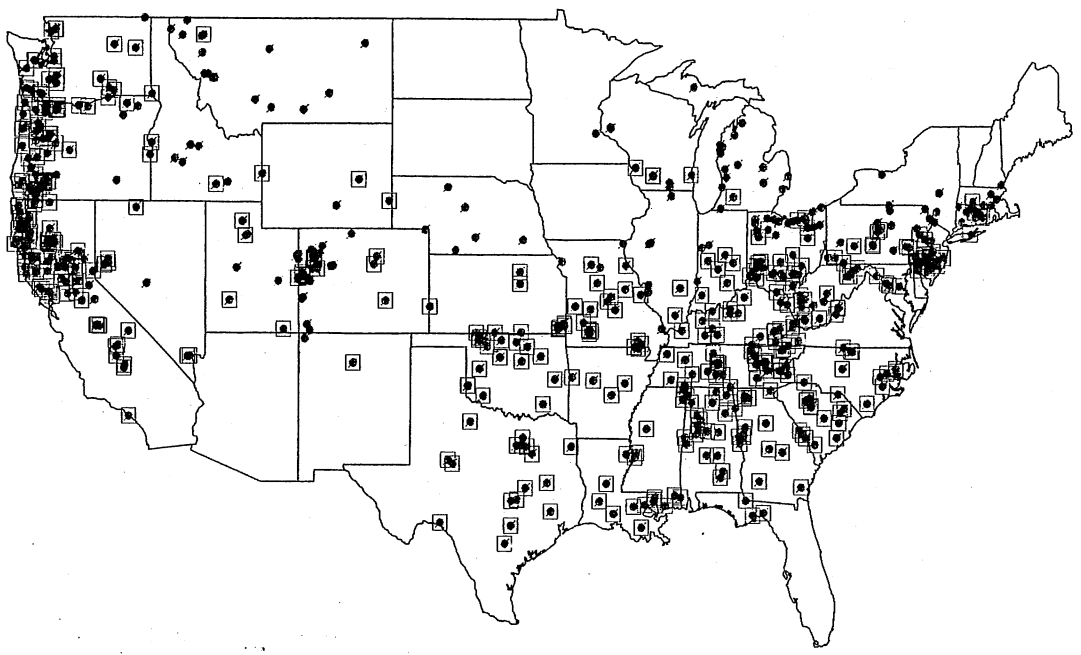
□ 1xCO_2 Climate Condition
• 2xCO_2 Climate Condition

Ghost shiner



With 0 °C as the minimum temperature tolerance

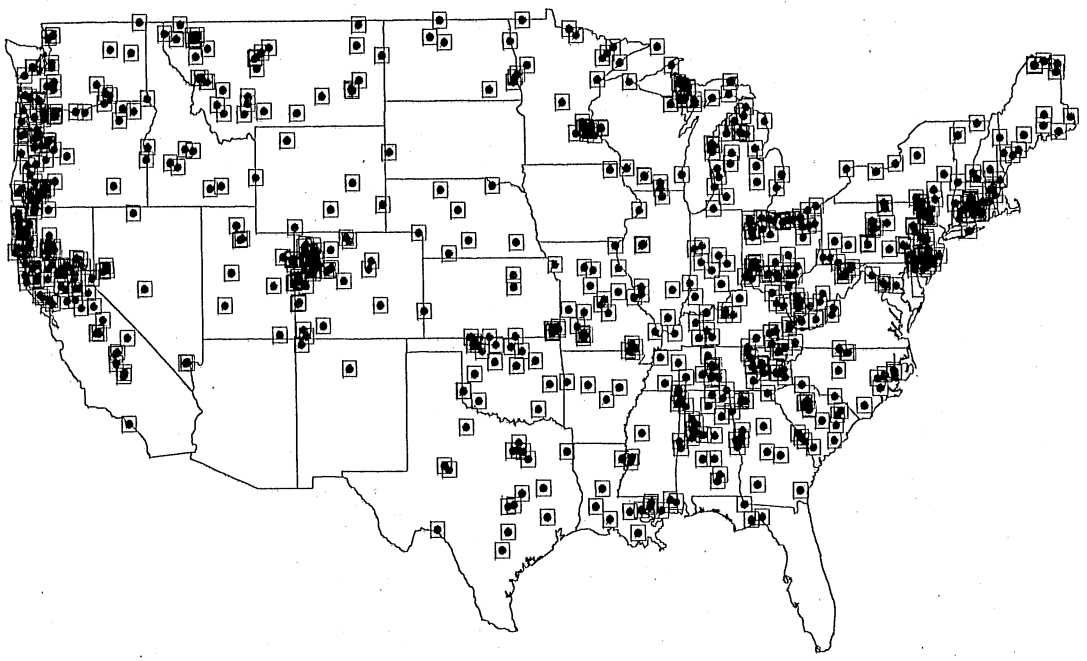
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

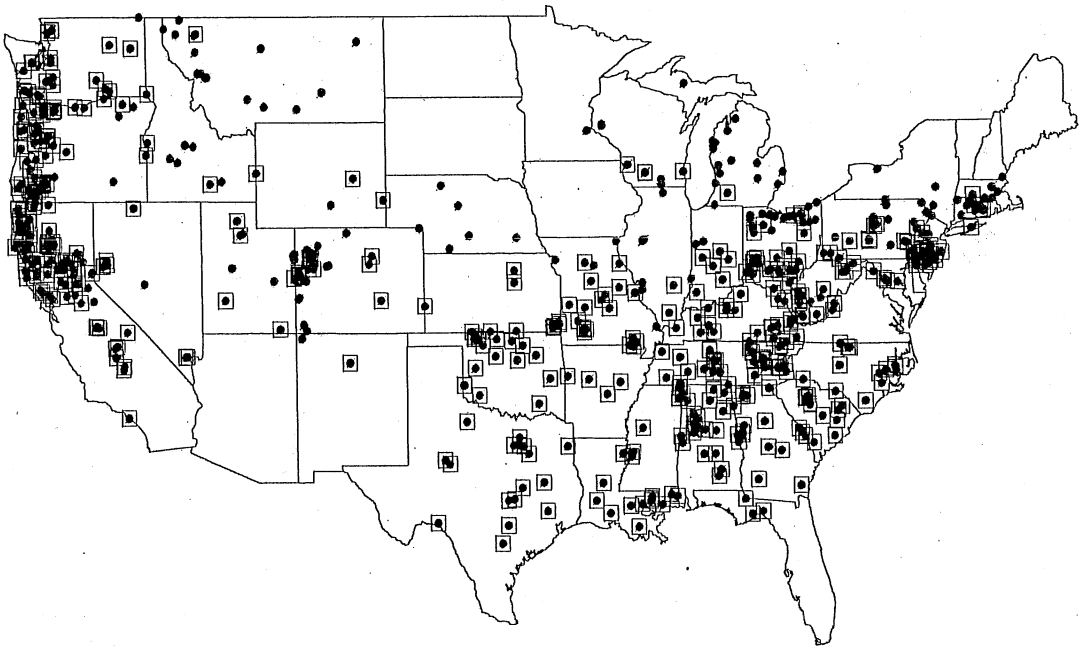
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Gizzrd shad



With 0 °C as the minimum temperature tolerance

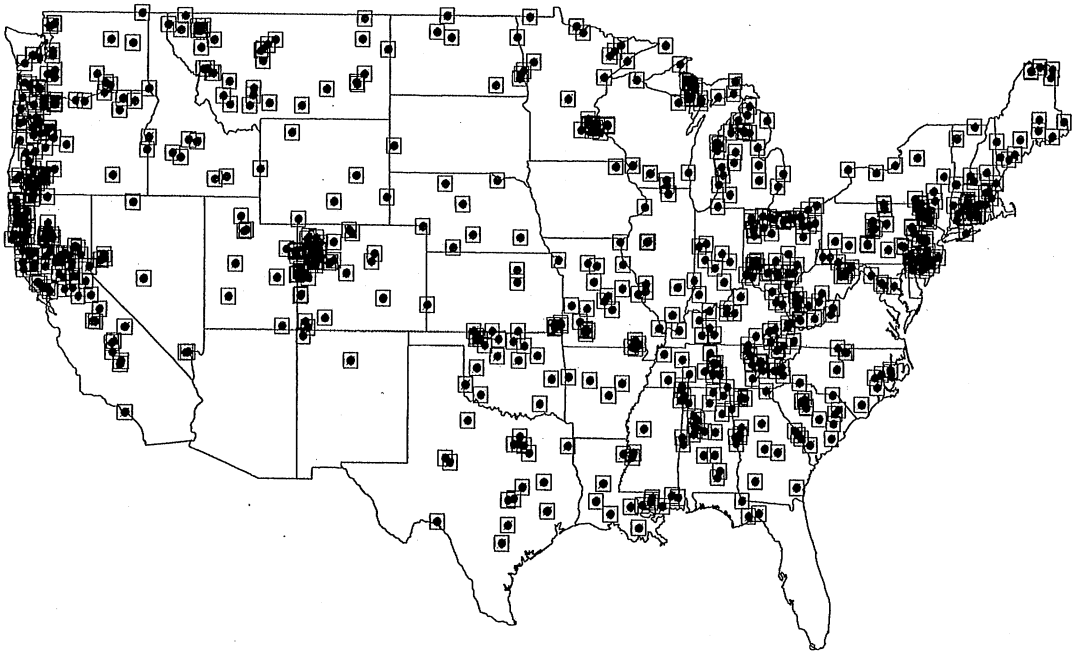
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

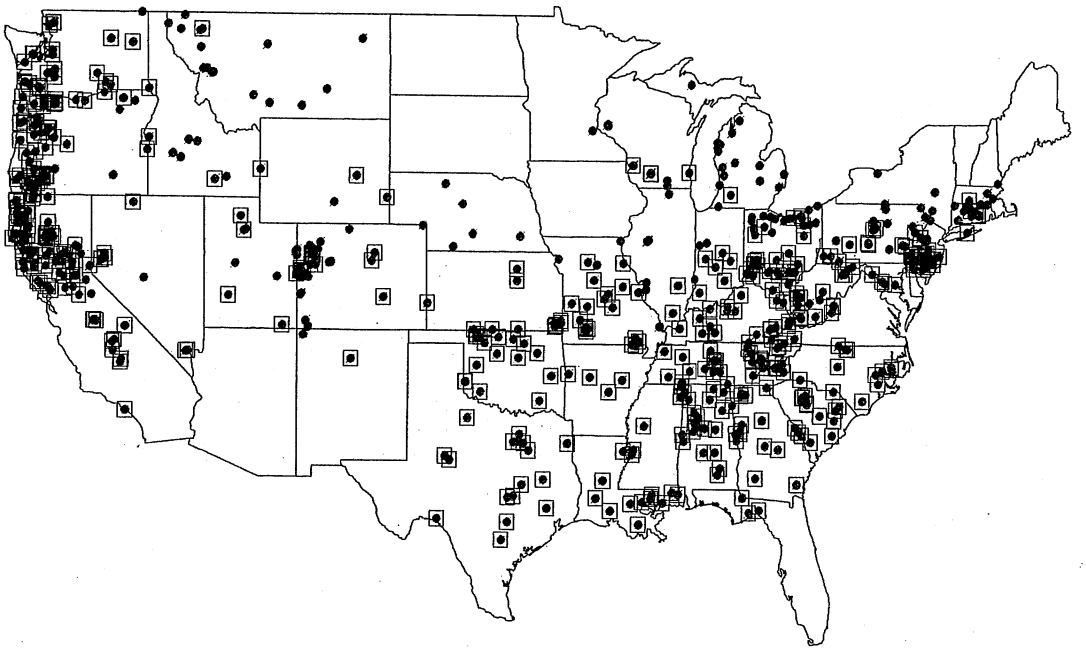
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Green sunfish



With 0 °C as the minimum temperature tolerance

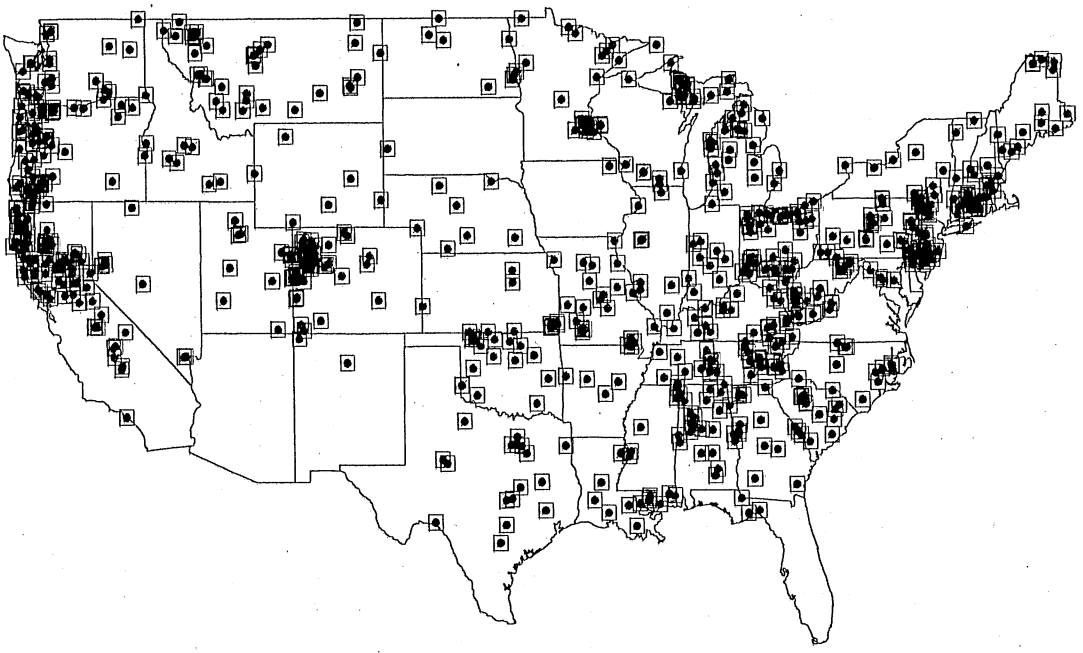
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

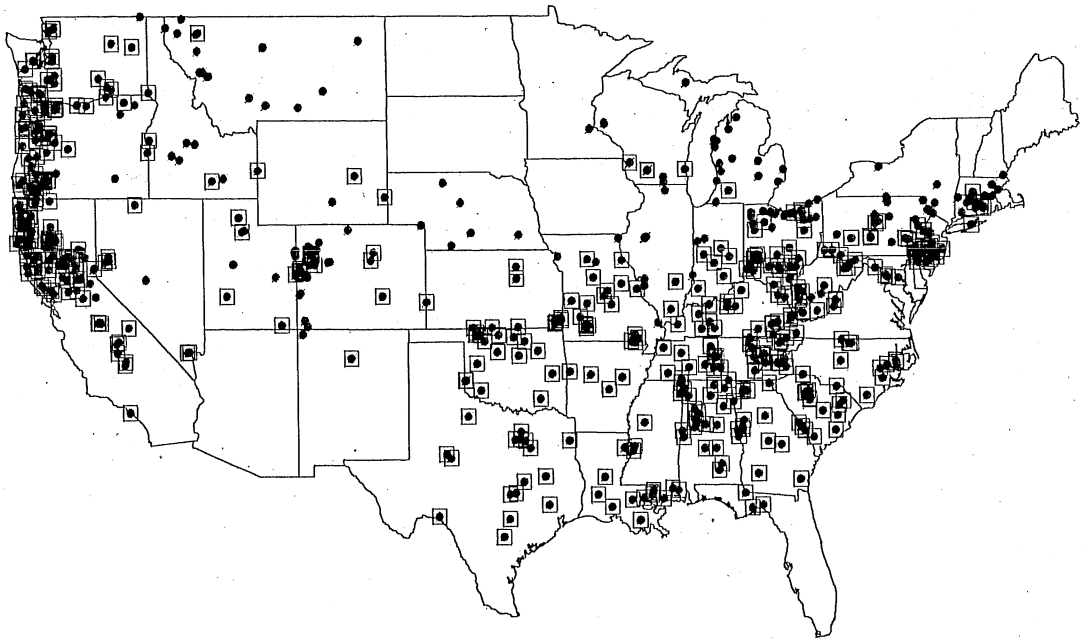
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Longear sunfish



With 0 °C as the minimum temperature tolerance

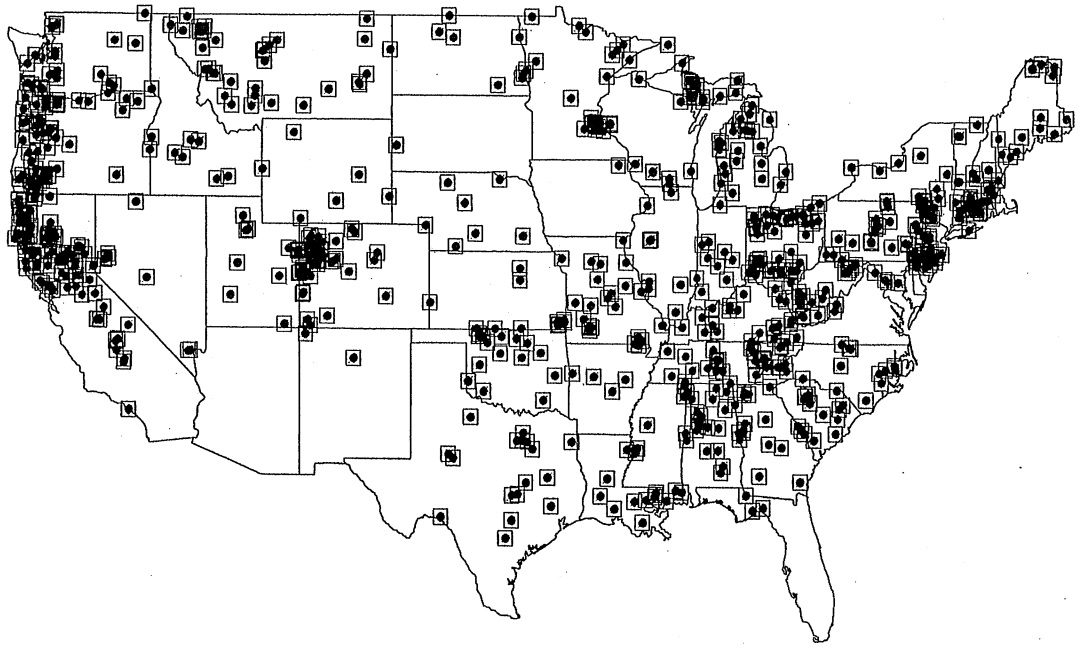
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

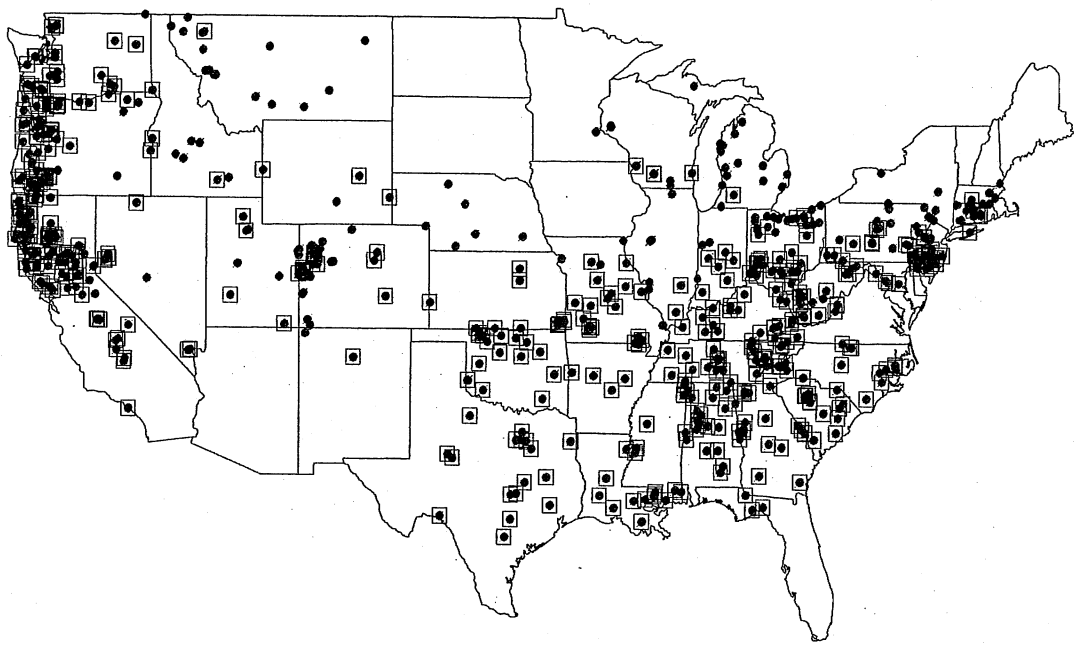
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Mosquitofish



With 0 °C as the minimum temperature tolerance

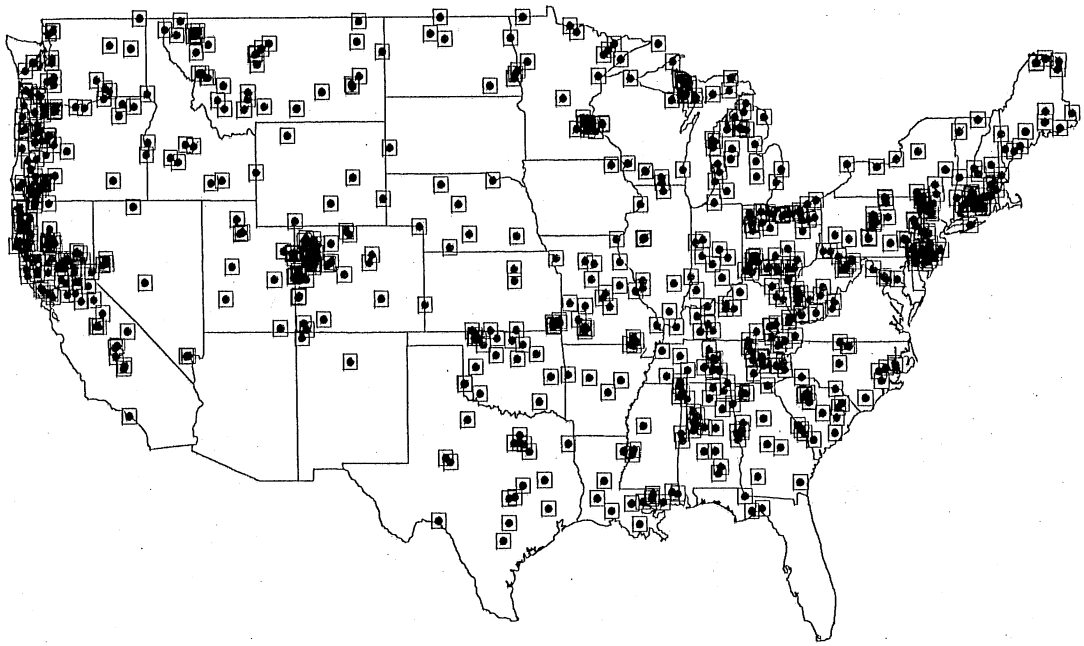
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

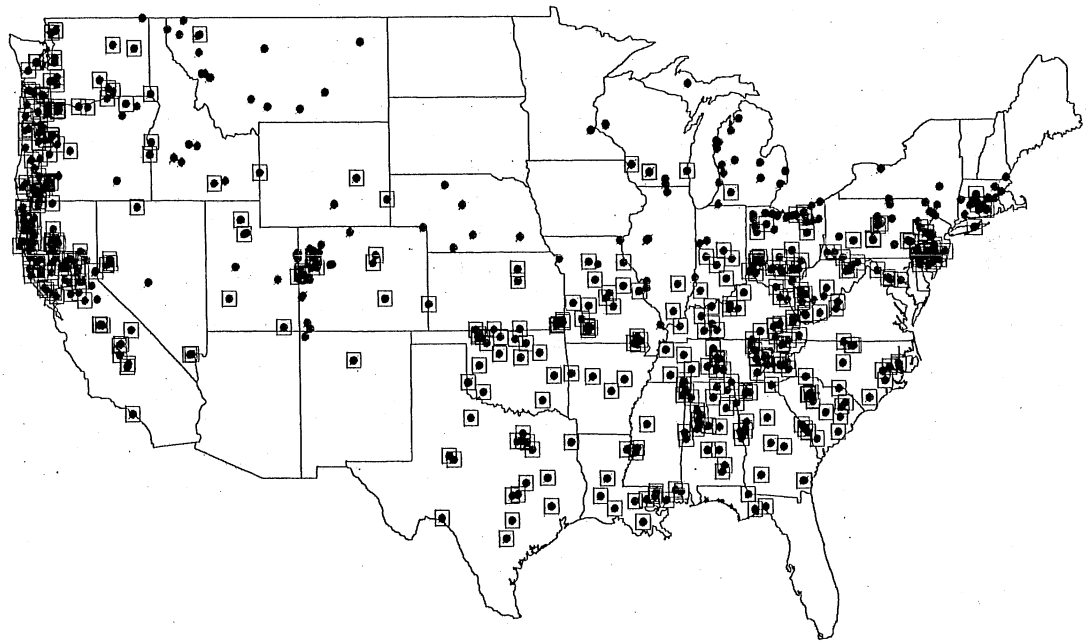
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Red shiner



With 0 °C as the minimum temperature tolerance

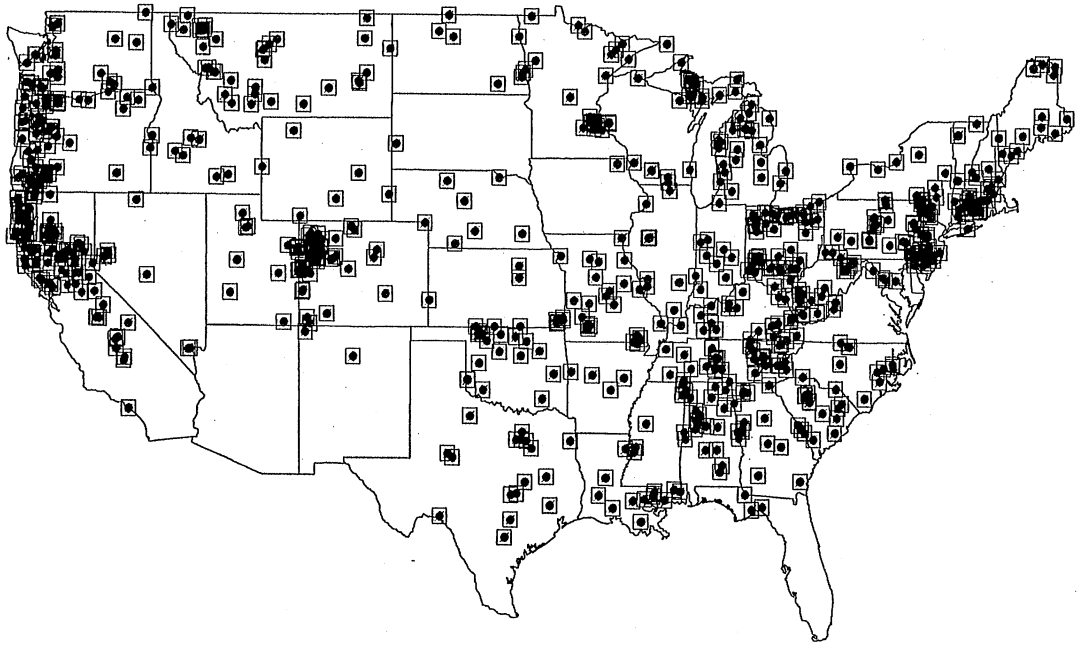
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

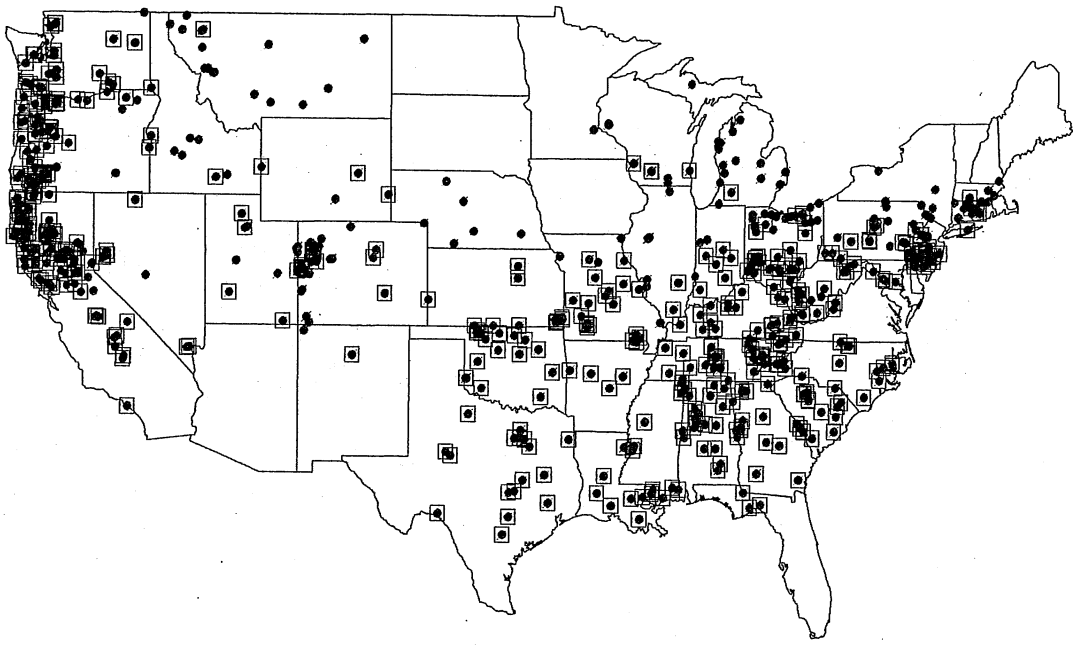
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Smallmouth buffalo



With 0 °C as the minimum temperature tolerance

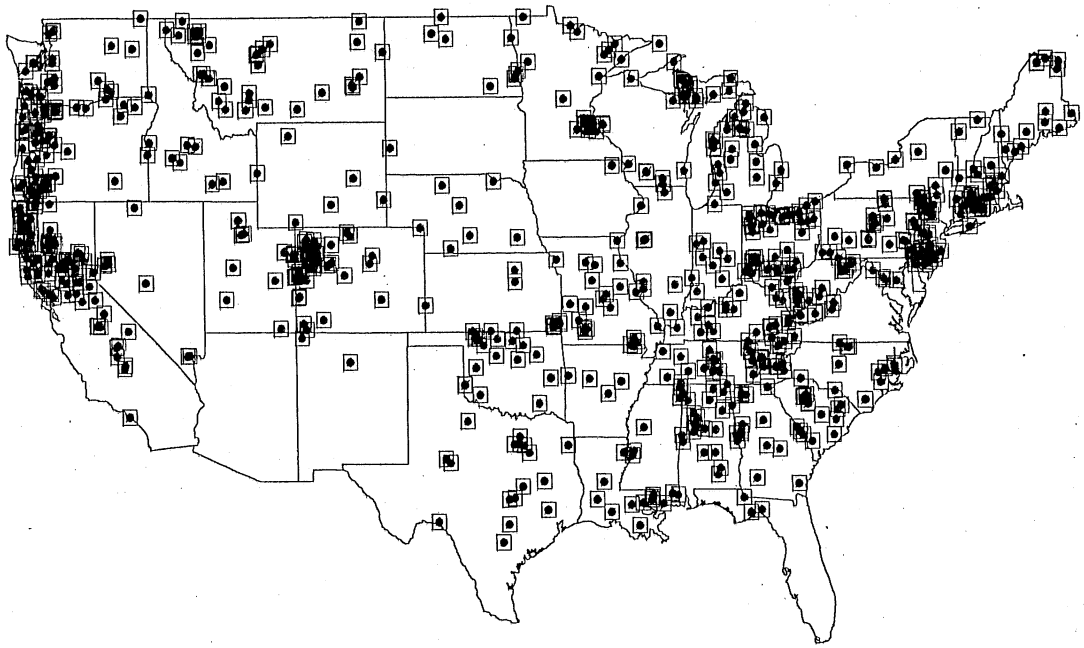
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

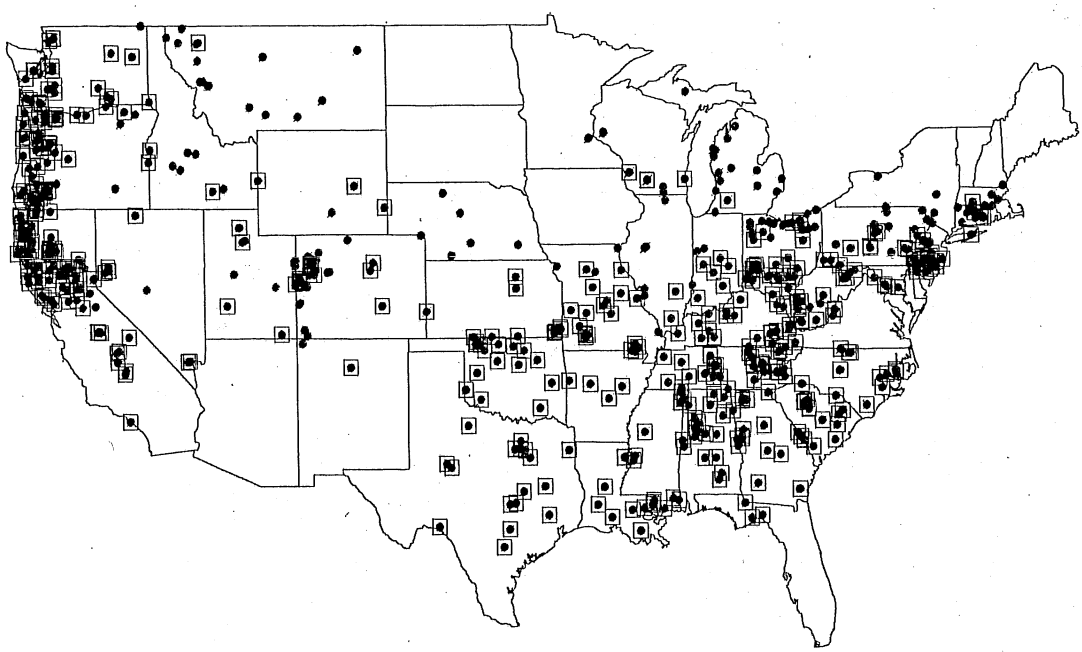
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Warmouth



With 0 °C as the minimum temperature tolerance

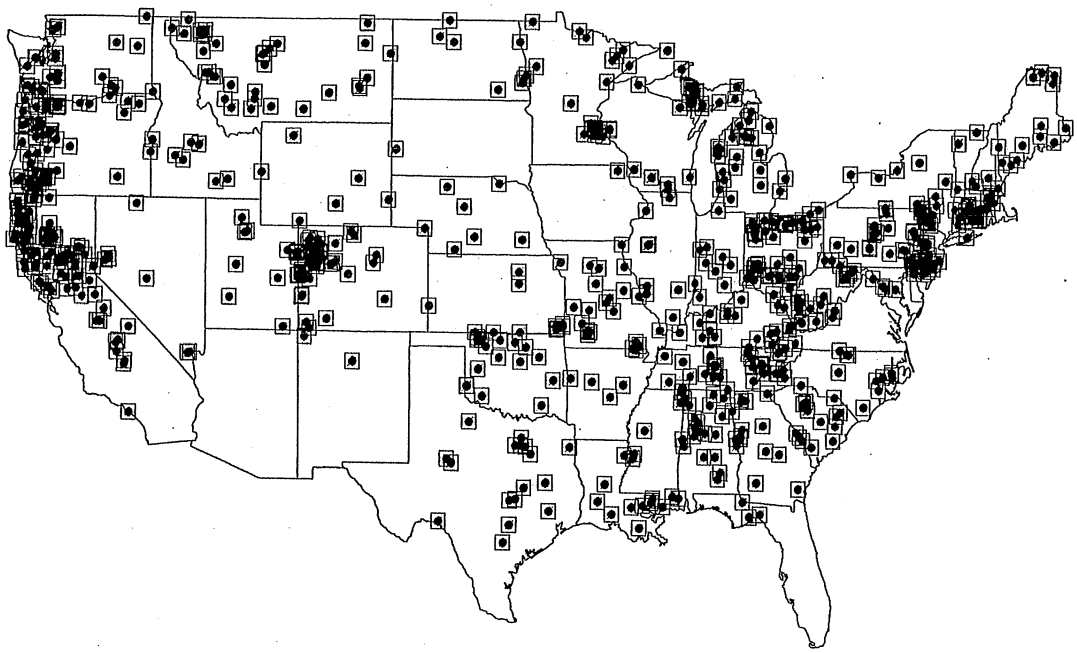
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

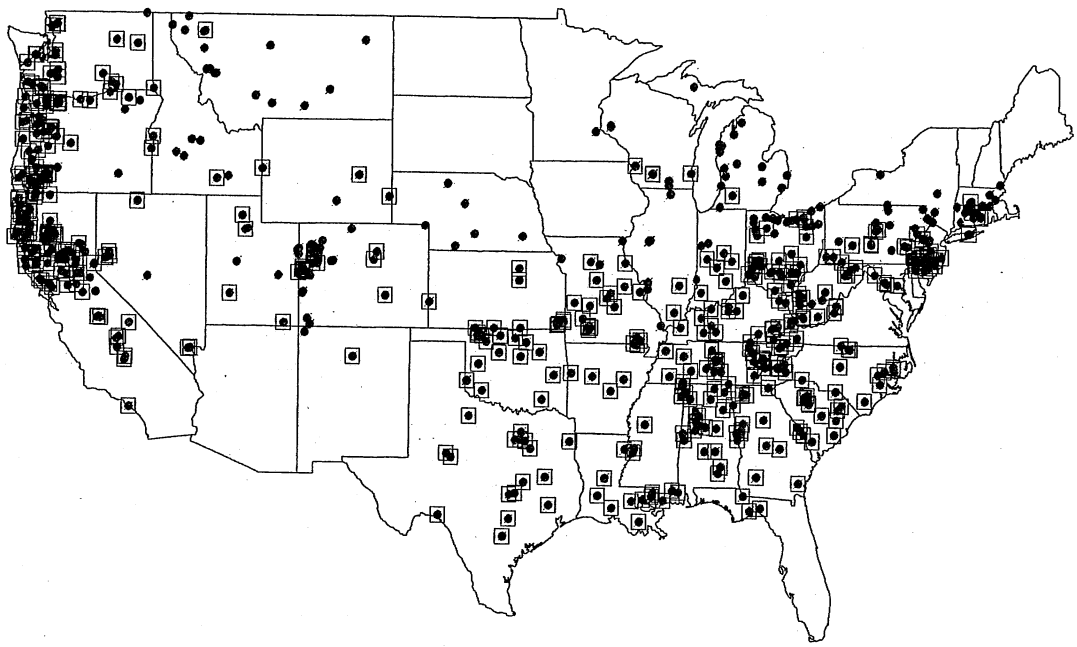
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Common carp



With 0 °C as the minimum temperature tolerance

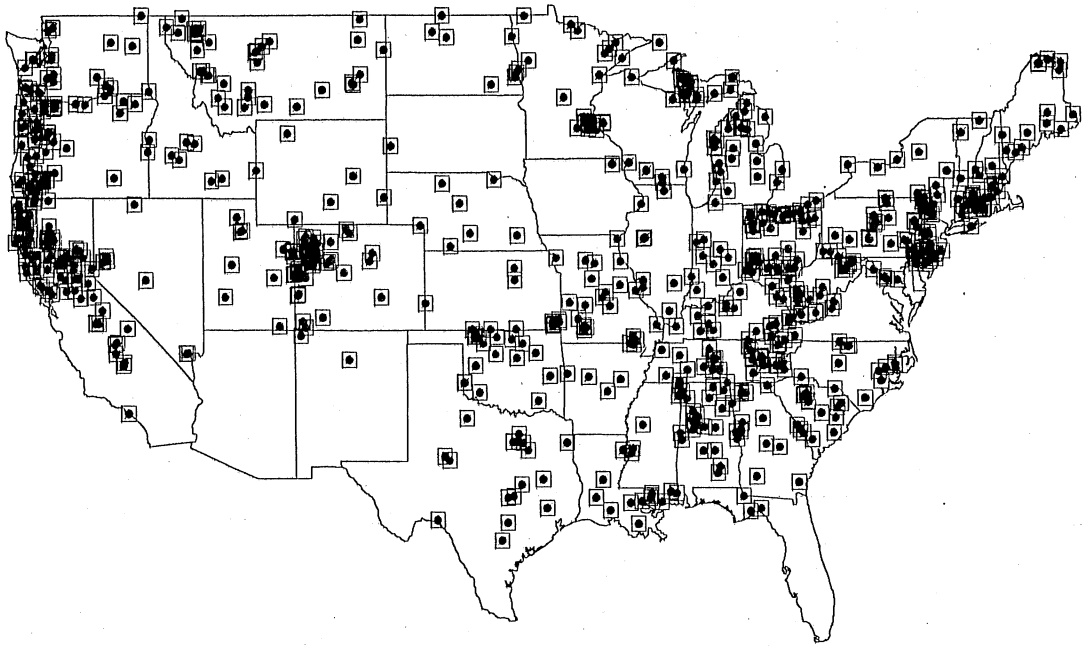
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

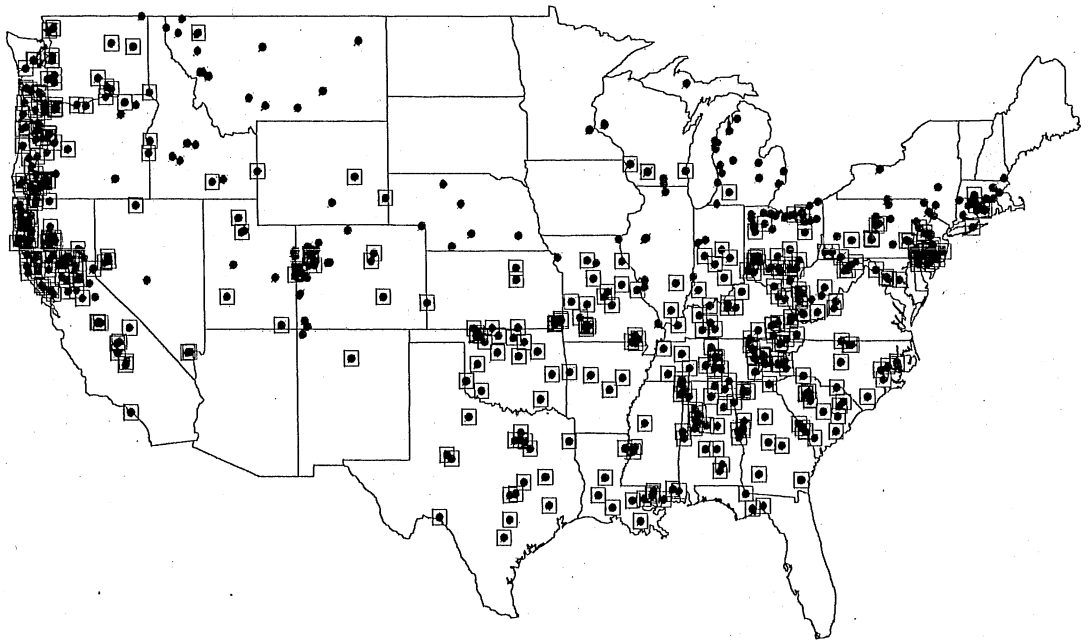
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Channel catfish



With 0 °C as the minimum temperature tolerance

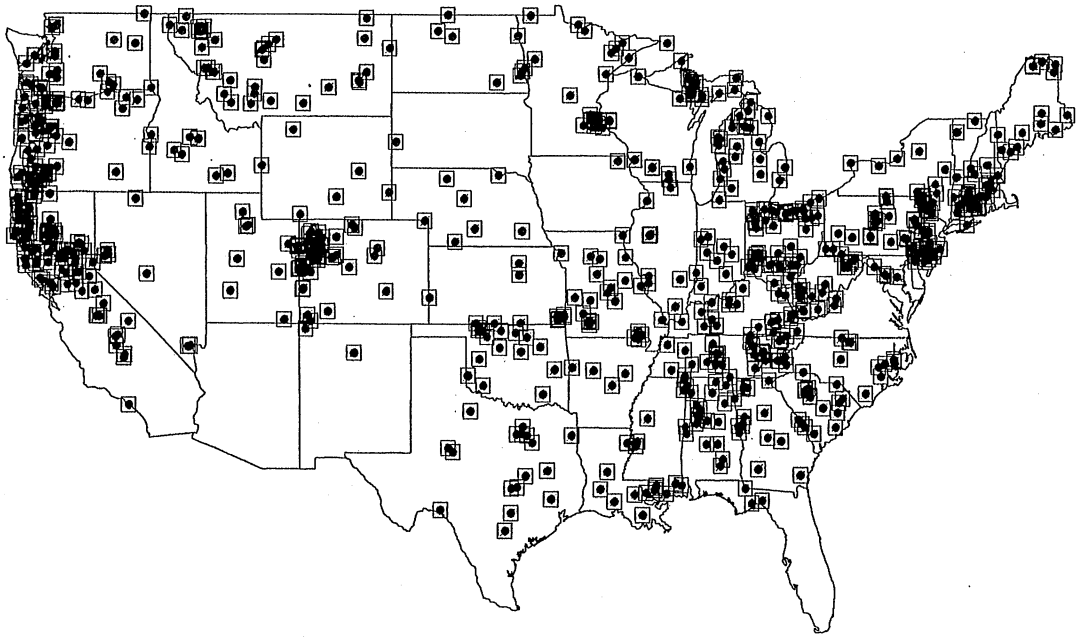
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

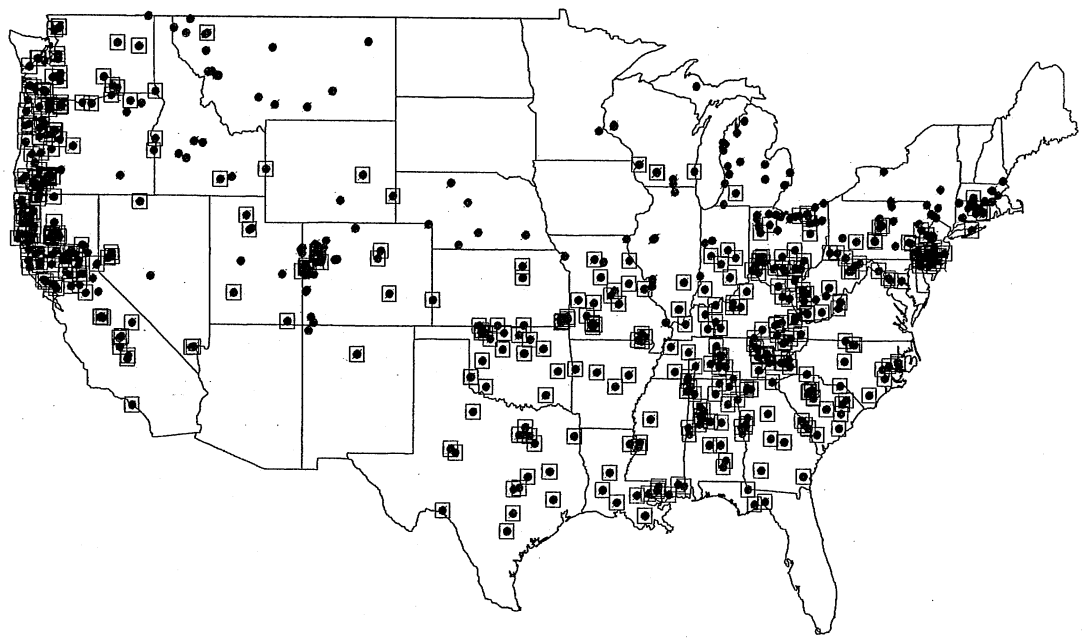
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Largemouth bass



With 0 °C as the minimum temperature tolerance

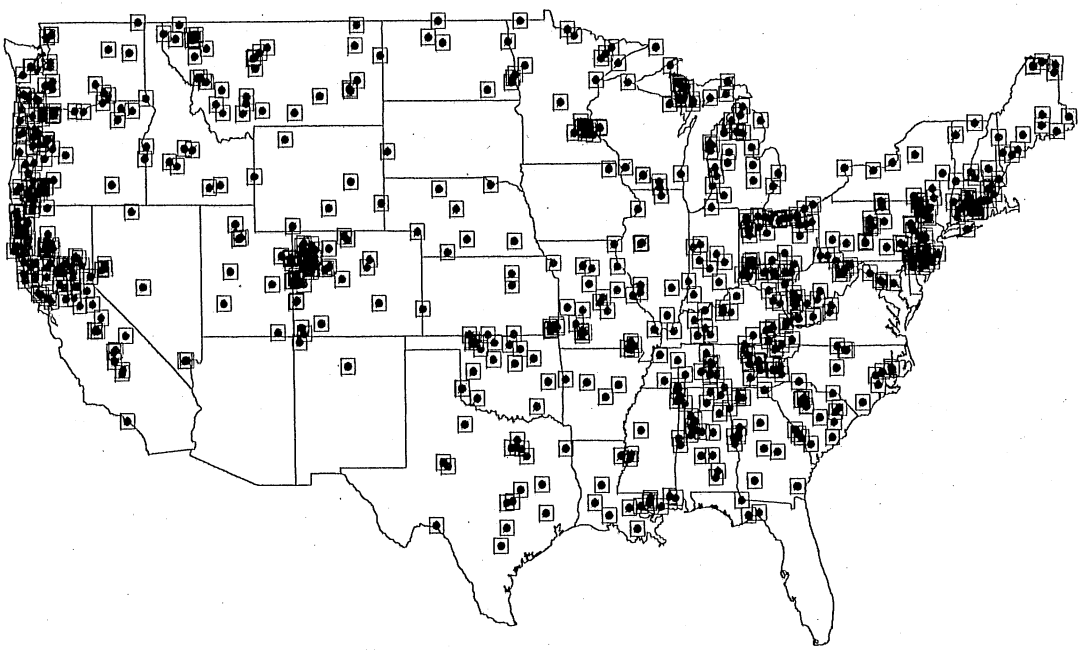
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition



With 2 °C as the minimum temperature tolerance

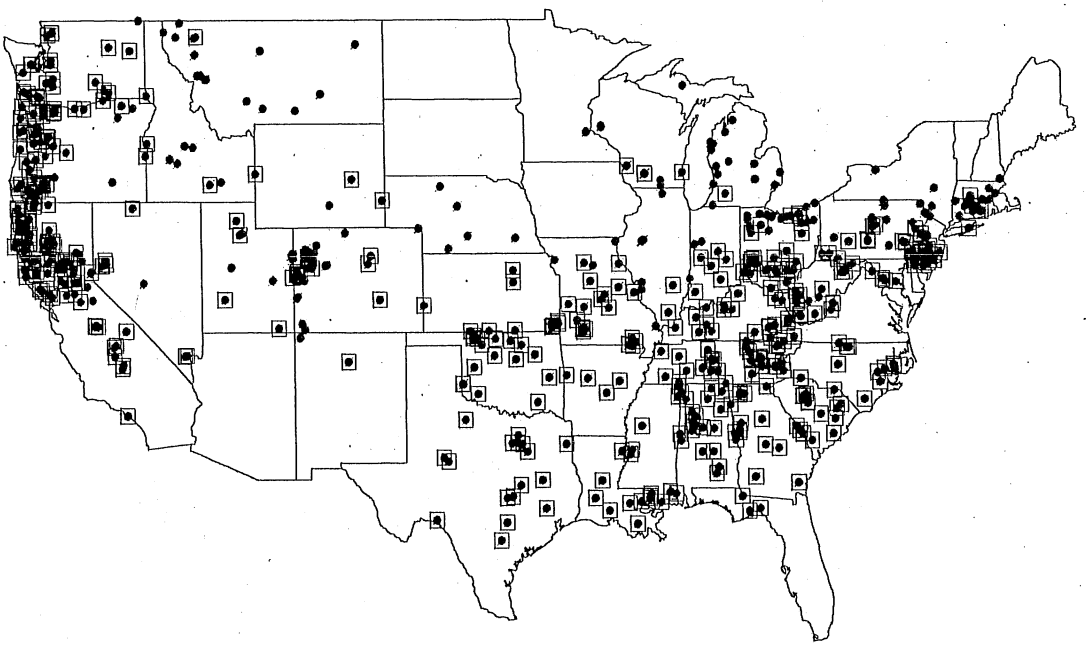
□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Bluegill



With 0 °C as the minimum temperature tolerance

□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

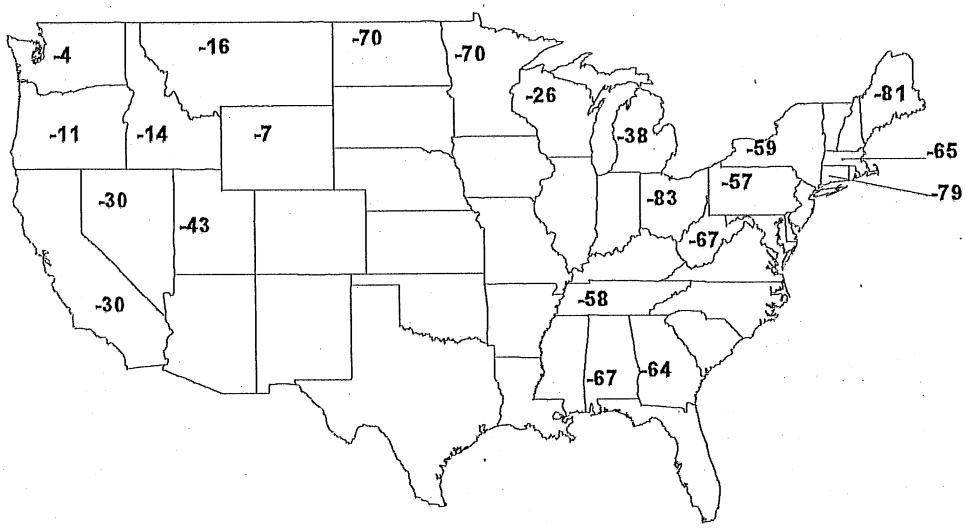


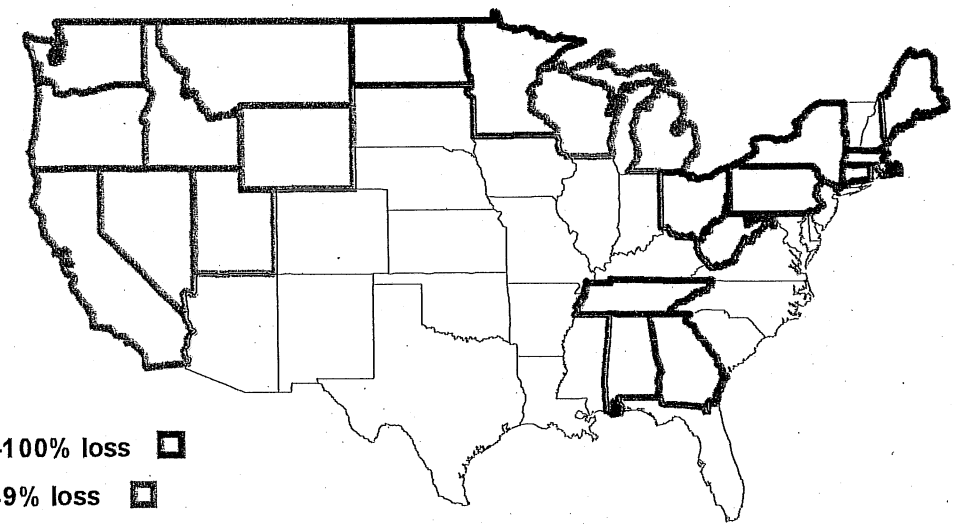
With 2 °C as the minimum temperature tolerance

□ $1xCO_2$ Climate Condition
• $2xCO_2$ Climate Condition

Summary Maps

Cold-water fish percent decrease in potential habitat



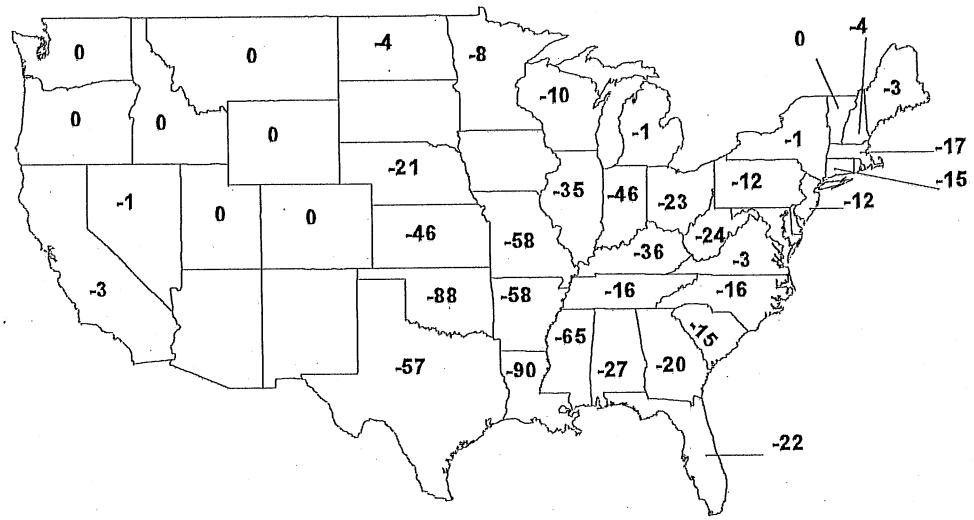


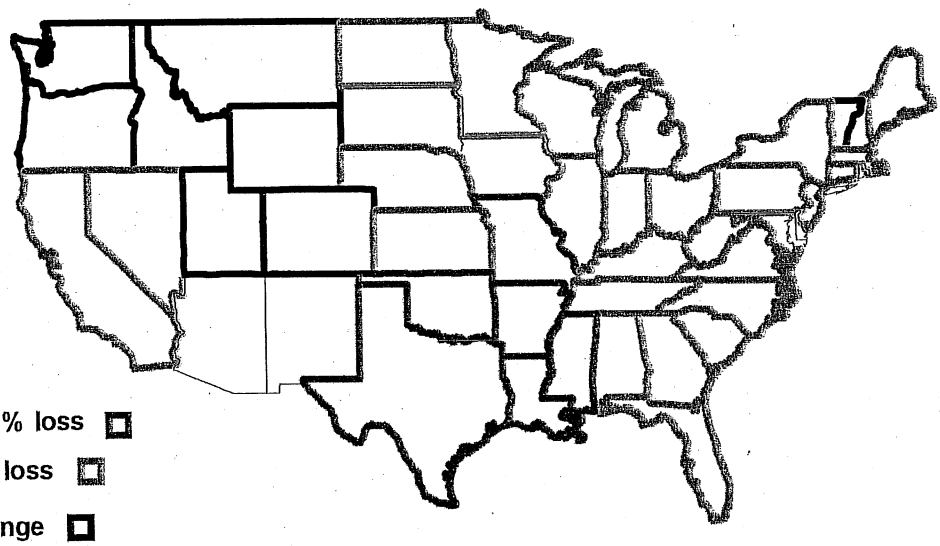
50-100% loss

1-49% loss

Not included in analysis

Cool-water fish percent change in potential habitat
0 °C minimum temperature tolerance





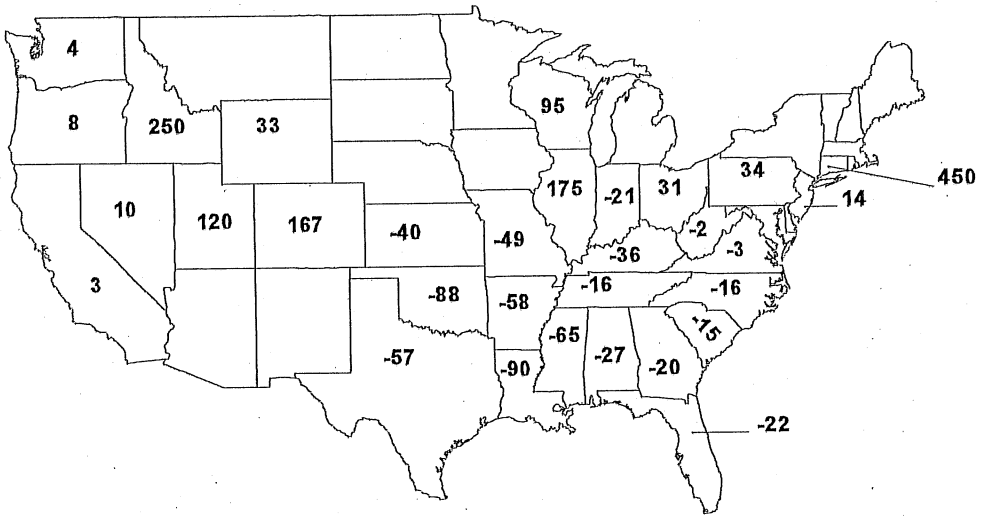
50-100% loss

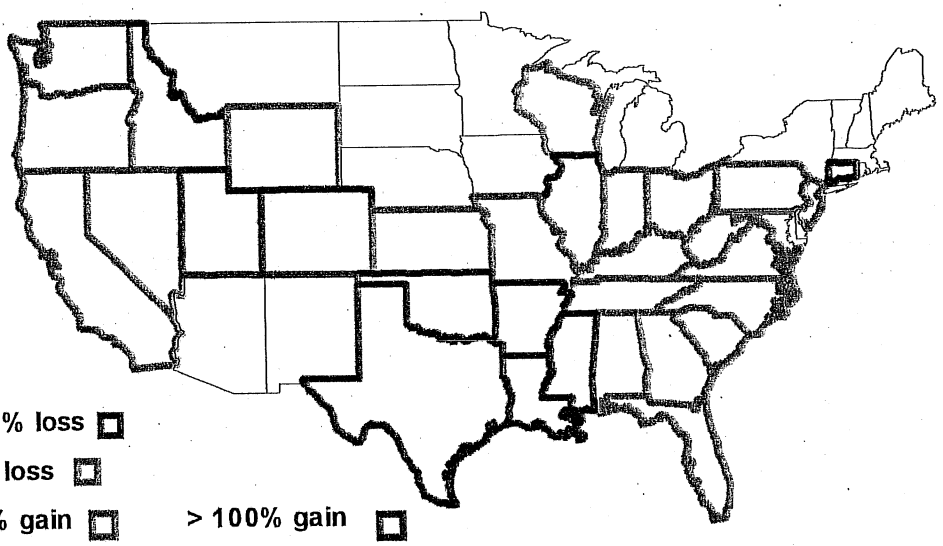
1-49% loss

no change

Not included in analysis

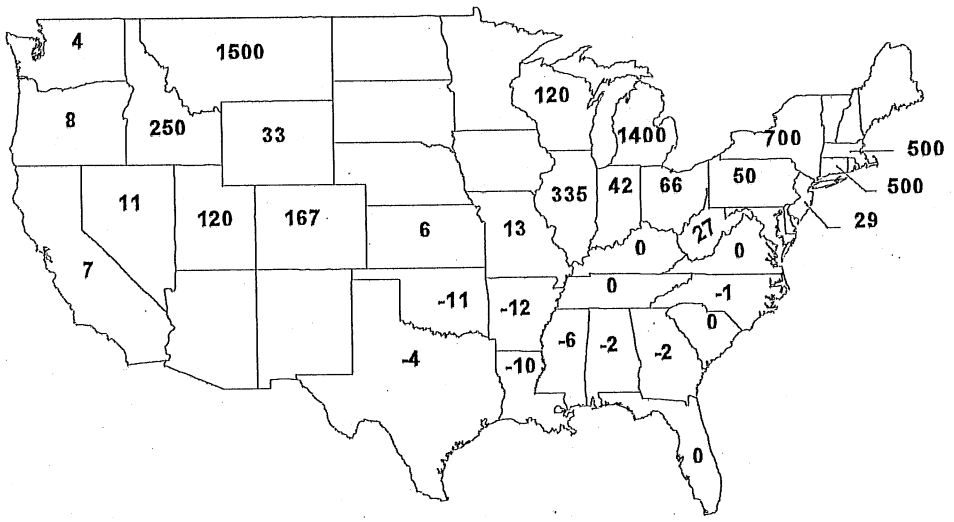
Cool-water fish percent change in potential habitat
2 °C minimum temperature tolerance

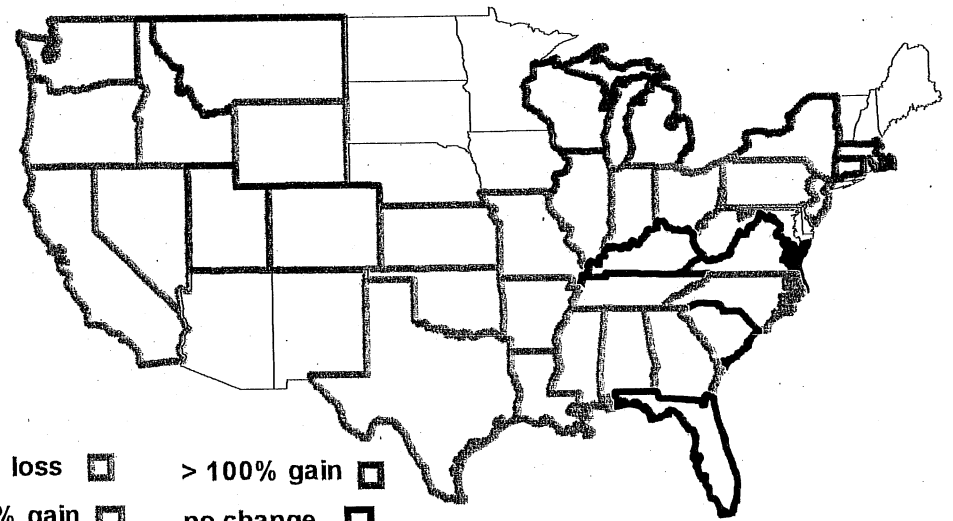




50-100% loss
1-49% loss
1 - 49% gain
50-100% gain
> 100% gain
Not included in analysis

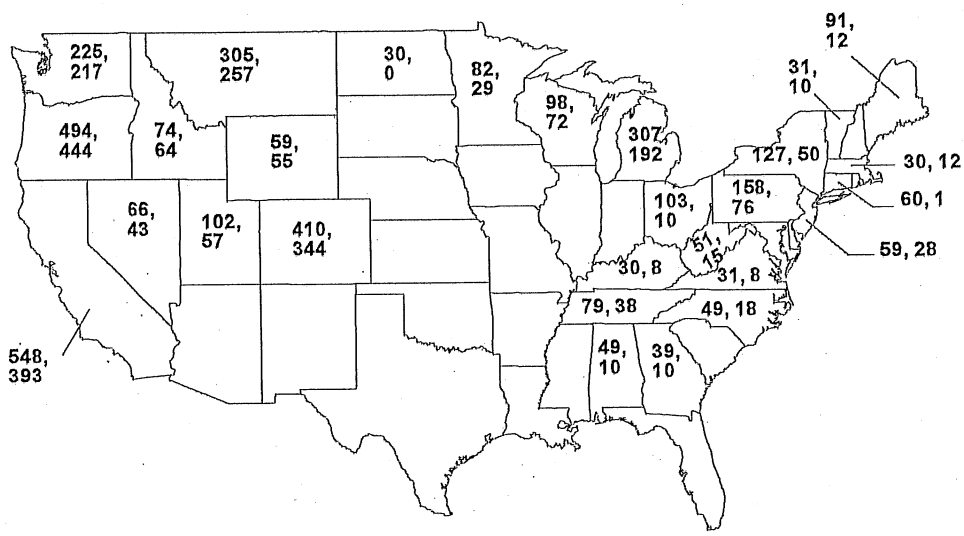
Warm-water fish percent change in potential habitat
2 °C minimum temperature tolerance



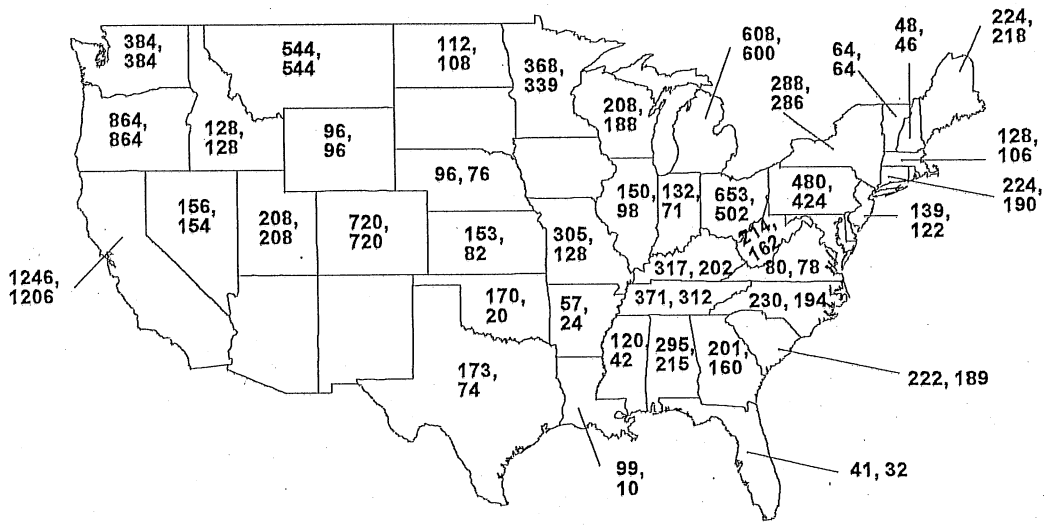


1-49% loss
1 - 49% gain
50-100% gain
> 100% gain
no change
Not included in analysis

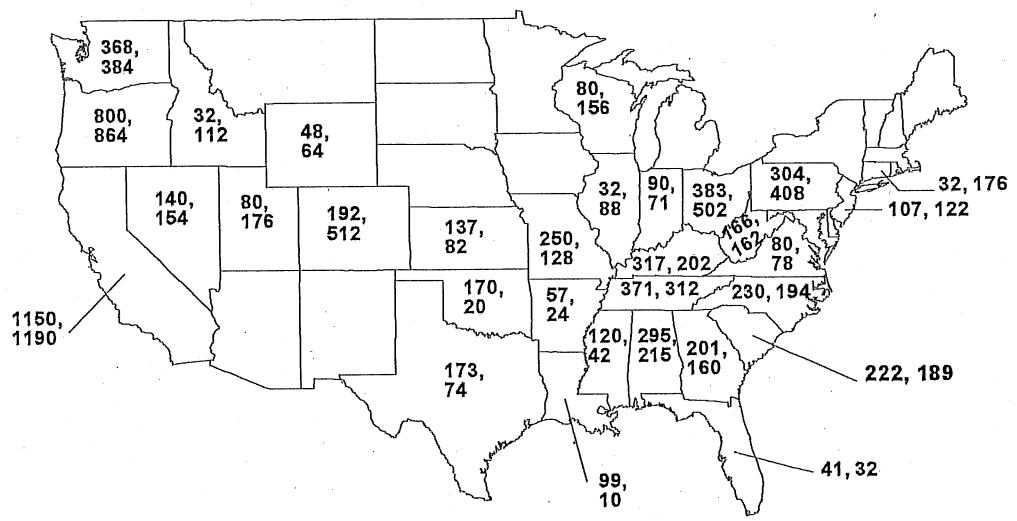
Total number of cold-water fish stations ($1xCO_2$,$2xCO_2$)
0 °C minimum temperature tolerance



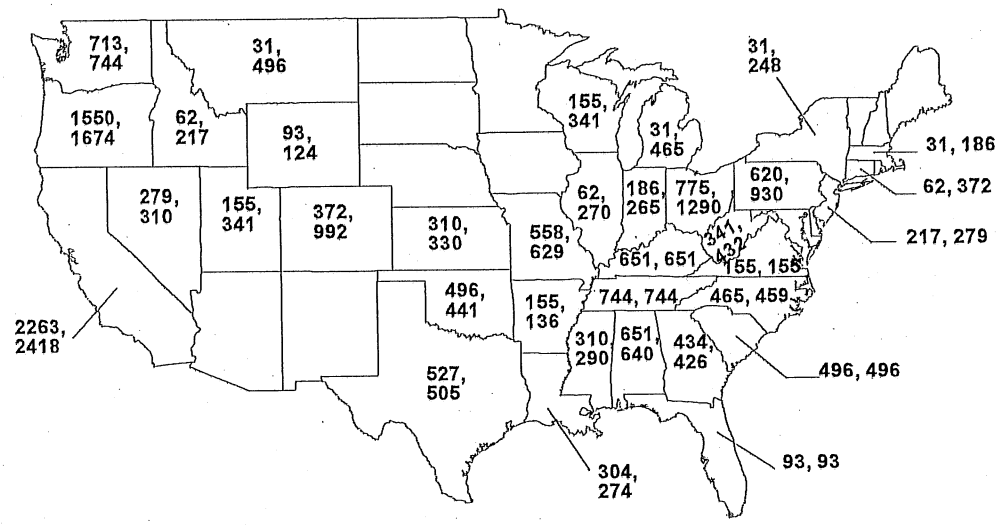
Total number of cool-water fish stations ($1xCO_2$,$2xCO_2$)
0 °C minimum temperature tolerance



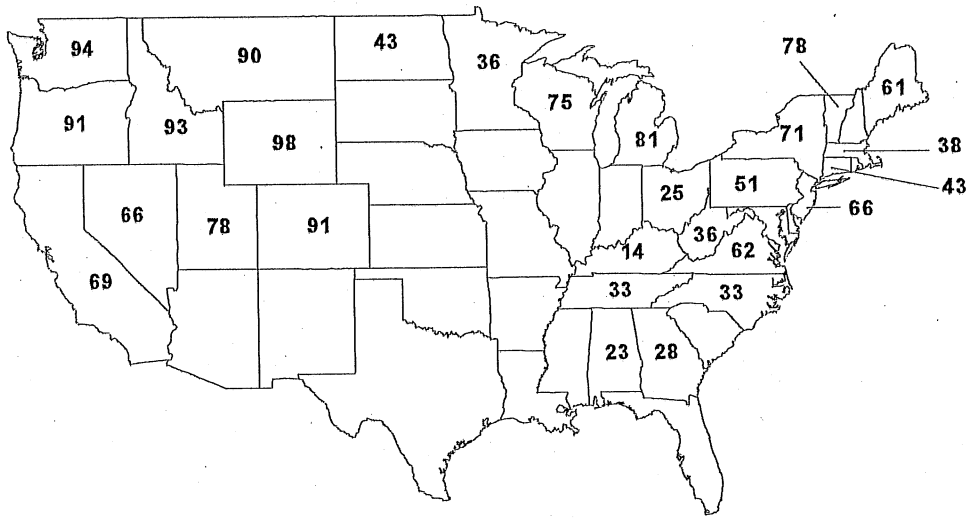
Total number of cool-water fish stations ($1xCO_2$, $2xCO_2$)
2 °C minimum temperature tolerance

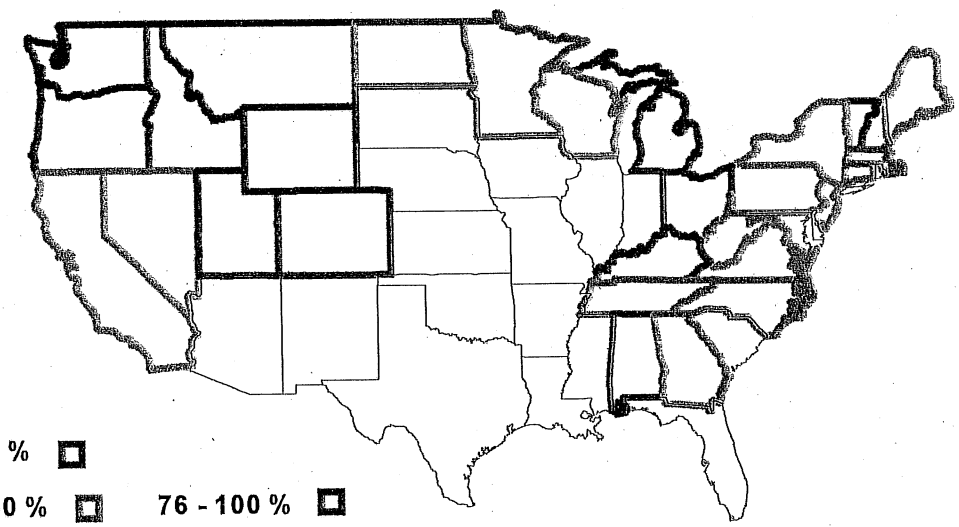


Total number of warm-water fish stations ($1xCO_2$,$2xCO_2$)
2 °C minimum temperature tolerance



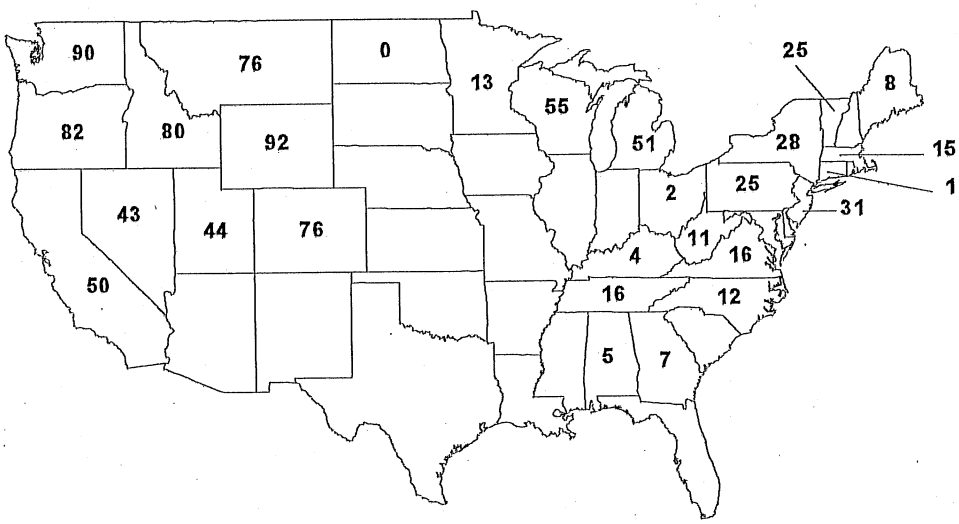
Cold-water fish.
Percent potential habitat with respect to maximum number of fish stations.
0 °C minimum temperature tolerance under 1xCO_2 climate conditions.

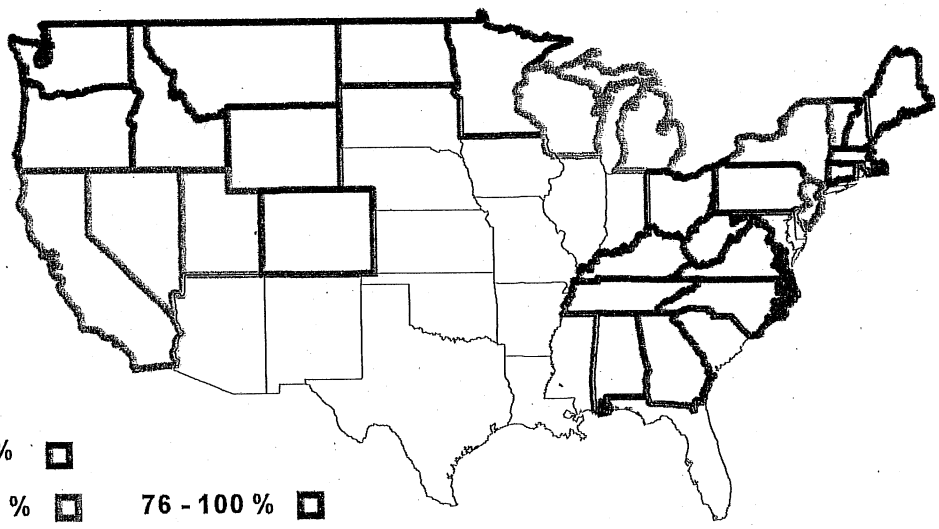




0 - 25 %
26 - 50 %
51 - 75 %
76 - 100 %
Not included in analysis

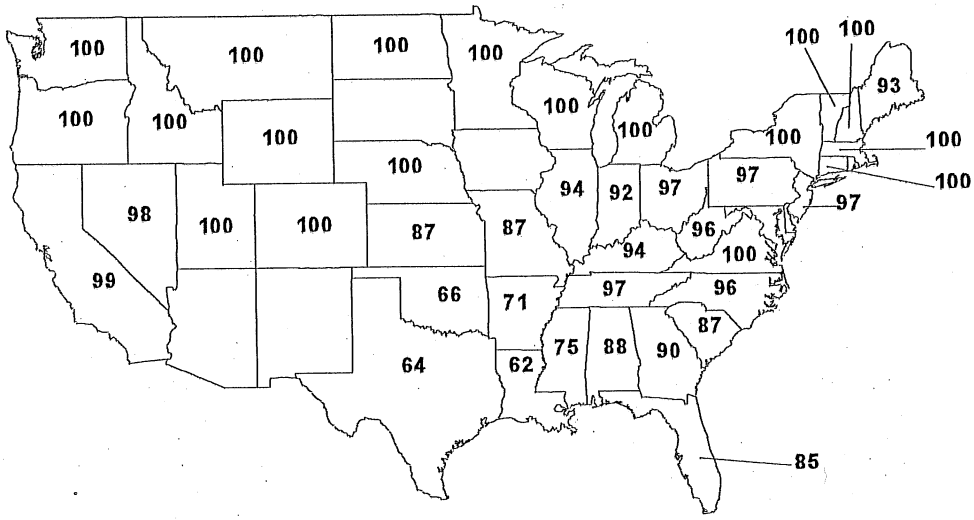
Cold-water fish.
Percent potential habitat with respect to maximum number of fish stations.
0 °C minimum temperature tolerance under 2xCO_2 climate conditions.

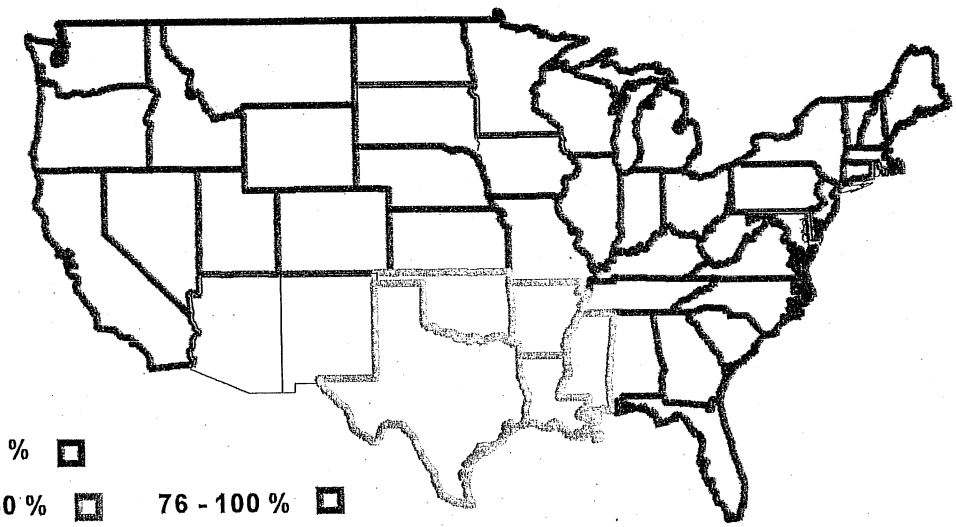




0 - 25 %
26 - 50 %
51 - 75 %
76 - 100 %
Not included in analysis

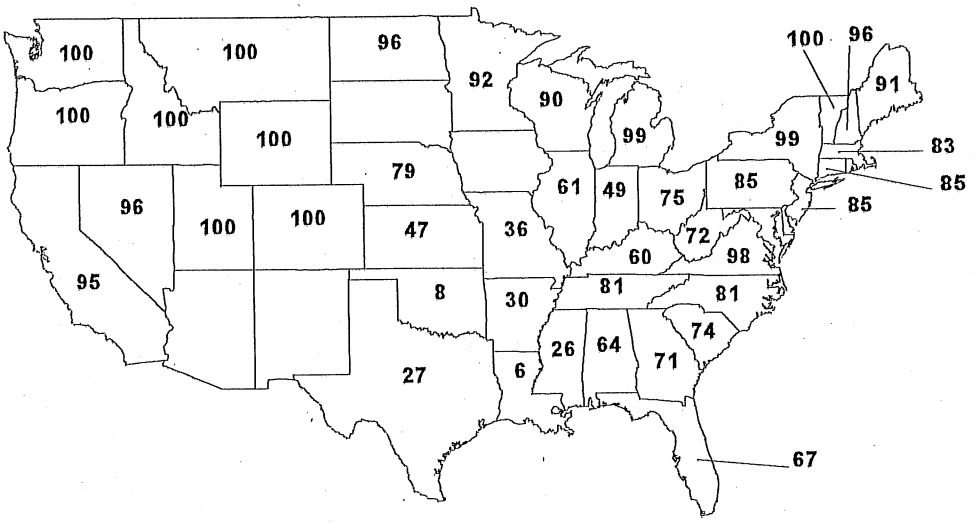
Cool-water fish.
Percent potential habitat with respect to maximum number of fish stations.
0 °C minimum temperature tolerance under 1xCO_2 climate conditions.

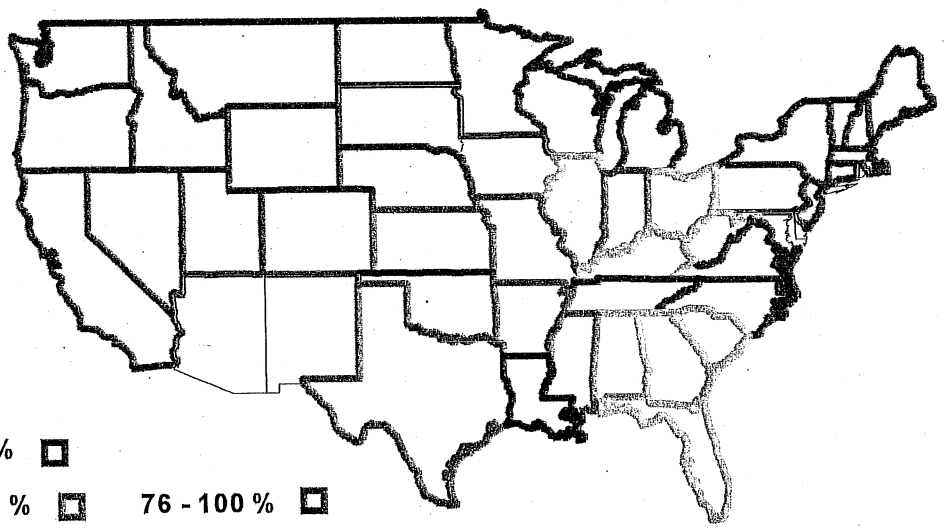




0 - 25 %
26 - 50 %
51 - 75 %
76 - 100 %
Not included in analysis

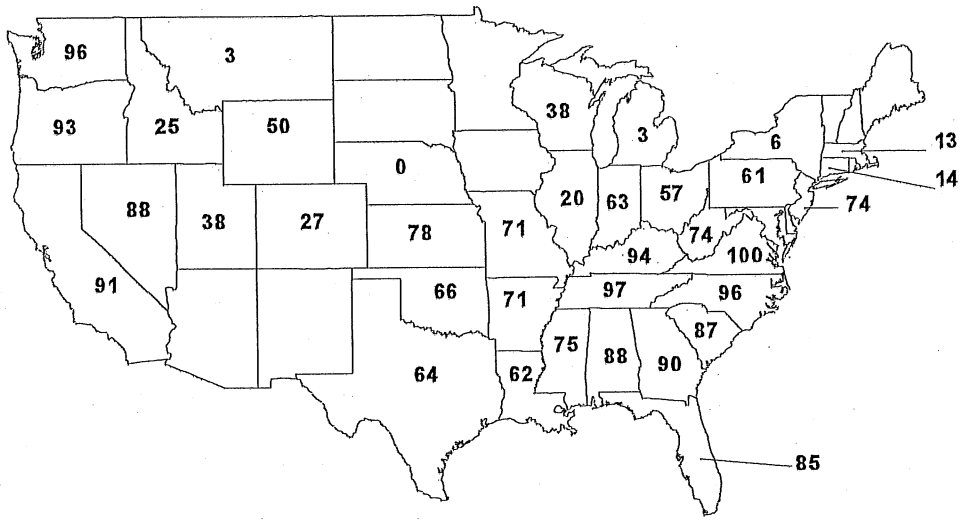
Cool-water fish.
Percent potential habitat with respect to maximum number of fish stations.
0 °C minimum temperature tolerance under $2xCO_2$ climate conditions.

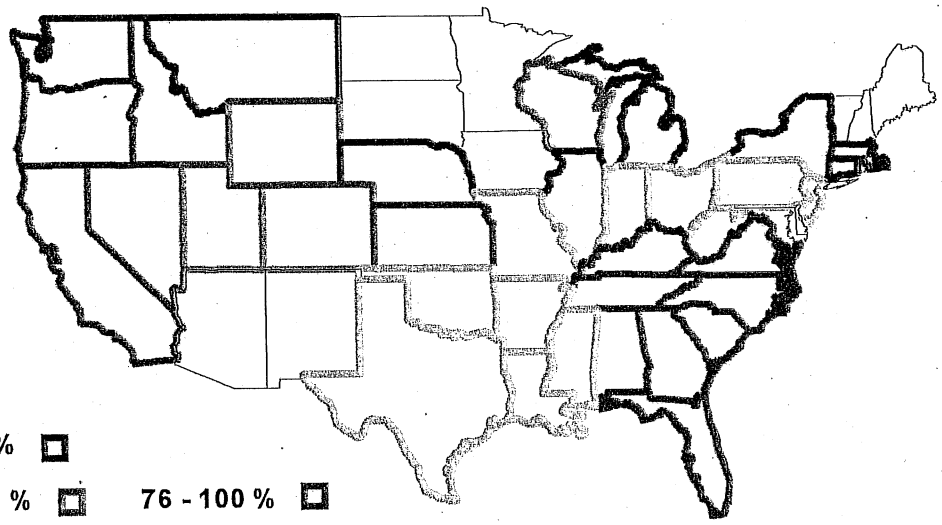




0 - 25 %
26 - 50 %
51 - 75 %
76 - 100 %
Not included in analysis

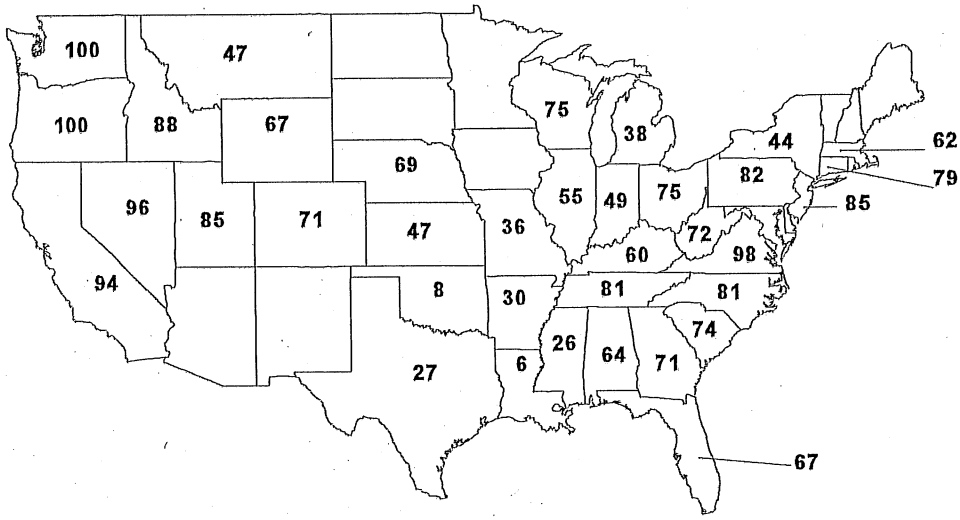
Cool-water fish.
Percent potential habitat with respect to maximum number of fish stations.
2 °C minimum temperature tolerance under 1xCO_2 climate conditions.

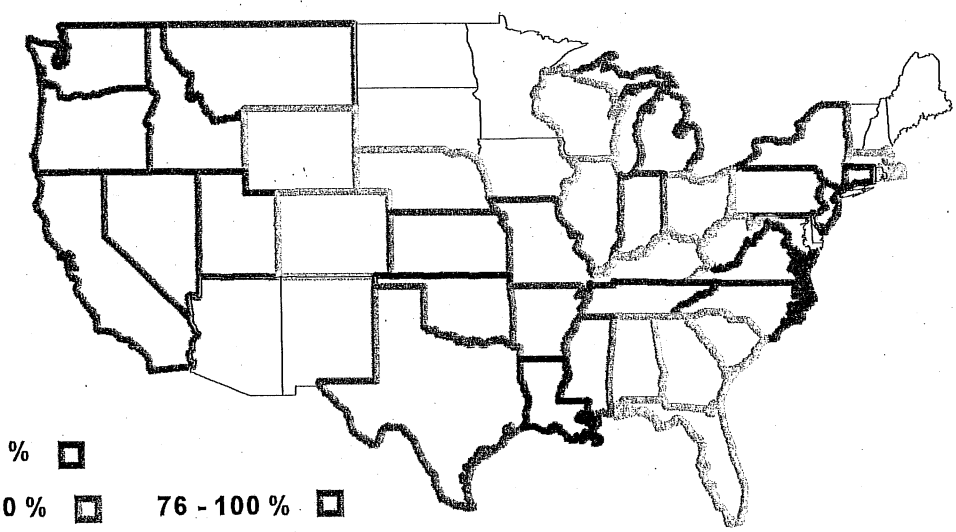




0 - 25 %
26 - 50 %
51 - 75 %
76 - 100 %
Not included in analysis

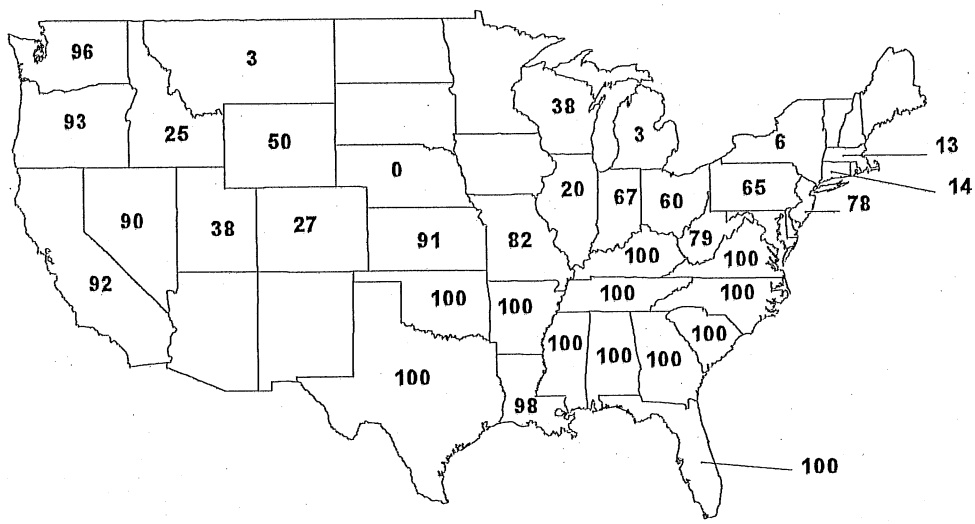
Cool-water fish.
Percent potential habitat with respect to maximum number of fish stations.
2 °C minimum temperature tolerance under 2xCO_2 climate conditions.

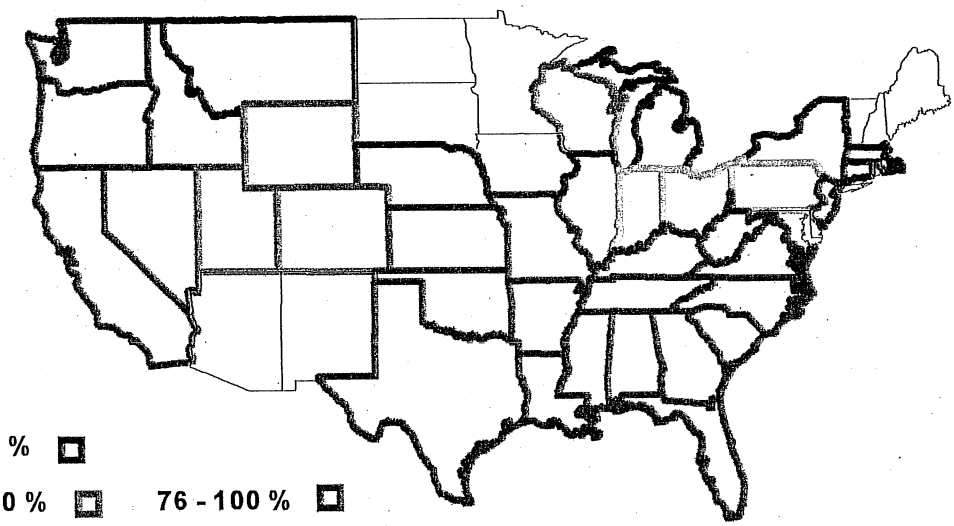




0 - 25 %
26 - 50 %
51 - 75 %
76 - 100 %
Not included in analysis

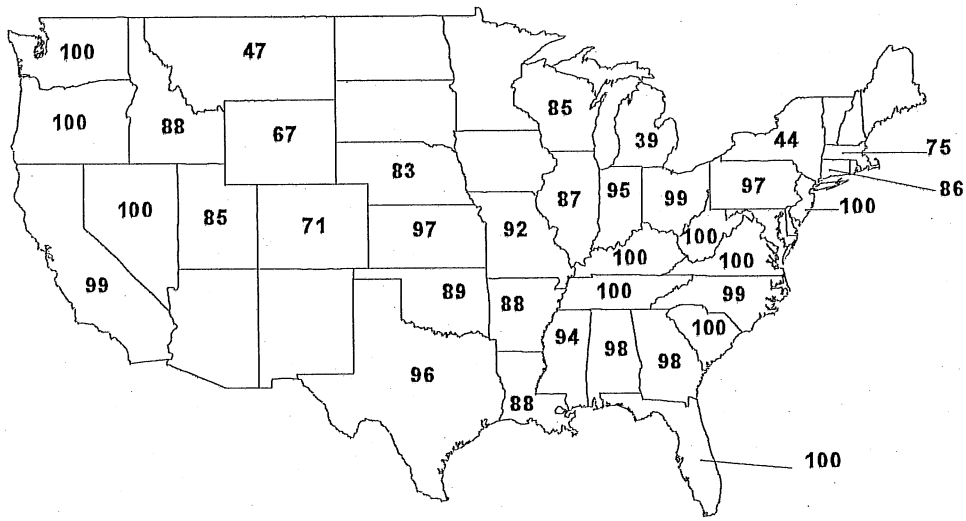
Warm-water fish.
Percent potential habitat with respect to maximum number of fish stations.
2 °C minimum temperature tolerance under 1xCO_2 climate conditions.

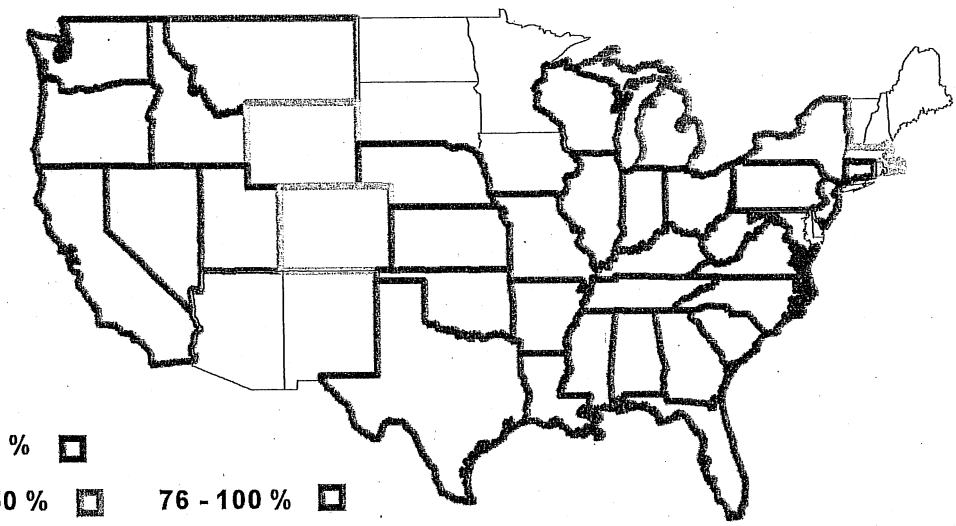




0 - 25 %
26 - 50 %
51 - 75 %
76 - 100 %
Not included in analysis

Warm-water fish.
Percent potential habitat with respect to maximum number of fish stations.
2 °C minimum temperature tolerance under 2xCO_2 climate conditions.





0 - 25 %
26 - 50 %
51 - 75 %
76 - 100 %
Not included in analysis